



PAGE PARTNERSHIP FOR ACTION
ON GREEN ECONOMY



वस्त्र मंत्रालय
MINISTRY OF
TEXTILES



INDIA TEXTILE TECHNOLOGY & INNOVATION COMPENDIUM

TECHNOLOGIES SHAPING
A COMPETITIVE, SUSTAINABLE
AND FUTURE-READY TEXTILE
VALUE CHAIN

Aligned with the 5F Vision



Vision 2030 | Viksit Bharat 2047

SEPTEMBER 2026



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Acknowledgements

This report has been developed by the United Nations Industrial Development Organization (UNIDO) under the Partnership for Action on Green Economy (PAGE), in close cooperation with the Ministry of Environment, Forest and Climate Change (MoEFCC) and the Ministry of Textiles, Government of India. PAGE is a joint United Nations initiative comprising UNEP, UNDP, ILO, UNIDO and UNITAR, supporting countries in advancing inclusive, resource-efficient and low-carbon development.

UNIDO expresses its sincere appreciation to Ms. Arti Kanwar (IAS), Additional Secretary, Ministry of Textiles, Government of India, for her strategic leadership in advancing the sustainable transformation of the textile sector; Mr. Gopal, Director (Sustainability), Ministry of Textiles, for his valuable technical and policy guidance throughout the preparation of this report; and Mr. Amit Raj, Director (HSMD), Ministry of Environment, Forest and Climate Change (MoEFCC), for his strategic direction and support to the PAGE programme.

The report benefited from the technical oversight and guidance of Dr. Cristiano Pasini, UNIDO Representative and Director of the UNIDO Sub-Regional Office in India; Ms. Ozunimi ITI Lilian, Industrial Development Officer, UNIDO (Vienna); and Dr. Pankaj Kumar, National Project Coordinator, UNIDO (India). Special appreciation is extended to Ms. Bahumi Motthanka Botho and Mr. Carlo Giuseppe Gussoni of UNIDO, and Ms. Manisha Choudhary, National Coordinator, PAGE Programme, UNEP India, for their constructive reviews, continuous support, and valuable contributions throughout the preparation of this report.

UNIDO gratefully acknowledges the lead authorship of the Centre for Environment Education (CEE) for undertaking the assignment under PAGE, including the development of the Technology and Innovation Roadmap, baseline assessment, and Technology Compendium featuring more than 100 proposed technologies. The background analysis and stakeholder consultations undertaken as part of this work significantly contributed to the development of the Technology and Innovation Roadmap for Sustainable Textile Manufacturing in India 2047.

UNIDO also extends its appreciation to representatives from industry, government, academia, research institutions, and other stakeholders who contributed valuable insights throughout the consultation process, including through stakeholder workshops organised by CEE in collaboration with the Textile Machinery Manufacturers Association (TMMA) and the Clothing Manufacturers Association of India (CMAI) in Mumbai, the Gujarat Chamber of Commerce and Industry (GCCl) in Ahmedabad, and the Ministry of Textiles, Government of India, in New Delhi.

PAGE also acknowledges the generous support of its funding partners, including the European Union, the Governments of Germany, Finland, Norway and the Republic of Korea, the Swedish International Development Cooperation Agency (Sida), and the Swiss State Secretariat for Economic Affairs (SECO). The collective contributions of all partners and stakeholders have been invaluable in shaping this report and advancing the sustainable transformation of India's textile sector.



CONTENTS

1. The Transformation Imperative	01
1.1. The Export Challenge - Why Technology-Led Transformation Is Needed	02
1.1.1. The \$100 Billion Bridge - Where Will the Growth Come From?	03
1.2. The 5F Vision - Technology Alignment	04
1.3. Global Leaders’ Technology Profile	07
1.4. India's Technology Gaps (Baseline Summary).	11
2. Technology Transformation Pathway.	15
2.1. Align (2026–2030)	16
2.2. Amplify (2030–2035)	17
2.3. Accelerate (2035–2047)	18
3. Technology Inventory.	19
3.1. Where Urgency Concentrates: Technology Priority Map	20
3.2. Foundational Technologies	22
3.2.1. F0 Technology Priority.	22
3.2.2. Align (2026–2030)	26
3.2.3. Amplify (2030–2035)	27
3.2.4. Accelerate (2035-2047).	28
3.3. Farm (F1): Raw Material and Primary Processing	30
3.3.1. F1 Technology Priority Stack.	31
3.3.2. Align (2026–2030).	32
3.3.3. Amplify (2030–2035).	32
3.3.4. Accelerate (2035–2047).	33
3.3.5. Stage Linkage.	34
3.4. Fibre (F2): Spinning, Texturing and Recycled Fibre.	34
3.4.1. F2 Technology Priority Stack.	35
3.4.2. Align (2026–2030).	37

3.4.3. Amplify (2030–2035). 39

 3.4.4. Accelerate (2035–2047). 40

 3.4.5. Stage Linkage. 41

3.5. Factory - Dry (F3): Weaving and Knitting. 42

 3.5.1. F3 Dry Technology Priority Stack. 43

 3.5.2. Align (2026–2030). 45

 3.5.3. Amplify (2030–2035). 45

 3.5.4. Accelerate (2035–2047). 46

 3.5.5. Stage Linkage. 47

3.6. Factory – Wet (F3): Dyeing, Printing and Finishing. 47

 3.6.1. F3 Wet Technology Priority Stack 49

 3.6.2. Align (2026–2030) 52

 3.6.3. Amplify (2030–2035) 53

 3.6.4. Accelerate (2035–2047). 55

 3.6.5. Stage Linkage 57

3.7. Fashion (F4): Garmenting and Apparel Manufacturing 57

 3.7.1. F4 Technology Priority Stack. 59

 3.7.2. Align (2026–2030) 60

 3.7.3. Amplify (2030–2035) 61

 3.7.4. Accelerate (2035–2047). 61

 3.7.5. Stage Linkage 63

3.8. Foreign (F5): Traceability, Compliance and Export Readiness 63

 3.8.1. F5 Technology Priority Stack. 65

 3.8.2. Align (2026–2030) 66

 3.8.3. Amplify (2030–2035) 67

 3.8.4. Accelerate (2035–2047). 67

 3.8.5. The Data Thread: How Technology Investments Connect to Export Access. 68

4. Implementation Framework 71

4.1. The Transformation Imperative 72

4.2. Upgradation Pathway 73

4.3. Enabling Conditions 75

 4.3.1. EC 1 - Financing and Investment 75

 4.3.2. EC 2 - Regulatory and Policy Signals 75

 4.3.3. EC 3 - Skills and Institutional Capacity 76

5. Way Forward Towards Roadmap. 77

6. Annexures 79

 6.1. Annexure I – Technologies At A Glance 80

 6.2. Annexure II – Technology Cards 85

LIST OF FIGURES

Figure 1 - Country-wise Exports 2024. 02

Figure 2 - Technology Gap Heatmap - India's 5F Value Chain 21

Figure 3 - The 5F Data Thread - From T1 Technology Investment to DPP Issuance 69

LIST OF TABLES

Table 1 - 5F Technology Map - Gaps, Technologies, and Compendium Coverage 06

Table 2 - Consolidated Technology Gap Assessment. 11

Table 3 - 5F Primary Export Levers 12

Table 4 - Technology Priority Stack for Foundational Technologies 24

Table 5 - Technology Priority Stack for Farm Stage 31

Table 6 - Technology Priority Stack for Fibre Stage 36

Table 7 - Technology Priority Stack for Factory (Dry) Stage. 44

Table 8 - Technology Priority Stack for Factory (Wet) Stage 49

Table 9 - Technology Priority Stack for Fashion Stage. 59

Table 10 - Technology Priority Stack for Foreign Compliance. 65

Table 11 - 5F Cost vs Opportunity. 72

ABBREVIATIONS

Abbreviation	Full Form
5F	Farm to Fibre to Factory to Fashion to Foreign
AI	Artificial Intelligence
AOP	Advanced Oxidation Process
BAU	Business-as-Usual
BAT	Best Available Techniques
BCI	Better Cotton Initiative
BREF	Best Available Techniques Reference Document
CAD/CAM	Computer-Aided Design / Computer-Aided Manufacturing
CAPEX	Capital Expenditure
CBAM	Carbon Border Adjustment Mechanism
CEE	Centre for Environment Education
CAGR	Compound Annual Growth Rate
DPP	Digital Product Passport
EC	Enabling Condition
ESG	Environmental, Social and Governance
ESPR	Ecodesign for Sustainable Products Regulation
ETP	Effluent Treatment Plant
EU	European Union
EVFTA	EU-Vietnam Free Trade Agreement
FTA	Free Trade Agreement
GI	Geographical Indication
GOTS	Global Organic Textile Standard
GRS	Global Recycled Standard
IoT	Internet of Things
ISM	Integrated Spinning Management
LLR	Low Liquor Ratio

MBR	Membrane Bioreactor
MES	Manufacturing Execution System
MITRA	Mega Integrated Textile Region and Apparel
MMCF	Man-Made Cellulosic Fibre
MMF	Man-Made Fibre
MRSL	Manufacturing Restricted Substances List
MSME	Micro, Small and Medium Enterprises
NFC	Near-Field Communication
NHDC	National Handloom Development Corporation
NIR	Near-Infrared
NTTM	National Technical Textiles Mission
OPEX	Operational Expenditure
PAGE	Partnership for Action on Green Economy
PALF	Pineapple Leaf Fibre
PFAS	Per- and Polyfluoroalkyl Substances
PIB	Press Information Bureau
PLA	Polylactic Acid
PLI	Production Linked Incentive
RFID	Radio Frequency Identification
R&D	Research and Development
RPET	Recycled Polyethylene Terephthalate
RWS	Responsible Wool Standard
TRL	Technology Readiness Level
UASB	Upflow Anaerobic Sludge Blanket
UNIDO	United Nations Industrial Development Organization
ZDHC	Zero Discharge of Hazardous Chemicals
ZLD	Zero Liquid Discharge

EXECUTIVE SUMMARY

India's textile and apparel sector stands at a pivotal moment in its transformation towards **Viksit Bharat 2047**. Contributing approximately **USD 175.7 billion** in domestic production, **USD 37.7 billion** in exports (FY 2024–25), and providing direct employment to over **45 million** people, the sector is one of India's largest manufacturing industries and among the few globally with a fully integrated **Farm to Fibre to Factory to Fashion to Foreign (5F)** value chain. Despite these structural strengths, India accounts for only around **4.1% of global textile and apparel trade**, ranking as the world's sixth-largest textile exporter. The Government of India has set an ambitious target of **USD 100 billion in textile and apparel exports by 2030**, alongside the broader vision of positioning the textile sector as a key contributor to **Viksit Bharat 2047**. Achieving this ambition requires a significant acceleration beyond the current business-as-usual trajectory and demands a technology-led transformation across the entire value chain.

The **India Textile Technology & Innovation Roadmap 2047** establishes the long-term vision, strategic priorities, and phased transformation pathway for the sector. **This Technology Compendium complements the Roadmap by translating that vision into a practical technology reference.** It provides a structured catalogue of technologies that can enhance productivity, sustainability, competitiveness, circularity, resilience, and regulatory readiness across every stage of India's textile value chain. The Compendium serves as a decision-support resource for policymakers, manufacturers, industry associations, technology providers, financial institutions, researchers, and investors by presenting technology options according to their maturity, applicability, expected benefits, and implementation considerations.

Recognising the diversity of India's textile ecosystem, the Compendium does not prescribe a

single technology pathway. Instead, it enables different stakeholders to identify technology solutions suited to their manufacturing context, investment capacity, and transformation priorities while supporting implementation of the broader Roadmap.

Indicator	Current Position
Domestic textile production	USD 175.7 billion
Textile and apparel exports	USD 37.7 billion
Direct employment	45+ million people
Global position	6th largest textile exporter
Share of global textile trade	Approximately 4.1%
National ambition	USD 100 billion exports by 2030
Long-term vision	Globally competitive, sustainable, technology-enabled textile ecosystem by 2047

Why Technology Matters

Global textile manufacturing is undergoing rapid transformation. Automation, artificial intelligence, advanced manufacturing, industrial digitalisation, biotechnology, advanced materials, and data-driven production systems are reshaping manufacturing competitiveness. Simultaneously, sustainability requirements are becoming central to international trade through evolving regulations such as Digital Product Passports, the Ecodesign for Sustainable Products Regulation, carbon disclosure requirements, enhanced traceability expectations, and circular economy policies.

Competitiveness is therefore no longer determined solely by labour cost or manufacturing scale. It increasingly depends on productivity, resource efficiency, product quality, digital integration, innovation capability, supply chain transparency, and regulatory compliance. Technology has emerged as the critical enabler of these capabilities.

India's integrated manufacturing base provides a unique competitive advantage. However, technology adoption remains uneven across the value chain, creating gaps productivity, sustainability, and value addition. This

Compendium identifies technologies capable of addressing these gaps and accelerate the transformation priorities established in the Roadmap.

Technology Priorities Across the 5F Value Chain

The Government of India's **Farm to Fibre to Factory to Fashion to Foreign (5F)** framework provides the organising structure for this Compendium. Technology interventions are mapped to each stage of the value chain, recognising that improvements at one stage reinforce competitiveness across downstream manufacturing.

5F Stage	Current Technology Context	Technology Themes Covered in this Compendium	Expected Outcomes
Farm	India has the world's largest cotton acreage at 113.6 lakh hectares, but cotton productivity remains around 448 kg/ha, compared with approximately 750 kg/ha globally. Fibre contamination and limited fibre diversification continue to affect downstream quality and competitiveness.	Precision agriculture, smart irrigation, fibre quality monitoring, contamination control, digital traceability, alternative fibres, recycled fibres, biotechnology-enabled fibres.	Higher productivity, improved fibre quality, diversified raw material base, and enhanced sustainability.
Fibre	India operates approximately 54.5 million spindles, yet adoption of intelligent spinning, digital monitoring, recycled fibre processing, automation, and advanced spinning technologies remains uneven across mills.	Intelligent spinning, process automation, digital production systems, recycled fibre processing, advanced yarn manufacturing, predictive maintenance, quality monitoring.	Higher productivity, improved yarn quality, greater resource efficiency, and enhanced manufacturing competitiveness.
Factory (Dry Processing)	India's weaving and knitting sectors remain technologically heterogeneous. Approximately 60 to 70 percent of weaving capacity continues to rely on conventional shuttle looms, limiting productivity, automation, and premium fabric production.	Shuttleless weaving, advanced knitting, industrial automation, digital production planning, predictive maintenance, intelligent quality control, connected manufacturing systems.	Higher fabric quality, increased productivity, improved manufacturing flexibility, and stronger export competitiveness.
Factory (Wet Processing)	Wet processing remains the sector's largest resource and compliance hotspot. Conventional processing	Low-liquor-ratio dyeing, waterless dyeing, digital colour management, advanced	Reduced water, energy and chemical consumption, improved environmental

	typically consumes 80 to 150 litres of water per kilogram of fabric, approximately three to four times global best practice, while also driving high energy, chemical, and wastewater consumption.	Low-liquor-ratio dyeing, waterless dyeing, digital colour management, advanced finishing, wastewater recycling, heat recovery, cleaner chemistry, intelligent process control, resource monitoring.	Reduced water, energy and chemical consumption, improved environmental compliance, lower operating costs, and enhanced sustainability performance.
Fashion	Garment manufacturing remains predominantly labour-intensive, with limited adoption of digital product development, automation, and intelligent production systems despite India's large manufacturing base.	CAD/CAM, automated cutting, sewing automation, digital product development, 3D sampling, collaborative robotics, intelligent production planning, digital quality management.	Faster lead times, improved productivity, reduced material waste, and enhanced responsiveness to global markets.
Foreign	International buyers increasingly require traceability, product carbon footprints, lifecycle data, ESG reporting, and Digital Product Passports, while digital compliance infrastructure remains limited across much of the sector.	Digital Product Passports, blockchain-enabled traceability, product carbon footprint tools, lifecycle assessment platforms, supply chain intelligence, ESG reporting systems, compliance management platforms.	Improved market access, regulatory readiness, enhanced buyer confidence, and stronger participation in global value chains.
Foundational Technologies	Financing, digital infrastructure, workforce capabilities, innovation capacity, and industrial ecosystems continue to influence technology adoption across every stage of the value chain.	Artificial intelligence, Industrial Internet of Things, advanced analytics, renewable energy integration, circular economy technologies, workforce upskilling, digital infrastructure, innovation platforms.	Sector-wide productivity gains, technology diffusion, resilience, and long-term industrial competitiveness.

Technology Transformation Horizons

2. Amplify (2030 to 2035)

The Compendium aligns technology solutions with the three implementation horizons established in the **India Textile Technology & Innovation Roadmap 2047**.

Focuses on scaling advanced manufacturing capabilities through intelligent automation, connected factories, industrial digitalisation, advanced materials, circular manufacturing systems, and integrated traceability infrastructure to strengthen India's position within global value chains.

1. Align (2026 to 2030)

Focuses on commercially mature technologies capable of delivering immediate improvements in productivity, resource efficiency, quality, digitalisation, sustainability, and regulatory compliance. Priority is given to technologies that can be rapidly deployed across existing manufacturing facilities, particularly MSMEs and brownfield industrial clusters.

3. Accelerate (2035 to 2047)

Explores emerging and frontier technologies expected to shape the future textile industry, including artificial intelligence, robotics, biotechnology, advanced materials, autonomous manufacturing, digital manufacturing ecosystems, and next-generation circular production technologies. Rather than prescribing fixed technologies,

this horizon identifies strategic technology directions that can strengthen India's long-term innovation leadership.

Enabling Technology Adoption

Technology availability alone will not transform the textile sector. Accelerating adoption requires supportive financing mechanisms, industrial infrastructure, skilled human resources, research and innovation ecosystems, digital public infrastructure, standards, testing facilities, and enabling policy frameworks.

National initiatives such as **PM MITRA**, **Textile Export Excellence Mission (TEEM)**, and **Tex Eco** provide important opportunities to accelerate technology deployment and industrial modernisation. At the same time, upgrading existing manufacturing capacity across major textile clusters such as Surat, Tiruppur, Coimbatore, Ludhiana, Panipat, Bhilwara, and Erode offers the greatest opportunity for achieving near-term productivity improvements and sustainability gains.

Purpose of this Compendium

This Technology Compendium is intended to support implementation of the **India Textile Technology & Innovation Roadmap 2047** by providing a structured repository of technology options across the textile value chain. It enables stakeholders to understand available and emerging technologies, their applications, expected benefits, maturity levels, implementation requirements, and strategic relevance across within different manufacturing contexts.

By linking technology solutions to the **5F value chain**, the **three transformation horizons**, and the Roadmap's strategic transformation directions, the Compendium provides a practical bridge between long-term vision and implementation. Together, the Roadmap provides the strategic direction, while this Compendium provides the technology pathways that can enable India's textile sector to become globally competitive, sustainable, resilient, and innovation-driven by **2047**.

01

THE TRANSFORMATION
IMPERATIVE

THE GLOBAL TECHNOLOGY GAP
Technologies Global Leaders Have, That - India Must Adopt

1.1.THE EXPORT CHALLENGE - WHY TECHNOLOGY-LED TRANSFORMATION IS NEEDED

Global textile competitiveness is increasingly shaped by automation, sustainability compliance, traceability, MMF adoption, and speed-to-market capabilities. Competing textile economies are investing aggressively in technology modernization to capture shifting global supply chains and emerging export opportunities arising from China+1 diversification and evolving regulatory requirements.

India possesses one of the world's most integrated textile value chains, spanning farm to fashion, yet captures only about 4.1% of global textile and apparel trade. Achieving the national ambition of USD 100 billion in textile and apparel exports by 2030 will require a significant acceleration in competitiveness, productivity, and technology adoption across the sector.¹

India's textile and apparel exports stood at approximately **USD 37.7 billion in FY 2024–25**, growing at a historical CAGR of **3–4%**. The Government has articulated a vision for **USD 100 billion in combined textile and apparel exports by 2030**¹.

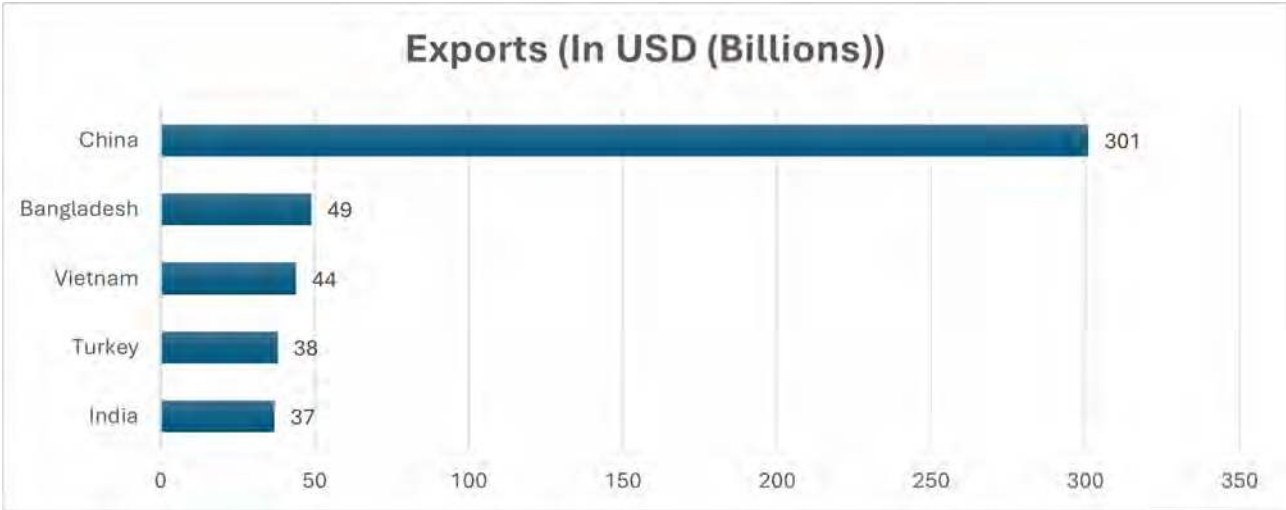


Figure 1 - Country wise Exports 2024

Source: Indian Express (Aug 2025)²

India's textile and apparel exports stood at approximately **USD 37.7 billion in FY 2024–25**, reflecting historical growth of roughly **3–4% annually**. At this trajectory, exports would remain substantially below the **USD 100 billion target by 2030**, indicating the need for a fundamentally different growth pathway driven by technology modernization, productivity enhancement, and higher value addition.

The challenge is therefore not only one of scale, but of competitiveness capability across the textile value chain.

PIB (Aug 2025) - Seizing opportunities, thrust on quality and zero defect and Enhancing Export Competitiveness of Indian Textile Industry
Indian Express (Aug, 2025) - Top 10 largest textile-exporting countries

1.1.1.THE \$100 BILLION BRIDGE - WHERE WILL THE GROWTH COME FROM?

The binding constraint is not demand or market access, it is India's inability to produce export-grade, compliant, traceable, fast-turnaround products at scale. Business-as-usual (BAU) growth could deliver approximately **\$45 billion** in exports by 2030; **technology-led transformation** must therefore deliver the **remaining \$55 billion**.

The gap cannot be closed by adding capacity alone. The constraint is **productivity, quality, speed-to-market, and sustainability compliance**, all of which require technology-enabled transformation.

Technology impacts exports through four quantifiable mechanisms

The gap cannot be closed by adding capacity alone. The constraint is **productivity, quality, speed-to-market, and sustainability compliance**, all of which require technology-enabled transformation.

Technology impacts exports through four quantifiable mechanisms



Source: Press Information Bureau (PIB), Ministry of Textiles, Government of India, “Seizing opportunities, thrust on quality and zero defect and Enhancing Export Competitiveness of Indian Textile Industry”



India can make this acceleration both urgent and achievable through **four converging shifts**:



Implication: The 2030 target is not achievable through volume expansion or cost reduction alone. It requires a technology-led transformation across the entire 5F value chain, from farm-level fibre quality to factory-floor automation to foreign-market compliance. This compendium catalogues technologies that, if adopted at the pace and scale of India's competitors, can bridge the \$55 billion gap between business-as-usual and India's 2030 ambition.

1.2. THE 5F VISION - TECHNOLOGY ALIGNMENT

The Government of India's 5F Strategy, Farm to Fibre to Factory to Fashion to Foreign provides the organizing framework for technology interventions across the textile value chain. The framework reflects the increasingly interconnected nature of textile competitiveness, where improvements in one stage directly influence performance in downstream stages.

This compendium aligns technology interventions across the **5F framework** to support productivity enhancement, sustainability performance, value addition, speed-to-market, and export competitiveness.

The previous section established that India requires approximately **USD \$55 billion** in additional technology-led export growth to achieve the USD \$100 billion target by 2030. However, this growth cannot be achieved through isolated interventions at individual stages of manufacturing. It depends on compounding gains across the value chain, including improved fibre quality, more productive fabric manufacturing, resource-efficient processing, faster garment production, and export-ready traceability

systems.

Originally articulated as a strategic vision for the textile sector's growth pathway, the 5F framework serves in this compendium as the organizing principle for technology mapping and prioritization across the textile value chain.

Every technology case card in annexure is tagged to its primary 5F stage, enabling policymakers, industry associations, and manufacturers to identify interventions relevant to their position in the value chain

As mentioned in baseline report, India's unique strength is that it participates in **all five stages**, from cotton



farming (world's largest acreage at 113.6 lakh hectares³) through spinning (54.5 million spindles⁴), fabric formation (including 16 lakh powerlooms⁵), wet processing (clusters across 7+ states), garment manufacturing (highest women jobs). No other nation major competitor has this degree of end-to-end integration. China comes closest but lacks India's raw material base; Bangladesh and Vietnam are strong in downstream apparel but dependent on imported fabric and yarn.

This integrated structure creates the opportunity for vertically linked modernization and traceability across the value chain, rather than isolated technology upgrades.

However, **India's technology adoption is uneven across the 5F chain**. Spinning has pockets of global-standard mills alongside vintage equipment. Weaving remains 60–70% on shuttle looms⁶. Wet processing consumes 3–4x the water of global benchmarks. Garment manufacturing is largely manual. And export compliance infrastructure consisting of traceability, carbon tracking, digital product passports is nearly absent. The table 2 below maps these gaps against the technologies this compendium covers.

³ Ministry of Textiles - Annual Report 2024-25

⁴ Department of Textiles, Govt of Tamil Nadu - Spinning

⁵ PIB - Powerloom Sector

⁶ MoT, Fourth All India Handloom Census Report

Table 1 - 5F Technology Map - Gaps, Technologies, and Compendium Coverage

5F STAGE	SCOPE	CRITICAL GAP	KEY TECHNOLOGIES
FARM	Cultivation, raw material quality, ginning	Cotton productivity at 448 kg/ha vs. global 750 kg/ha ⁷ indicating low productivity; India remains cotton-dominant with limited diversification toward MMF and sustainable fibre ecosystems ⁸	Precision agriculture, quality traceability, alt-fibers (PLA, Lyocell), hemp, recycled cotton
FIBRE	Spinning (ring, compact, rotor, vortex), yarn manufacturing, fiber processing	Technology heterogeneity persists with lower penetration of rotor spinning, automation, digital monitoring, and recycled fibre processing compared to global leaders	Compact spinning, vortex/MVS, rotor for recycled fibers, automated quality monitoring, IoT-enabled ISM
FACTORY	Weaving, knitting, wet processing (dyeing, printing, finishing), effluent treatment	Low shuttleless loom penetration, resource-intensive wet processing with high liquor ratio dyeing and water consumption, and limited digital textile printing adoption	Shuttleless looms, LLR dyeing, digital printing, ZLD systems, advanced finishing
FASHION	Garment design, cutting, sewing, finishing, quality inspection, packaging	Garment manufacturing remains largely labour-intensive with uneven adoption of automation and digital systems across organized and MSME segments;	CAD/CAM, automated cutting, robotic sewing cells, 3D virtual sampling, AI vision inspection, servo sewing machines
FOREIGN	Export compliance, traceability, supply chain visibility, market access, sustainability certification	Limited readiness for traceability, Digital Product Passport (DPP), ESG disclosures, and emerging EU sustainability compliance requirements among MSMEs	Blockchain traceability, RFID/NFC tagging, Digital Product Passport systems, carbon footprint tools, certification platforms

Source: Gap data from Baseline Assessment Report 2026 (UNIDO-PAGE).

⁷ Business India - Weaving momentum
⁸ Fibre2Fashion - Industry backs India Budget push for MMF-led textile growth
⁹ PIB, Powerloom Sector

The distribution of technologies across the 5F framework reflects where the most critical transformation gaps exist within India's textile value chain. Each stage addresses a distinct competitiveness challenge.



The 5F stages are interdependent rather than isolated. Improvements in garment manufacturing depend on upstream fabric quality and processing efficiency, while traceability and compliance requirements at the export stage rely on data generation across Farm, Fibre, and Factory stages. Technology adoption must therefore proceed in a coordinated manner across the value chain.

Technology adoption must therefore proceed **in a coordinated manner across the value chain**, rather than sequentially. This is why the Compendium addresses all stages together, ensuring that improvements in one stage are supported by corresponding capabilities in others

The key question, therefore, is not whether technology matters, but how competing textile economies have

1.3. GLOBAL LEADERS' TECHNOLOGY PROFILE

Competing countries have strengthened their global export positions through sustained investments in technology modernization, manufacturing capability, and integrated industrial ecosystems. While each country followed a distinct pathway, all leveraged technology as a central driver of competitiveness.

used technology to strengthen export competitiveness and capture global market share.

³ Ministry of Textiles - Annual Report 2024-25
⁴ Department of Textiles, Govt of Tamil Nadu - Spinning
⁵ PIB - Powerloom Sector
⁶ MoT, Fourth All India Handloom Census Report

 CHINA Full value chain, everything from fibre to fashion. But this is the exception, not the rule, and driven by unique scale + state investment. TECHNOLOGY HIGHLIGHTS  • Connected machinery at scale (700k+ machines).  • AI-driven quality control.  • Industrial IoT as standard, not exception → TAKEAWAY: Scale automation	 VIETNAM Focused on mid-to-downstream — fabric processing and garment assembly. FDI brings the technology. They're building upstream capability but it's still thin. TECHNOLOGY HIGHLIGHTS  • Rules of Origin (RoO) compliance systems.  • Speed-to-market logistics.  • FDI through ready infrastructure (PM Mitra parallel) → TAKEAWAY: FTA readiness infrastructure
 BANGLADESH Focused on apparel only — they import yarn and fabric, process and export garments. Their technology investments are laser-focused on garment production + green certification. TECHNOLOGY HIGHLIGHTS  • 200+ leed certifications.  • Green transformation fund.  • Making sustainability a competitive differentiator, not a cost → TAKEAWAY: Green factory at scale	 TÜRKİYE Focused on premium, speed-sensitive segments — denim, home textiles, fast-fashion knitwear. They don't compete on commodity yarns or basic fabrics. TECHNOLOGY HIGHLIGHTS  • 4–6-week lead times.  • Industry 4.0 in organized mills.  • Design capability and ODM model. → TAKEAWAY: Speed through digitalization

The evidence suggests that no single technology pathway defines success. Instead, each of India's principal competitors, namely China, Vietnam, Bangladesh, and Türkiye, has built competitive advantage through a technology strategy aligned to its own structural strengths and market positioning. India's pathway will require selective adaptation rather than wholesale replication. Unlike most competing textile economies, India possesses substantial domestic presence across all stages of the textile value chain, creating a unique opportunity for vertically integrated modernization and end-to-end digitalisation.

Despite differences in development pathways, several common competitiveness patterns emerge across leading textile-exporting economies. Higher levels of automation, digital integration, sustainability readiness, speed-to-market capability, and value-added manufacturing are increasingly associated with stronger export performance and resilience within global textile supply chains.

Four patterns emerge from this competitive assessment, each with direct implications for India's technology strategy: compliance infrastructure consisting of traceability, carbon tracking, digital product passports is nearly absent. The table 2 below maps these gaps against the technologies this compendium covers.

01 PATTERN 1: Technology drives exports, not the reverse   In every competitor country, technology investment preceded export growth.  Vietnam's textile exports doubled after FDI brought automated factories, Bangladesh crossed \$48B after \$5 billion in machinery upgrades. And Türkiye's denim dominance followed Industry 4.0 adoption.  India cannot wait for export revenue to fund technology— it must invest first, as competitors did, using policy instruments (PLI, PM MITRA) to de-risk the investment cycle.

The comparative assessment highlights that global textile competitiveness is increasingly shaped by technology capability, sustainability readiness, digital integration, and speed-to-market rather than labour cost advantages alone.

China demonstrates the importance of large-scale automation and integrated industrial ecosystems. Vietnam highlights the role of export-oriented manufacturing integration and trade-linked competitiveness. Bangladesh illustrates how sustainability and green manufacturing can strengthen buyer alignment and export positioning. Türkiye demonstrates the strategic importance of agile production systems and speed-to-market responsiveness.

Implication: India's competitors did not stumble into their export positions, they built them through deliberate, sustained technology investment in specific domains. India's technology strategy must be equally deliberate, simultaneously targeting automation (learning from China), sustainability (learning from Bangladesh), speed-to-market (learning from Türkiye), and compliance infrastructure (learning from Vietnam). The following section (1.4) quantifies India's specific gaps against these benchmarks to identify the highest-priority technology interventions.

1.4. INDIA'S TECHNOLOGY GAPS (BASELINE SUMMARY)

The Baseline Assessment identified technology gaps across every stage of India's textile value chain, spanning manufacturing modernization, digital infrastructure, sustainability performance, resource efficiency, and compliance readiness.

The previous section demonstrated how competing countries strengthened export competitiveness through technology transformation strategies supported by enabling government policies and industrial ecosystems.

This section turns the focus inward to examine the specific competitiveness gaps India must address to strengthen its position within the global textile industry.

The baseline assessment identified gaps across all five stages of the 5F value chain and across six competitiveness dimensions, namely manufacturing automation, digital and IoT integration, sustainability and circularity, speed-to-market, value addition, and compliance readiness.

The analysis indicates that these gaps are not isolated to individual production segments, but systemic in nature. In several cases, weaknesses in one stage directly constrain competitiveness outcomes in downstream stages. For example, garment-level traceability depends on upstream data generation across fibre, fabric, and processing stages, while improvements in speed-to-market depend on productivity and efficiency gains throughout the manufacturing chain.

Table 2 - Consolidated Technology Gap Assessment

5F Stage	Core Competitiveness Risk	Severity	Strategic Consequence Across the Value Chain
F1 Farm	Fibre quality inconsistency, contamination, and limited sustainable fibre ecosystems	High	Upstream raw material inconsistencies reduce yarn quality, increase processing losses, and constrain premium export positioning downstream
F2 Fibre	Limited modernization in spinning, recycled fibre capability, and traceability systems	Critical	Weak yarn traceability and limited recycled fibre capability constrain compliance readiness, sustainable product development, and value-added textile manufacturing
F3 Dry Factory	Low shuttleless penetration and uneven modernization across weaving and knitting	Critical	Lower productivity and inconsistent fabric quality reduce downstream processing efficiency and limit export-grade fabric competitiveness
F3 Wet Factory	Resource-intensive and compliance-sensitive wet processing systems	Critical	High water, energy, chemical, and effluent intensity create the largest sustainability, cost, and buyer-compliance risks across the textile value chain

F4 Fashion	Labour-intensive garment manufacturing and slower speed-to-market	High	Longer lead times, lower flexibility, and uneven quality constrain competitiveness in fast-cycle and higher-value apparel markets
F5 Foreign	Limited readiness for traceability, DPP, and evolving ESG compliance requirements	Critical	Export competitiveness increasingly depends on verified sustainability, traceability, and digital compliance capabilities generated upstream across all stages
Cross-Cutting Energy & Water	Limited resource monitoring, decarbonization readiness, and energy-efficiency systems	High	Weak measurement and decarbonization infrastructure constrain long-term competitiveness, emissions reduction, and future carbon compliance readiness across the sector

Table 3 highlights the concentration of these gaps across the value chain. Wet processing emerges as the most resource-intensive and compliance-sensitive segment of the value chain; while weaving and garment manufacturing continue to face productivity, quality, and lead-time constraints relative to competing textile-exporting economies. At the same time, digitalization gaps increasingly compound physical technology gaps by limiting process visibility, traceability, and supply-chain integration.

The assessment also indicates that these gaps are systemic rather than isolated. In several cases, weaknesses in one stage directly constrain competitiveness outcomes in downstream stages. For example, garment-level traceability depends on upstream data generation across fibre, fabric, and processing stages, while improvements in speed-to-market depend on productivity and efficiency gains throughout the manufacturing chain.

Table 3 - Consolidated Technology Gap Assessment

5F STAGE	PRIMARY EXPORT LEVER	MECHANISM
FARM/FIBRE	Higher-value yarn & sustainable fibres for export	Recycled content mandates; MMF expansion; quality premium yarns
FACTORY (Fabric)	Fabric exports replacing yarn exports (value addition)	Shuttleless transition enabling export-grade fabric; digital printing for short runs
FACTORY (Wet)	Compliance-ready processing enabling buyer retention	Water/energy efficiency meeting sustainability audits; ZDHC compliance
FASHION	Garment export growth through speed & quality	Automated production; faster lead times; lower defect rates; 3D sampling
FOREIGN	New market access through compliance & traceability	DPP readiness; FTA utilization; certification infrastructure

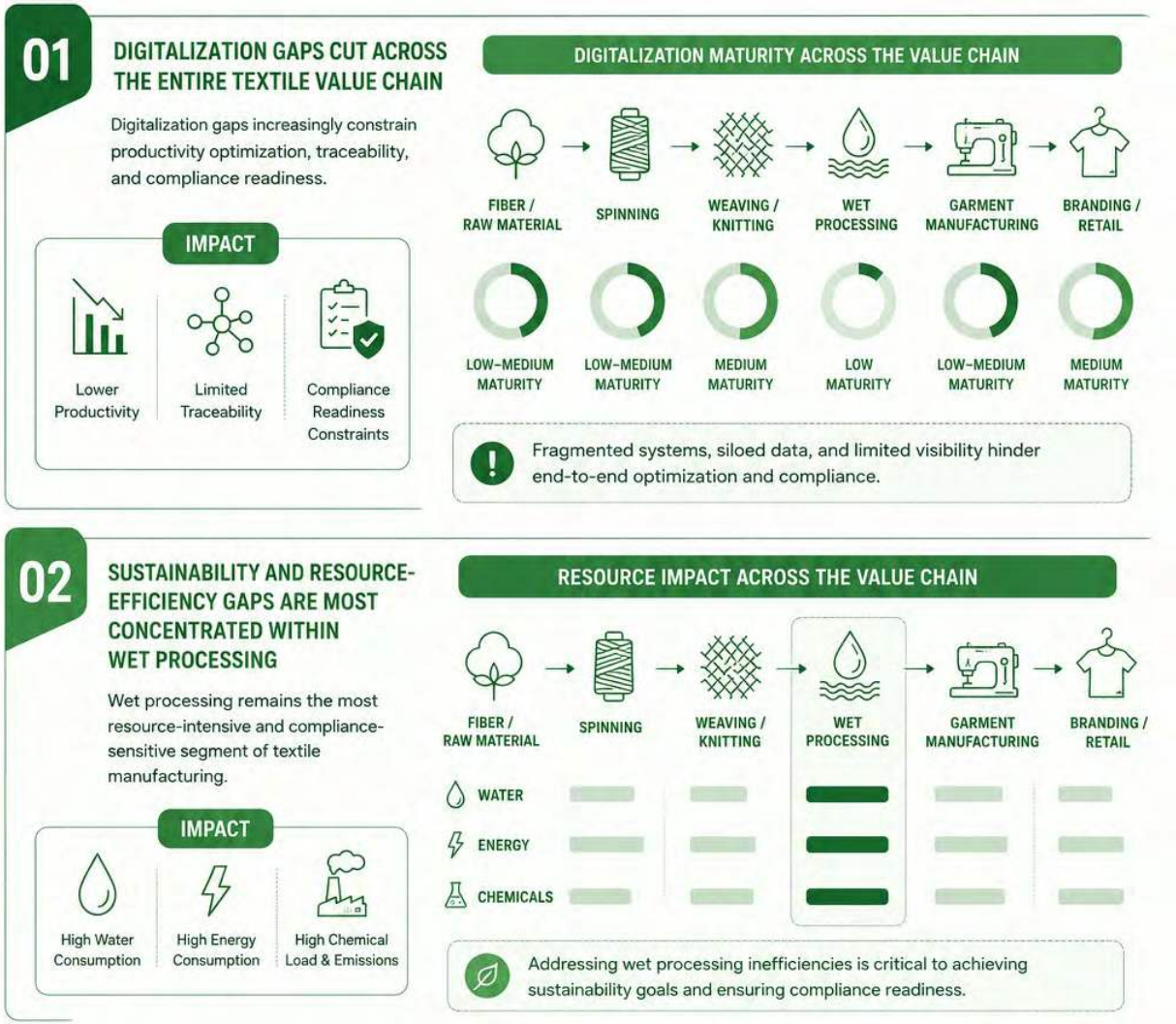
Estimated contributions are derived from:

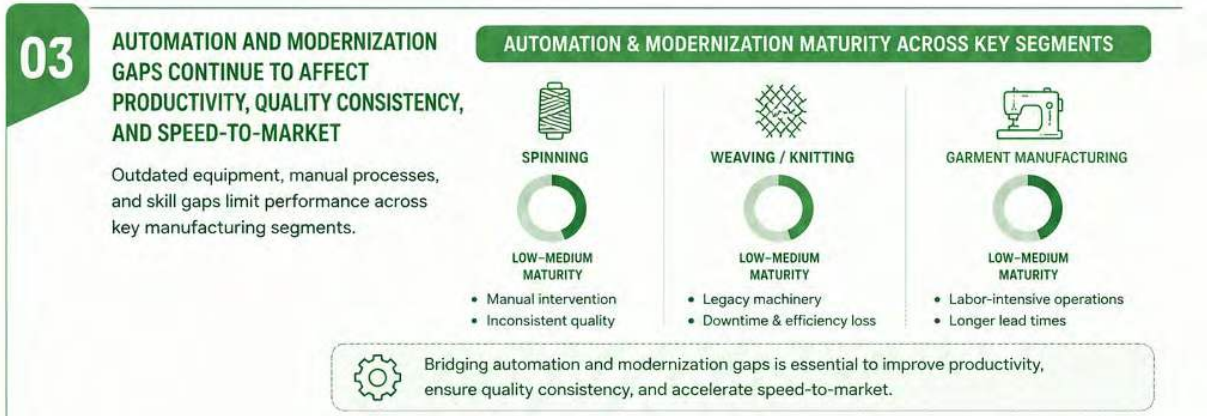
- i. decomposition of India's current export base by value chain segment with technology-driven growth multipliers benchmarked against competitor trajectories.
- ii. gap-closure analysis from the Baseline Assessment 2026;
- iii. cross-validation against global market share scenarios. Ranges reflect conservative-to-optimistic adoption assumptions.

The export levers demonstrate that technology adoption influences competitiveness through multiple pathways simultaneously, including productivity enhancement, sustainability compliance, value addition, speed-to-market, and market-access readiness. The largest opportunities emerge where technology interventions simultaneously improve operational efficiency and export positioning.

Critically, the 5F stages are interdependent rather than isolated. Improvements in garment manufacturing depend on upstream fabric quality and processing efficiency, while export-stage compliance increasingly depends on traceability and sustainability data generated across Farm, Fibre, and Factory stages. Technology adoption must therefore proceed in a coordinated manner across the value chain.

Three findings emerge from reading the gap assessment by dimension:





The gap assessment demonstrates that India's competitiveness challenge is systemic rather than isolated. Addressing these gaps will require coordinated modernization across the 5F framework rather than fragmented technology adoption at individual stages of manufacturing.

To support prioritization and implementation sequencing, the identified technology interventions have been organized into three horizons based on their urgency, systemic relevance, and competitiveness impact. The framework establishes a clear sequencing logic for technology adoption across the value chain.

Implication: If India does not close these gaps, the \$100 billion export target becomes a \$55-65 billion ceiling. The gap is not theoretical, it is the measured distance between India's current technology base and the minimum required for competitive market access by 2030. The cost of inaction is not merely missed growth; it includes potential loss of existing orders as competitors upgrade their capabilities and buyers redirect sourcing.

02 TECHNOLOGY TRANSFORMATION PATHWAY

The technologies presented in this Compendium span the entire textile value chain, ranging from commercially proven solutions available today to emerging technologies that will shape the industry's future. They do not all require the same response. Some are ready for immediate deployment while. Others require industry-wide scaling. A third group represents innovation pathways that demand sustained research, demonstration, and ecosystem development.

To guide investment and implementation, the technologies are organised into three transformation horizons that align with the **India Textile Technology and Innovation Roadmap 2047**. These horizons are not defined by calendar years alone, but by the readiness of technologies, the enabling conditions required for their adoption, and the strategic role they play in achieving the sector's long-term transformation.

Together, they provide a structured pathway from **technology adoption** to **technology scaling**, and ultimately **technology origination**.

Align (2026 - 2030) horizon require immediate intervention because they are either Critical in severity, face regulatory deadlines, or block structural productivity improvements.

Amplify (2030 - 2035) horizon require scale-up investment using proven technologies that need broader deployment.

Accelerate (2035 - 2047) are techonology directions that strategically important for 2047 vision.

2.1. ALIGN (2026–2030)

The Align horizon focuses on commercially proven technologies that are available today and can be deployed using existing policy instruments, financing mechanisms, and supplier ecosystems. The technologies identified for this period establish the operational foundations for competitiveness by improving productivity, resource efficiency, compliance, quality, and digital readiness.



They represent current best practice and should become the new industry baseline across India's textile value chain.

The priority during this horizon is widespread adoption rather than technological innovation. Investments are directed towards reducing resource intensity, strengthening manufacturing capability, improving product quality, and establishing the digital infrastructure required for future traceability and sustainability reporting.

Although the technologies themselves are mature, successful adoption depends equally on management capability. Equipment installation alone does not deliver transformation. Energy monitoring systems, automated process controls, Manufacturing Execution Systems, and digital quality platforms create value only when operational data is reviewed routinely and used to improve production decisions. For this reason, the Align horizon combines technology deployment with organisational capability, creating the operational platform on which subsequent transformation depends.

2.2. AMPLIFY (2030–2035)

The Amplify horizon focuses on scaling technologies that are already commercially established internationally but remain underutilized within India's textile sector. These technologies strengthen competitiveness through higher productivity, greater flexibility, improved circularity, advanced manufacturing capability, and digital integration.

The principal constraint during this period is no longer technology availability. It is the ability to deploy these technologies at scale through appropriate financing, workforce capability, supplier ecosystems, and enabling infrastructure.

This horizon also coincides with increasing regulatory and market expectations. Product traceability, lifecycle assessment, Digital Product Passports, chemical management, and science-based emissions reporting become integral components of international competitiveness rather than supplementary sustainability initiatives.



Accordingly, the emphasis shifts from adopting individual technologies towards integrating them into connected manufacturing systems that continuously generate trusted operational data and support higher-value production.

2.3. ACCELERATE (2035–2047)

The Accelerate horizon shifts from deploying existing technologies to building India's long-term capability to originate, develop, and commercialise the next generation of textile technologies. Beyond 2035, advances in artificial intelligence, advanced materials, biotechnology, robotics, and digital engineering are expected to significantly shorten technology development and commercialisation cycles. Technologies currently considered emerging may mature more rapidly than anticipated, while entirely new technologies are likely to reshape textile manufacturing over the same period.

Accordingly, the technologies identified in this horizon should be viewed as **representative innovation pathways rather than a definitive list of future solutions**. Their purpose is to indicate the strategic direction of technology development and the capabilities India should build to realise the Roadmap's vision of a **low-carbon, circular, globally competitive, and technology-originating textile sector**.

Strategic investment during this horizon should therefore focus not only on individual technologies, but also on strengthening research infrastructure, pilot facilities, demonstration platforms, standards development, industry-academia collaboration, startup ecosystems, and commercialisation mechanisms that enable India to continuously evaluate, validate, and scale emerging innovations.

Across the value chain, the innovation priorities identified in this Compendium represent the technological frontiers most likely to shape the competitiveness of India's textile sector over the coming decades. These examples are illustrative rather than exhaustive and should be interpreted as indicators of future capability development rather than fixed technology prescriptions.

03 TECHNOLOGY INVENTORY

TECHNOLOGY CASE CARDS

ORGANIZED BY 5F VALUE CHAIN STAGE
FARM → FIBRE → FACTORY → FASHION → FOREIGN

Chapter 1 established that India's USD 37.7 billion textile and apparel export base must reach USD 100 billion by 2030. Under business-as-usual conditions, exports are projected to reach only about USD 45 billion. Closing the remaining USD 55 billion gap requires coordinated technology transformation across all five stages of the value chain, not isolated upgrades at individual stages. The constraint is no longer demand alone. It is India's ability to produce export-grade, compliant, traceable, and fast-turnaround products at scale.

The chapter also reflects the interconnected nature of the textile value chain. Performance at one stage directly influences competitiveness outcomes in downstream stages, making technology adoption across the 5F framework cumulative rather than isolated.

3.1. WHERE URGENCY CONCENTRATES: TECHNOLOGY PRIORITY MAP

Before mapping individual technologies, one diagnostic question must be answered: across the five stages and six competitiveness dimensions, where does India face the most critical and most concentrated gaps? The heatmap below answers this. It draws directly from the gap assessment conducted across India's textile value chain and maps severity against the six dimensions Chapter 1 identified: manufacturing automation, digital and IoT integration, sustainability and circularity, speed-to-market, value addition, and compliance readiness.

HOW TO READ THIS CHAPTER

This chapter answers one question for each competitiveness gap: Which technology closes it, and why does that intervention matter across the value chain.

1.
START
HERE

Understand the value chain flow (Read first)

F1 → F2 → F3 → F4 → F5 → F6

FARM → FIBRE → DRY → WET → FASHION → FOREIGN

The chapter follows the physical flow of production.

Fibre quality at F1 shapes spinning performance at F2 → Yarn quality determines weaving and knitting outcomes at F3 → Fabric consistency influences wet-processing compliance at F4 → Production and traceability data determine export readiness at F5

2.
FOR EACH
STAGE

Read each stage section in this order

A → B → C → D

BINDING CONSTRAINT → TIERED TECHNOLOGY STACK (T1/T2/T3) → WHY THIS INTERVENTION MATTERS DOWNSTREAM → SEQUENCING RATIONALE

This structure is consistent across all stages.

3.
UNDERSTAND
THE TIERS

Technologies are presented in three tiers

T1 → T2 → T3

IMMEDIATE PRIORITY → SCALE-UP PRIORITY → R&D HORIZON

Proven, deployable now. Direct impact on competitiveness. → Ready to scale. Requires capacity, ecosystem and investment. → Emerging technologies. Invest today for future competitiveness.

4.
FOR DETAILED
NUMBERS

Go to the Annexure (Read after the main chapter)

Detailed operational data is provided in the Annexure:

ADOPTION LEVELS	CAPEX	OPEX	VENDOR LANDSCAPE	PAYBACK PERIODS	CROSS-MEDIA EFFECTS
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5.
KEEP THIS
MINDSET

Read this chapter as an integrated modernization pathway, not a menu of standalone technologies.

NOT THIS → BUT THIS

Isolated investments without system integration → Sequenced interventions across the value chain

Continued constraints and limited impact → Compliance → Traceability → Competitiveness → Export readiness

Priority levels indicate the relative importance of each dimension at every stage to drive competitiveness and export readiness.

STAGE	MFG. AUTOMATION	DIGITAL / IOT	SUSTAINABILITY	SPEED-TO-MARKET	VALUE ADDITION	COMPLIANCE
F1 FARM	MEDIUM	HIGH	HIGH	MEDIUM	MEDIUM	HIGH
F2 FIBRE	HIGH	CRITICAL	HIGH	MEDIUM	MEDIUM	HIGH
F3 DRY	CRITICAL	CRITICAL	HIGH	HIGH	MEDIUM	MEDIUM
F3 WET	HIGH	HIGH	CRITICAL	MEDIUM	MEDIUM	CRITICAL
F4 FASHION	HIGH	HIGH	MEDIUM	CRITICAL	HIGH	HIGH
F5 FOREIGN	MEDIUM	HIGH	HIGH	MEDIUM	MEDIUM	CRITICAL

Figure 2 - Technology Gap Heatmap - India's 5F Value Chain

Rating	Meaning
Critical (Red)	Creates immediate market-access, compliance, or export competitiveness risk
High (Orange)	Creates structural productivity, quality, or cost disadvantages versus competitors
Medium (Yellow)	Limits value addition, efficiency, or speed-to-market without immediately threatening exports

Three insights stand out.

- Digital and IoT gaps are rated Critical or High across every stage except F1, indicating that India's digital infrastructure gap is now as significant as its mechanical technology gap.
- F3 Wet Processing carries the highest concentration of Critical gaps, particularly in sustainability, resource efficiency, and compliance readiness.
- F5 compliance readiness depends entirely on upstream data generation across F2–F4. Traceability, CBAM, and Digital Product Passport systems cannot function credibly without reliable production, process, and environmental

3.2. FOUNDATIONAL TECHNOLOGIES

Foundational technologies are the cross-cutting capabilities that enable transformation across the entire textile value chain, irrespective of manufacturing segment or process. Unlike value chain-specific technologies that address individual production stages, these technologies establish the enterprise systems, digital infrastructure, operational capabilities, resource optimization, clean energy solutions, and sustainability platforms required to modernize textile manufacturing. Together, they create the foundation for connected, intelligent, resource-efficient, and low-carbon industrial operations while strengthening productivity, quality, resilience, and global competitiveness. data generated throughout the value chain.

3.2.1. F0 TECHNOLOGY PRIORITY STACK

The foundational technologies presented in Table 4 is organized across five capability domains: **Enterprise Systems, Digital Infrastructure, Smart Manufacturing, Automation & Resource Optimization, Clean Energy & Industrial Decarbonization**, and **Sustainability Platforms**. Collectively, these domains support the progressive digitalization and decarbonization of India's textile sector by integrating enterprise management, connected manufacturing, operational excellence, industrial automation, clean energy transition, and enterprise-wide sustainability management.

The technologies below are organized across three implementation horizons:

- **Align (2026–2030):** Establish the foundational digital, operational, and resource optimization capabilities through enterprise systems, connected infrastructure, smart manufacturing solutions, and energy-efficient technologies that deliver immediate improvements in productivity, traceability, and sustainability.
- **Amplify (2030–2035):** Scale advanced manufacturing intelligence, industrial automation, clean energy systems, and enterprise-wide sustainability platforms to accelerate industrial decarbonization, operational excellence, and supply chain competitiveness.
- **Accelerate (2035–2047):** Develop next-generation manufacturing capabilities through digital twins, green hydrogen, and other frontier technologies that strengthen technology sovereignty, industrial resilience, and India's global leadership in sustainable textile manufacturing.

Together, these foundational technologies create an integrated digital and industrial transformation ecosystem that supports innovation, resource-intelligent manufacturing, low-carbon industrial development, and a globally competitive textile sector aligned with India's Vision 2047.

Table 4 - Technology Priority Stack for Foundational Technologies

Card No.	Technology Name	Technology Focus Area	Transformation Direction	Roadmap Horizon
Enterprise Systems				
F0-01	Enterprise Resource Planning (ERP) Systems	Enterprise Systems	Manufacturing Capability at Scale	Align (2026–2030)
Digital Infrastructure				
F0-02	Industrial Internet of Things (IIoT) Platforms	Digital Infrastructure	Digital Infrastructure & Traceability	Align (2026–2030)
F0-03	Edge Computing & Industrial Cloud Platforms	Digital Infrastructure	Digital Infrastructure & Traceability	Amplify (2030–2035)
F0-04	Industrial Cybersecurity Systems	Digital Infrastructure	Digital Infrastructure & Traceability	Amplify (2030–2035)
Smart Manufacturing, Automation & Resource Optimization				
F0-05	Manufacturing Execution Systems (MES)	Smart Manufacturing	Digital Infrastructure & Traceability	Align (2026–2030)
F0-06	PLC and SCADA Industrial Control Systems	Automation Technology	Industrial Automation	Align (2026–2030)
F0-07	Enterprise Energy Management Systems (EMS)	Resource Management	Resource-Intelligent Manufacturing	Align (2026–2030)
F0-08	Industrial Water Management & Monitoring Systems	Resource Management	Resource-Intelligent Manufacturing	Align (2026–2030)
F0-09	Predictive Maintenance Systems	Asset Management	Manufacturing Capability at Scale	Align (2026–2030)
F0-10	Computer Vision & Automated Quality Inspection	Quality Management	Digital Infrastructure & Traceability	Align (2026–2030)
F0-11	Industrial Robotics & Collaborative Robots (Cobots)	Industrial Automation	Manufacturing Capability at Scale	Amplify (2030–2035)
F0-12	Artificial Intelligence & Machine Learning for Manufacturing	Smart Manufacturing	Innovation & Technology Origination	Amplify (2030–2035)
F0-13	Digital Twin Platforms	Smart Manufacturing	Innovation & Technology Origination	Accelerate (2035–2047)

F0-14	Variable Frequency Drives (VFDs)	Resource Management	Resource-Intelligent Manufacturing	Align (2026–2030)
F0-15	High-Efficiency Motors (IE3/IE4 Class)	Resource Management	Resource-Intelligent Manufacturing	Align (2026–2030)
F0-16	Permanent Magnet Screw Air Compressors	Resource Management	Resource-Intelligent Manufacturing	Align (2026–2030)
F0-17	High-Efficiency LED Lighting Systems	Resource Management	Resource-Intelligent Manufacturing	Align (2026–2030)
F0-18	Intelligent Steam Management & Heat Recovery Systems (formerly Steam Trap Monitoring & Condensate Recovery Systems)	Resource Management	Resource-Intelligent Manufacturing	Align (2026–2030)
Clean Energy & Industrial Decarbonization				
F0-19	Renewable Energy Integration & Microgrid Management	Clean Energy	Resource-Intelligent Manufacturing	Amplify (2030–2035)
F0-20	Cogeneration & Industrial Energy Recovery Systems	Clean Energy	Resource-Intelligent Manufacturing	Amplify (2030–2035)
F0-21	Renewable Bioenergy Process Heat Systems (expanded from Biomass Boiler Systems)	Clean Energy	Resource-Intelligent Manufacturing	Amplify (2030–2035)
F0-22	Industrial Process Heat Electrification Systems	Clean Energy	Resource-Intelligent Manufacturing	Amplify (2030–2035)
F0-23	Industrial Solar Thermal Systems	Clean Energy	Resource-Intelligent Manufacturing	Amplify (2030–2035)
F0-24	Green Hydrogen Energy Systems	Decarbonization	Technology Sovereignty	Accelerate (2035–2047)
Sustainability Platforms				
F0-25	Carbon Accounting & ESG Management Platforms	Sustainability Management	Resource-Intelligent Manufacturing	Amplify (2030–2035)

Every mill across all F-stages faces three converging pressures:

- CBAM-driven carbon cost exposure on exports,
- Science-based target commitments cascading from global brands to tier 1 and tier 2 suppliers,
- Domestic regulatory tightening from CPCB and MoEFCC.

3.2.2. Align (2026–2030)

The **Align** horizon establishes the foundational digital and resource-efficiency infrastructure required to improve productivity, operational visibility, and international competitiveness across India's textile manufacturing sector. These technologies create the digital backbone for data-driven decision-making while delivering immediate gains in quality, resource efficiency, equipment reliability, and compliance. Their implementation forms the prerequisite for the advanced automation and artificial intelligence applications envisaged in subsequent roadmap horizons.

The **Align (2026–2030)** horizon establishes the foundational enterprise, digital, and operational capabilities required to improve productivity, resource efficiency, and global competitiveness across India's textile manufacturing sector. The technologies prioritised in this phase focus on strengthening digital connectivity, operational excellence, and resource optimization through commercially mature solutions that deliver immediate business value while creating the foundation for advanced automation, artificial intelligence, and industrial decarbonization in subsequent roadmap horizons.

Enterprise Resource Planning (ERP) Systems (**F0-01**) establish the enterprise-wide digital backbone by integrating core business functions, production planning, procurement, inventory, finance, and supply chain management into a unified platform. Complementing this, Industrial Internet of Things (IIoT) Platforms (**F0-02**) connect production assets, utilities, and sensors, while Manufacturing Execution Systems (MES) (**F0-05**) enable real-time production visibility, work-order execution, and shop-floor control. Together, these technologies establish the connected manufacturing environment required for data-driven decision-making and end-to-end operational transparency.

The Align horizon also prioritises technologies that strengthen operational performance and manufacturing reliability. Enterprise Energy Management Systems (EMS) (**F0-06**) and Industrial Water Management & Monitoring Systems (**F0-07**) provide continuous visibility into utility consumption and resource performance, while Predictive Maintenance Systems (**F0-08**) and Computer Vision & Automated Quality Inspection (**F0-09**) improve equipment reliability, reduce unplanned downtime, and enhance product quality through real-time monitoring and automated analytics.

To deliver immediate improvements in resource efficiency and manufacturing competitiveness, the roadmap prioritises proven industrial technologies including Variable Frequency Drives (VFDs) (**F0-13**), High-Efficiency Motors (IE3/IE4 Class) (**F0-14**), Permanent Magnet Screw Air Compressors (**F0-15**), High-Efficiency LED Lighting Systems (**F0-16**), and Intelligent Steam Management & Heat Recovery Systems (**F0-17**). These commercially mature technologies provide rapid reductions in energy consumption, operating costs, and greenhouse gas emissions while improving overall plant performance and supporting India's transition towards resource-intelligent manufacturing.

3.2.3. AMPLIFY (2030–2035)

The **Amplify** horizon builds upon the digital foundation established during the Align phase by integrating intelligent automation, advanced analytics, and low-carbon energy systems. These technologies enable manufacturing enterprises to transition from monitoring operations to optimising them autonomously, improving productivity, resilience, and sustainability at scale.

The **Amplify (2030–2035)** horizon builds upon the digital and operational foundations established during the Align phase by scaling intelligent manufacturing, industrial automation, clean energy systems, and enterprise-wide sustainability capabilities. The technologies prioritised during this period enable greater manufacturing flexibility, advanced analytics, industrial decarbonisation, and enhanced compliance with evolving global sustainability and traceability requirements.

Edge Computing & Industrial Cloud Platforms (**F0-03**) and Industrial Cybersecurity Systems (**F0-04**) strengthen the digital infrastructure required to securely process, store, and exchange large volumes of operational data across interconnected manufacturing systems. These technologies enable low-latency analytics, cloud-based collaboration, and secure integration of enterprise applications, production systems, and industrial assets, providing the digital resilience necessary for large-scale smart manufacturing.

Within manufacturing operations, Industrial Robotics & Collaborative Robots (Cobots) (**F0-10**) and Artificial Intelligence & Machine Learning for Manufacturing (**F0-11**) accelerate the transition towards intelligent and adaptive production systems. AI-driven analytics leverage production, quality, maintenance, and resource data generated during the Align phase to optimise production planning, process control, predictive maintenance, quality assurance, and resource utilisation, while robotics improve manufacturing flexibility, production consistency, worker safety, and operational productivity across repetitive and precision-intensive processes.

The Amplify horizon also marks the large-scale deployment of **Clean Energy & Industrial Decarbonization** technologies. Renewable Energy Integration & Microgrid Management (**F0-18**) increases the utilisation of renewable electricity while enhancing energy resilience and grid flexibility. Cogeneration & Industrial Energy Recovery Systems (**F0-19**) improve overall energy efficiency through simultaneous production of electricity and process heat, while Renewable Bioenergy Process Heat Systems (**F0-20**) enable the substitution of fossil fuels with sustainable biomass, biogas, and biomethane for industrial steam generation. Industrial Process Heat Electrification Systems (**F0-21**) and Industrial Solar Thermal Systems (**F0-22**) further support the transition towards low-carbon thermal energy by expanding electrified process heating and renewable solar-based heat generation for textile manufacturing.

Carbon Accounting & ESG Management Platforms (**F0-24**) provide enterprise-wide capabilities for emissions accounting, sustainability reporting, ESG performance management, and value-chain transparency. These platforms support compliance with emerging international regulatory frameworks and buyer requirements while establishing the digital foundation for future capabilities such as Product Carbon Footprints (PCFs), Digital Product Passports (DPPs), and broader supply chain sustainability reporting.

3.2.4. ACCELERATE (2035-2047)

The Accelerate horizon shifts from adopting advanced manufacturing technologies to building India's capability to lead the next generation of intelligent, autonomous, and net-zero industrial systems. Beyond 2035, rapid advances in artificial intelligence, digital simulation, autonomous manufacturing, clean energy systems, and industrial decarbonisation are expected to fundamentally transform how textile production is designed, operated, and optimised. Rather than prescribing a fixed set of future technologies, the priority is to strengthen India's capability to develop, adapt, and commercialise breakthrough manufacturing technologies that enhance global competitiveness while supporting long-term sustainability objectives.

The **Accelerate (2035–2047)** horizon focuses on establishing India's leadership in next-generation manufacturing technologies by advancing autonomous production systems, industrial intelligence, deep decarbonisation, and technology sovereignty. Building upon the digital, operational, and clean energy foundations established during the Align and Amplify horizons, this phase emphasises the development, integration, and commercialisation of frontier technologies capable of transforming the competitiveness and resilience of India's textile manufacturing sector.

Strategic investment during this horizon should focus on four long-term innovation priorities:

- **Autonomous Manufacturing Systems:** Develop intelligent manufacturing environments that integrate Digital Twins, Artificial Intelligence, Industrial Internet of Things (IIoT), Robotics, and Advanced Analytics to enable self-optimising, adaptive, and resilient production systems.
- **Industrial Intelligence & Virtual Manufacturing:** Strengthen capabilities in digital twins, predictive simulation, virtual commissioning, advanced process modelling, and data-driven optimisation to reduce development cycles, improve operational performance, and support continuous innovation across the textile value chain.
- **Deep Industrial Decarbonisation:** Accelerate the commercialisation of breakthrough low-carbon technologies capable of eliminating fossil fuel dependence in industrial process heat, including green hydrogen and future zero-carbon thermal energy systems for high-temperature manufacturing applications.
- **Technology Sovereignty & Innovation Ecosystems:** Build collaborative innovation platforms connecting industry, technology providers, research institutions, startups, and government to accelerate indigenous technology development, pilot demonstration, standards development, workforce capability, and commercial deployment of next-generation manufacturing technologies.

These priorities should be supported through sustained investment in research and development, pilot-scale demonstration facilities, testbeds, standards development, industry-academia collaboration, technology commercialisation, and innovation financing. Rather than preparing for a predefined set of technologies, India should build the institutional capability to continuously evaluate, develop, validate, and scale emerging technologies as they mature.

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- **Deep Industrial Decarbonisation:** Accelerate the commercialisation of breakthrough low-carbon technologies capable of eliminating fossil fuel dependence in industrial process heat, including green hydrogen and future zero-carbon thermal energy systems for high-temperature manufacturing applications.
- **Technology Sovereignty & Innovation Ecosystems:** Build collaborative innovation platforms connecting industry, technology providers, research institutions, startups, and government to accelerate indigenous technology development, pilot demonstration, standards development, workforce capability, and commercial deployment of next-generation manufacturing technologies.

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Within the foundational technology portfolio, **Digital Twin Platforms (F0-12)** represent the convergence of enterprise systems, connected manufacturing, artificial intelligence, and advanced simulation. By creating dynamic virtual representations of manufacturing assets and processes, digital twins enable predictive optimisation, virtual commissioning, scenario analysis, and autonomous decision support, forming a critical building block for future intelligent factories.

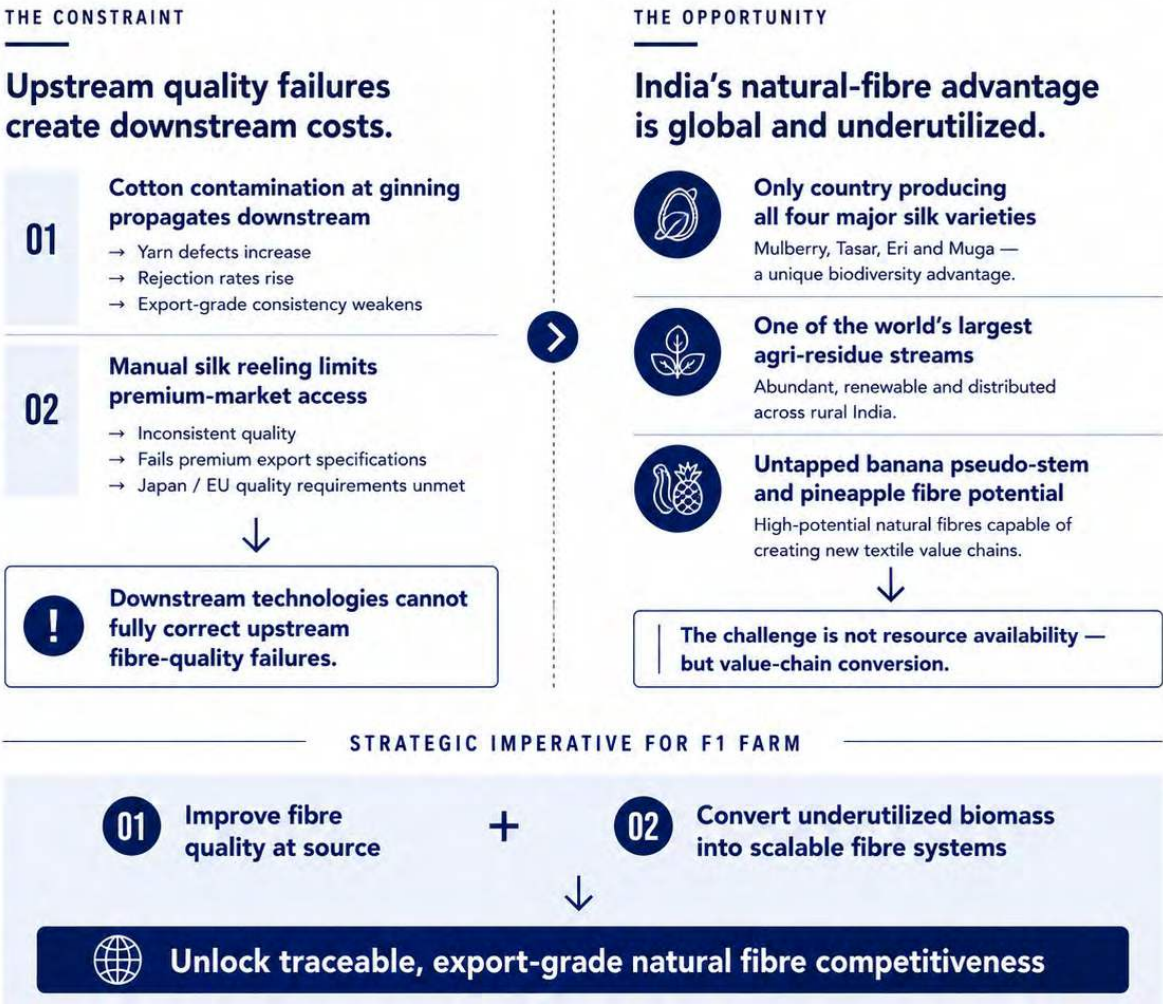
Similarly, **Green Hydrogen Energy Systems (F0-23)** represent a long-term pathway for deep industrial decarbonisation and technology sovereignty. While widespread deployment will depend on the continued development of hydrogen production, storage, transport, and utilisation infrastructure, green hydrogen is expected to play an important role in decarbonising high-temperature industrial processes where direct electrification remains technically or economically challenging.

3.3 FARM (F1): RAW MATERIAL AND PRIMARY PROCESSING

The Farm stage establishes the quality, traceability, and sustainability foundation for the entire textile value chain. Fibre quality, contamination, origin, and certification established at the farm and ginning stages influence spinning efficiency, fabric quality, processing performance, and ultimately export competitiveness.

India starts this stage with a significant structural advantage. It possesses one of the world's most diverse natural fibre ecosystems, spanning cotton, silk, wool, jute, and emerging bio-based materials. The opportunity is not to produce more fibre alone, but to produce fibre that is verifiably higher quality, traceable, and globally differentiated.

The technologies presented in this chapter have therefore been prioritised according to three objectives: improving fibre quality and market access in the near term, expanding commercial natural fibre value chains over the medium term, and positioning India for next-generation bio-based materials over the longer term.



3.3.1. F1 TECHNOLOGY PRIORITY STACK

The technologies in Table 5 have been prioritised using the three implementation horizons adopted.

- **Align (2026–2030):** Establish the quality, certification, and traceability foundation required for market access.
- **Amplify (2030–2035):** Scale commercially proven technologies through stronger ecosystem development, aggregation, and certification infrastructure.
- **Accelerate (2035–2047):** Build long-term innovation capability in next-generation natural fibres and bio-based material systems.

Together, these technologies strengthen both the quality foundation and the long-term diversification of India's natural fibre ecosystem.

Table 5 - Technology Priority Stack for Farm Stage

Card No	Technology Name	Technology Focus	Transformation Direction	Roadmap Horizon
F1-01	Near-Infrared (NIR) & Optical Cotton Contamination Detection	Fibre Quality	Natural Fibre Leadership	Align (2026–2030)
F1-02	Multi-End Automatic Silk Reeling	Fibre Quality	Natural Fibre Leadership	Align (2026–2030)
F1-03	Fibre Identification & IoT Tagging	Digital Traceability	Digital Infrastructure & Traceability	Amplify (2030–2035)
F1-04	Digital Fibre Traceability Platform	Digital Traceability	Digital Infrastructure & Traceability	Amplify (2030–2035)
F1-05	Mechanical Decortication for Bast, Leaf & Agricultural Residue Fibres	Future Fibre Materials	Natural Fibre Leadership	Amplify (2030–2035)
F1-06	Mycelium-Based Leather Materials	Future Fibre Materials	Innovation & Technology Origination	Accelerate (2035–2047)
F1-07	Bio-based PLA & Emerging Bio-fibre Production	Future Fibre Materials	Innovation & Technology Origination	Accelerate (2035–2047)

3.3.2. ALIGN (2026–2030)

Align technologies address constraints that either cannot be corrected once fibre moves downstream or have already become prerequisites for market access. The priority is to establish the quality, certification, and traceability foundation upon which subsequent manufacturing stages depend.

Multi-end automatic silk reeling is prioritised within the Align horizon because India's competitiveness in silk is constrained more by reeling quality than by raw silk production. Modern reeling systems enable consistent production of premium export-grade silk while requiring relatively modest capital investment and offering attractive commercial returns.¹¹

Organic cotton certification Organic cotton certification is prioritised within the Align horizon because sustainability certification is rapidly becoming a baseline requirement for participation in global textile supply chains. As buyer expectations and regulatory requirements continue to strengthen, certified fibre systems improve both market access and commercial differentiation.

- **NIR / Optical Contamination Detection** - Eliminates the only F1 quality gap that is physically irreversible downstream. Approximately 3% contamination at the gin can translate into an estimated 8–12% rejection at the ring frame stage.¹²
- **Multi-End Automatic Silk Reeling** - A relatively low-capital intervention with rapid payback through higher-grade silk output. Upgrading from 2A to 3A quality directly improves access to premium export markets.¹¹
- **Organic Cotton BCI / GOTS Certification** — Approximately 34% of global cotton production now comes from sustainable programmes¹³, while India's certified share remains below 6%. Under evolving EU ESPR requirements, certification is increasingly shifting from buyer preference to market-access prerequisite.

3.3.3. AMPLIFY (2030–2035)

Amplify technologies are commercially established. The principal challenge is scaling adoption through stronger aggregation systems, certification frameworks, digital traceability, and market development rather than advancing the technologies themselves.

Mechanical Decortication: banana, PALF, hemp is prioritised within the Amplify horizon because India possesses abundant agricultural residues that remain significantly underutilised. Commercial deployment depends primarily on developing organised feedstock aggregation systems capable of supplying industrial scale fibre production¹⁴.

¹⁰Uster Technologies. Foreign Fibre and Polypropylene Contamination in Cotton Spinning Systems. Uster Technical Bulletin, 2024
¹¹Ministry of Textiles, Government of India. Modernization and Upgraded Technology in Sericulture Sector under Silk Samagra-2. PIB Delhi, 2025
¹²TMMA Part-1: Technology Gap Analysis. Textile Machinery Manufacturers Association, 2024
¹³Materials Market Report 2025. Textile Exchange, 2025

GI Certification and IoT Fibre Tagging (Digital provenance systems) are prioritised within the Amplify horizon because they strengthen product authenticity and enable verifiable origin claims aligned with emerging traceability requirements. The technology has been demonstrated, but widespread deployment requires coordinated certification infrastructure across production clusters¹⁵.

Materials Matter Standard certification is categorized within the Amplify horizon because global markets are moving towards harmonised sustainability and traceability requirements across multiple fibre systems. While India's cotton sector provides an immediate opportunity, the broader significance of the standard lies in strengthening certified, traceable, and responsibly sourced natural fibres. Early adoption will improve market access and prepare Indian value chains for the evolving Textile Exchange framework¹⁶.

3.3.4. ACCELERATE (2035–2047)

The Accelerate horizon identifies innovation priorities rather than prescribing specific technologies. Beyond 2035, the pace of technological change makes it impractical to predict which individual materials or production systems will dominate future markets. The strategic objective is therefore to build the research capability, demonstration infrastructure, and commercialisation ecosystem required to develop, evaluate, and scale emerging technologies as they mature.

India's agricultural diversity and biomass resources provide a strong foundation for leadership in future natural fibre and bio-based material systems. Strategic investment should focus on areas such as advanced bio-based fibres, engineered biomaterials, agricultural residue valorisation, regenerative fibre systems, and next-generation sustainable materials. Current examples include mycelium-based materials, bio-based PLA fibres, engineered cellulose, agricultural residue-derived composites, and plant-based leather alternatives. These examples are illustrative rather than exhaustive.

Long-term competitiveness will depend less on adopting any single technology and more on building the institutional capability to originate and commercialise successive generations of textile innovation. This aligns directly with the Roadmap's vision of **Innovation and Technology Origination** and **Technology Sovereignty**.

- **Mycelium and Fungal Leather Alternatives** - Global players such as Bolt Threads and Ecovative hold a significant first-mover advantage, while India's agricultural residue base, including rice straw and bagasse, remains largely untapped as a substrate resource. These materials are expected to gain greater commercial relevance over the longer-term horizon.
- **Bio-Based PLA and Emerging Bio-fibres** - Commercial PLA systems have operated globally for over two decades, while India's sugarcane and citrus feedstock advantages remain underutilized. Delayed R&D investment risks limiting participation in future bio-fibre value chains.

¹⁴Ruagnarong C. et al. Evaluation of Mechanically Extracted Banana Fibers from Pseudostem Layers: A Sustainable Textile Raw Material. Heliyon, Vol. 10, Issue 21, 2024
¹⁵10 Mistakes to Avoid When Shopping from Kanchipuram Silk Sarees Manufacturers. Aikyatha Blog, 2025
¹⁶Textile Exchange. Materials Matter Standard. Textile Exchange, 2025

3.3.5. STAGE LINKAGE

Farm-stage fibre quality sets the performance ceiling for Fibre-stage spinning. No spinning technology can fully compensate for contaminated cotton, inconsistent silk denier, or variable agriwaste fibre quality.

F1 also establishes the origin and sustainability data foundation required for downstream traceability and future Digital Product Passport compliance. Investments at the Farm stage therefore represent one of the highest-leverage intervention points in the entire 5F value chain.



3.4. FIBRE (F2): SPINNING, TEXTURING AND RECYCLED FIBRE

The Fibre stage converts raw materials into the yarn systems that determine manufacturing quality, productivity, and downstream processing performance. It is also the stage where recycled content, man-made fibres, and certified sustainable materials become commercially viable products. The quality, consistency, and traceability established here directly influence weaving, knitting, wet processing, and export competitiveness.

India enters this stage with significant manufacturing strength., It accounts for approximately 25% of global ring spinning capacity with more than 54.5 million spindles. However, this strength remains concentrated in conventional spinning systems, while global demand is increasingly shifting towards recycled fibres, MMF blends, functional yarns, and certified sustainable materials. The challenge is therefore not expanding spinning capacity, but modernising it to deliver higher-value, traceable, and circular fibre systems.

The technology priorities presented in this chapter contribute primarily to **Natural Fibre Leadership**, **Manufacturing Capability at Scale**, and **Digital Infrastructure & Traceability**. They are organised according to the three implementation horizons adopted.

India's spinning sector is a global strength at scale.
But the technology base is misaligned with the global fibre transition.



3.4.1. F2 TECHNOLOGY PRIORITY STACK

The Fibre-stage technology portfolio is organised around three implementation horizons.

- Align (2026–2030):** Modernise existing spinning infrastructure, strengthen quality, and establish traceable recycled fibre systems.
- Amplify (2030–2035):** Expand advanced spinning capabilities, specialty fibres, automation, and certified circular materials.
- Accelerate (2035–2047):** Build long-term capability in next-generation fibre systems and circular material innovation.

Together, these priorities strengthen India's transition from volume-based spinning leadership to value-added, digitally enabled, and circular fibre manufacturing.

Table 6 - Technology Priority Stack for Fibre Stage				
Card No	Technology Name	Technology Focus	Transformation Direction	Roadmap Horizon
F2-01	Compact Ring Spinning with Intelligent Monitoring	Spinning Technologies	Manufacturing Capability at Scale	Align (2026–2030)
F2-02	Open-End Rotor Spinning	Spinning Technologies	Manufacturing Capability at Scale	Align (2026–2030)
F2-03	Automatic Cone Winding	Spinning Technologies	Manufacturing Capability at Scale	Align (2026–2030)
F2-04	Draw-Texturing (DTY/POY)	Spinning Technologies	Manufacturing Capability at Scale	Align (2026–2030)
F2-05	Automated Spinning Preparation	Spinning Technologies	Manufacturing Capability at Scale	Amplify (2030–2035)
F2-06	Air-Jet & Vortex Spinning	Spinning Technologies	Manufacturing Capability at Scale	Amplify (2030–2035)
F2-07	Draw Frame Auto-Levelling	Spinning Technologies	Manufacturing Capability at Scale	Amplify (2030–2035)
F2-08	High-Speed Combing	Spinning Technologies	Manufacturing Capability at Scale	Amplify (2030–2035)
F2-09	Two-for-One Twisting	Spinning Technologies	Manufacturing Capability at Scale	Amplify (2030–2035)
F2-10	Advanced Engineered Fibre Production	Spinning Technologies	Innovation & Technology Origination	Accelerate (2035–2047)
F2-11	Certified Recycled Polyester Processing	Circular Fibre Systems	Resource-Intelligent Manufacturing	Align (2026–2030)
F2-12	Recycled Cotton Processing	Circular Fibre Systems	Resource-Intelligent Manufacturing	Align (2026–2030)
F2-13	Certified Organic Cotton Processing	Circular Fibre Systems	Natural Fibre Leadership	Align (2026–2030)

F2-14	Mechanical Fibre Garneting	Circular Fibre Systems	Resource-Intelligent Manufacturing	Amplify (2030–2035)
F2-15	Regenerated Cellulosic Fibre Processing (Lyocell & Bamboo)	Circular Fibre Systems	Natural Fibre Leadership	Amplify (2030–2035)
F2-16	Chemical Recycling of Polyester	Circular Fibre Systems	Resource-Intelligent Manufacturing	Amplify (2030–2035)
F2-17	Next-Generation Circular Fibre Systems	Circular Fibre Systems	Resource-Intelligent Manufacturing	Accelerate (2035–2047)
F2-18	Advanced Bio-based Fibre Systems	Circular Fibre Systems	Innovation & Technology Origination	Accelerate (2035–2047)
F2-19	Integrated Blow Room with Contamination Detection	Spinning Technologies	Manufacturing Capability at Scale	Align (2026–2030)
F2-20	Auto-Doffing Ring Frames, High-Speed (≥1,008 Spindles)	Spinning Technologies	Manufacturing Capability at Scale	Align (2026–2030)
F2-21	Ring Frame Auto Piecer (India-Made)	Spinning Technologies	Technology Sovereignty	Align (2026–2030)
F2-22	Dope Dyeing and Solution-Dyed Mass Coloration	Circular Fibre Systems	Resource-Intelligent Manufacturing	Amplify (2030–2035)

3.4.2. ALIGN (2026–2030)

The Align horizon focuses on commercially proven technologies that strengthen quality, productivity, recycled fibre capability, and digital readiness across India's existing spinning base. The priority is to modernise current manufacturing systems while improving export competitiveness and sustainability performance.

Compact Ring Spinning with ISM is categorized here because India has widely deployed compact spinning infrastructure but very limited spindle-level monitoring adoption¹⁰. The machinery base exists; the missing layer is real-time production and quality data. ISM also creates the first machine-level digital record feeding

into the DPP traceability chain.¹⁷

Open-End Rotor Spinning is in this horizon because mechanically recycled cotton cannot be processed efficiently on conventional ring frames at commercial scale. Shorter and more variable recycled fibre requires rotor processing capability, making this an immediate order-qualification requirement as recycled-content mandates tighten globally¹³. Systems such as Saurer Autocoro and Trützschler Truecycled are designed specifically for recycled-fibre processing.

Automatic Cone Winding Autoconer represents the final quality-control stage before yarn leaves the mill. Export-grade yarn consistency depends on advanced winding capability, where India continues to rely heavily on imported systems^{18, 19}.

DTY and POY draw-texturing are categorized in this horizon because India produces polyester at scale but remains import-dependent for specialty filament yarns in higher-growth synthetic segments.

Panipat GRS certification is categorized here becauseas the competitiveness gap lies not in recycling capability but in certification, traceability, and market positioning. Panipat operates at large recycling scale, but much of the ecosystem remains informal and uncertified, limiting access to premium global recycled-textile markets linked to verified recycled-content supply chains.²⁰

In contrast, the Prato district in Italy has institutionalized recycling through organized consortium structures such as Corertex, standardized quality controls, traceability systems, and globally recognized recycled textile positioning²¹. The Prato model demonstrates that long-term competitiveness in recycled textiles depends not only on recycling volume, but on certification credibility, traceability, and premium-market integration. International buyers are increasingly prioritizing certified and traceable recycled fibre streams as circularity expectations tighten across global apparel supply chains.¹³

rPET GRS certification is categorized as T1 because India already exports significant volumes of recycled polyester fibre, but uncertified supply chains remain excluded from premium global brand markets. GRS certification costs remain relatively low compared to the export value unlocked through certified recycled-content positioning.

- Recycled Polyester Bottle-to-Fibre Production - India already has an established bottle-washing and rPET chip ecosystem across Gujarat, Maharashtra, and Rajasthan. The strategic task is formalization through GRS certification and traceable supply-chain integration rather than new recycling infrastructure creation.

¹⁷Rieter. Integrated Spinning Mill Monitoring and Digital Spinning Solutions. Rieter AG, 2025

¹⁸Werner et al. Textile Sector Development and Export Competitiveness (TSDEC) Textile Engineering Book 2025. TSDEC, 2025

¹⁹Saurer Group. Autoconer Automatic Cone Winding Technology for Quality Yarn Production. Saurer Technologies, 2025

²⁰H&M Foundation. How Can Panipat Lead a Circular Future That Is Not Only Efficient but Fair? H&M Foundation, 2025

²¹Corertex Consortium. Recycling Systems and Circular Textile Infrastructure in the Prato District. Corertex, 2025

3.4.3. AMPLIFY (2030–2035)

The **Amplify** horizon focuses on scaling commercially proven technologies that strengthen manufacturing capability, expand sustainable fibre systems, and accelerate circular material adoption. At this stage, the primary constraints are no longer technology availability, but investment, ecosystem readiness, certification, and integration into mainstream production. The objective is to expand beyond incremental productivity improvements towards higher-value, digitally enabled, and circular fibre manufacturing.

MMCF Lyocell Capability capability is prioritized because India's domestic lyocell ecosystem remains limited relative to global leaders such as Lenzing and Sateri despite production by organized players such as Birla Cellulose. The gap is not technology availability, but scale, specialty-grade capability, and wider downstream ecosystem integration.

Automated spinning preparation systems including Automated Sliver Transport, Auto-Levelling Draw Frames, High-Speed Combing Machines, and Two-for-One Twisters, are prioritised because they improve process stability, yarn quality, and manufacturing consistency across existing spinning infrastructure. These technologies are globally mature, but adoption within India remains uneven, particularly among MSMEs where manual handling continues to introduce contamination and process variation.

Recycled Cotton Mechanical Garneting is prioritised because India's recycling capability already exists at commercial scale, particularly in Panipat. The next stage of development is improving fibre consistency through automated feedstock preparation, contaminant removal, process standardisation, and certification, enabling recycled cotton to integrate more effectively into organised circular supply chains.

Bamboo Lyocell and Responsible Bamboo are prioritised as global sustainability expectations move away from conventional bamboo viscose towards closed-loop and traceable production systems. Expanding responsible bamboo processing strengthens India's sustainable fibre portfolio while improving compliance with evolving international market requirements.

Organic cotton processing certification extends traceability beyond certified fibre production into downstream processing. As traceability requirements mature, end-to-end chain-of-custody certification will become increasingly important for demonstrating product provenance and sustainability performance.

Open-End Rotor Spinning is also prioritised within this horizon as recycled fibre content increases across global textile markets. Rotor spinning enables efficient processing of shorter and more variable recycled cotton fibres that conventional ring spinning cannot process economically at scale, supporting the commercial expansion of recycled yarn systems.

Air-Jet and Vortex Spinning MVS - strengthen manufacturing capability by delivering substantially higher productivity than conventional ring spinning within suitable yarn count ranges. While capital requirements currently limit adoption primarily to larger organised mills, these technologies represent an important

²²Birla Cellulose. Lyocell Fibre Manufacturing and Closed-Loop MMCF Systems. Birla Cellulose, 2025

²³Trützschler Group. Integrated Spinning Preparation and Automated Sliver Transport Systems. Trützschler, 2025

²⁴Refashion. Mechanical Recycling of Textiles: Industrial Systems, Quality Challenges and Circular Textile Integration. Refashion France, 2025

pathway for improving productivity, responsiveness, and product consistency in higher-value market segments.

Chemical recycling of polyester textile-to-textile systems is currently at TRL 5–6 globally, with companies such as Carbios (France) and JEPLAN (Japan) moving toward early commercial deployment., Less than 1% of global recycled polyester currently originates from textile-to-textile recycling routes, leaving a major capability gap in circular polyester systems. Surat is the natural location for India's first textile-to-textile polyester recycling pilot because of its concentration of polyester fabric processing and associated waste generation.

Fibre-to-fibre cotton chemical recycling through technologies such as Iyocell and Infinited Fiber is also progressing at approximately TRL 5–6 globally., Delhi-NCR, Bengaluru and Tirupur already generate substantial post-industrial and post-consumer cotton waste streams that could serve as feedstock for future closed-loop recycling systems.

Recycled PA6 nylon systems address an immediate waste-value opportunity in Ludhiana's hosiery sector and Surat's synthetic textile clusters, where significant nylon waste continues to be landfilled. Structured collection and export linkage models with established recyclers such as Aquafil's ECONYL® system require comparatively low capital investment while enabling immediate value recovery from textile waste streams.

3.4.4. ACCELERATE (2035-2047)

The Accelerate horizon shifts from scaling proven technologies to building the capability to originate the next generation of fibre systems. Beyond 2035, technological change is expected to outpace today's investment cycles, making it neither practical nor desirable to prescribe a fixed set of future technologies. Instead, the priority is to strengthen India's innovation ecosystem so it can evaluate, develop, commercialise, and manufacture emerging fibre technologies as they mature.

Strategic investment during this horizon should focus on four innovation priorities:

Advanced Circular Fibre Systems - Develop next-generation closed-loop fibre systems capable of recovering textile waste at commercial scale while maintaining fibre quality across multiple recycling cycles. Future advances may include new recycling chemistries, intelligent material separation, and high-value fibre regeneration technologies.

Bio-based and Regenerative Fibre Systems - Leverage India's agricultural diversity and biomass resources to develop sustainable alternatives to conventional natural and synthetic fibres. Future opportunities may emerge from agricultural residues, bio-polymers, microbial processes, and regenerative feedstocks that reduce dependence on virgin fossil-based materials.

²⁵ Carbios. Enzymatic PET Biorecycling and Textile-to-Textile Circularity Systems. Carbios S.A., 2025
²⁶ JEPLAN Inc. BRING™ Chemical Recycling Technology for Polyester Textiles. JEPLAN, Japan, 2025
²⁷ Ioncell. Ioncell® Fibre-to-Fibre Regenerated Cellulose Technology. Aalto University, 2025
²⁸ Infinited Fiber Company. Infinna™ Circular Cotton Fibre Technology. Infinited Fiber, 2025
²⁹ Aquafil Group. ECONYL® Regenerated Nylon and Circular PA6 Recycling Systems. Aquafil S.p.A., 2025.

Advanced Engineered and Functional Fibres - Strengthen domestic capability in high-performance fibres for technical textiles, protective applications, medical textiles, mobility, aerospace, and other advanced manufacturing sectors. These materials are expected to become increasingly important as textile applications diversify beyond apparel.

Intelligent Fibre Manufacturing - Integrate artificial intelligence, digital twins, advanced sensing, autonomous process control, and smart manufacturing systems into fibre production. Future competitiveness will depend not only on fibre quality but also on the ability to optimise production continuously through data-driven manufacturing.

These priorities should be supported through long-term investments in research infrastructure, pilot facilities, demonstration projects, and industry-academia collaboration. Rather than preparing for one specific technology, India should build the institutional capability to identify, validate, and commercialise successive generations of fibre innovation.

Current developments such as advanced textile-to-textile recycling, bio-based polymers, engineered cellulose, microbial fibres, biofabricated materials, and intelligent manufacturing systems illustrate the direction of travel. They should be viewed as examples of emerging innovation pathways rather than a definitive list of future technologies.

Bio-based PLA fibre represents a longer-horizon strategic opportunity requiring ecosystem-scale investment comparable to global PLA leaders such as NatureWorks³⁰. India's sugarcane base provides a strong feedstock advantage, but commercial participation beyond 2030 depends on early-stage capability development and pilot-scale investment beginning now.

Biofabricated and lab-engineered fibres represent a long-horizon aimed at decoupling textile raw materials from conventional agricultural and petrochemical feedstocks. Technologies under development include microbial cellulose fibres, synthetic protein fibres, cultivated cotton-cellulose systems, and biofabricated leather alternatives. Most remain at pilot or early commercial stage globally, with limited textile-scale deployment as of 2026.^{31,32,33}

3.4.5. STAGE LINKAGE

Fibre-stage yarn quality sets the performance ceiling for Factory-stage fabric production. Looms and knitting systems cannot compensate for yarn irregularity, inconsistent count, or weak recycled-blend performance.

F2 also establishes the first machine-level production and traceability layer through ISM and yarn batch records, forming a critical upstream input for future Digital Product Passport systems at F5. Investments in advanced fabric-production technologies without corresponding improvements in yarn quality and data consistency at F2 will therefore underdeliver on productivity, quality, and compliance outcomes.

³⁰ NatureWorks LLC. Ingeo™ PLA Biopolymer Technology for Textile Fibre Applications. NatureWorks, 2025
³¹ Spiber Inc. Brewed Protein™ Fibre Technology for Textile Applications. Spiber Inc., Japan, 2025
³² Galy. Lab-Grown Cotton and Cellular Agriculture for Textile Fibre Production. Galy Co., 2025
³³ Nanollose Ltd. Microbial Cellulose Fibre Technology and Circular Textile Feedstocks. Nanollose, Australia, 2025



3.5. FACTORY - DRY (F3): WEAVING AND KNITTING

The Factory (Dry) stage determines the productivity, quality, and flexibility of fabric manufacturing. It is here that yarn is transformed into woven and knitted fabrics, making this stage a critical link between fibre production and downstream wet processing. Manufacturing performance established here directly influences resource efficiency, product quality, delivery reliability, and export competitiveness.

India possesses one of the world's largest weaving and knitting industries, yet much of its capacity continues to rely on ageing equipment and limited digital integration. Approximately 60–70% of weaving capacity still operates on shuttle looms, while adoption of real-time production monitoring remains significantly below competing textile economies. As a result, productivity, quality consistency, and operational visibility remain constrained despite investments in modern machinery.^{5,12}

The technologies presented in this chapter contribute primarily to **Manufacturing Capability at Scale**, **Digital Infrastructure & Traceability**, and **Resource-Intelligent Manufacturing**. They are prioritised according to the three implementation horizons adopted.

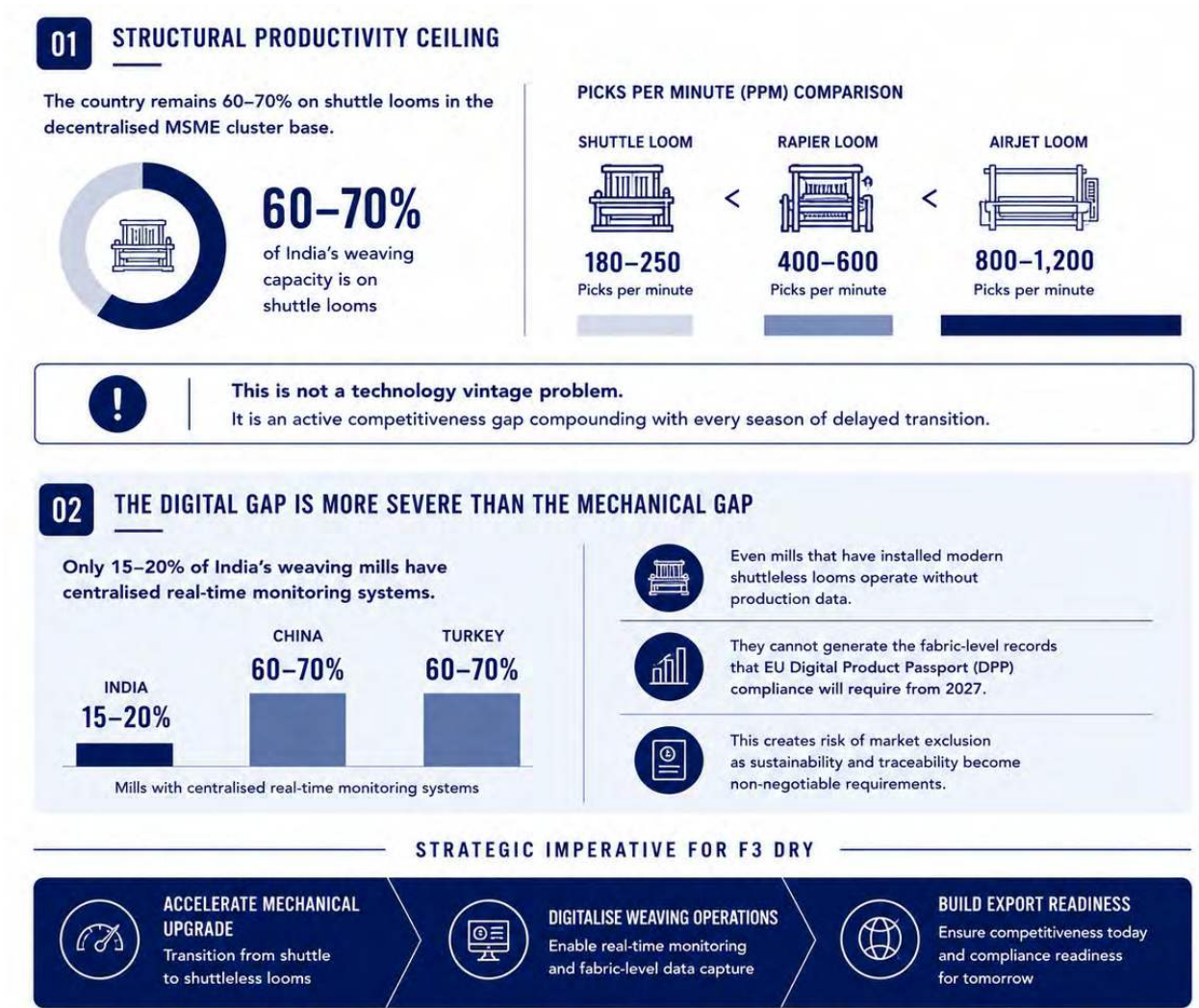
²⁵ Carbios. Enzymatic PET Biorecycling and Textile-to-Textile Circularity Systems. Carbios S.A., 2025

²⁶ JEPLAN Inc. BRING™ Chemical Recycling Technology for Polyester Textiles. JEPLAN, Japan, 2025

²⁷ Ioncell. Ioncell® Fibre-to-Fibre Regenerated Cellulose Technology. Aalto University, 2025

²⁸ Infinited Fiber Company. Infinna™ Circular Cotton Fibre Technology. Infinited Fiber, 2025

²⁹ Aquafil Group. ECONYL® Regenerated Nylon and Circular PA6 Recycling Systems. Aquafil S.p.A., 2025.



3.5.1. F3 DRY TECHNOLOGY PRIORITY STACK

The Factory (Dry) technology portfolio is organised around three implementation horizons.

- Align (2026–2030):** Modernise core weaving and knitting infrastructure while establishing digital production visibility.
- Amplify (2030–2035):** Expand automation, flexible manufacturing, and technical textile capability.
- Accelerate (2035–2047):** Build long-term capability in advanced textile manufacturing and intelligent production systems.

Together, these priorities strengthen India's transition from volume-based fabric production to digitally enabled, high-productivity, and value-added manufacturing.

Table 7 - Technology Priority Stack for Factory (Dry) Stage

Card No	Technology Name	Technology Focus	Transformation Direction	Roadmap Horizon
F3-01	Shuttleless Rapier Weaving	Weaving Technologies	Manufacturing Capability at Scale	Align (2026–2030)
F3-02	Air-Jet Weaving	Weaving Technologies	Manufacturing Capability at Scale	Align (2026–2030)
F3-03	Water-Jet Weaving	Weaving Technologies	Manufacturing Capability at Scale	Align (2026–2030)
F3-04	Real-Time Loom Monitoring	Weaving Technologies	Digital Infrastructure & Traceability	Align (2026–2030)
F3-05	High-Speed Sizing Systems	Weaving Technologies	Manufacturing Capability at Scale	Amplify (2030–2035)
F3-06	Advanced Warping Systems	Weaving Technologies	Manufacturing Capability at Scale	Amplify (2030–2035)
F3-07	Electronic Jacquard & Servo Dobby	Weaving Technologies	Manufacturing Capability at Scale	Amplify (2030–2035)
F3-08	Advanced Textile Manufacturing Systems	Weaving Technologies	Innovation & Technology Origination	Accelerate (2035–2047)
F3-09	Circular Knitting Modernisation	Knitting Technologies	Manufacturing Capability at Scale	Amplify (2030–2035)
F3-10	Seamless 3D Flatbed Knitting	Knitting Technologies	Manufacturing Capability at Scale	Amplify (2030–2035)
F3-11	Warp Knitting	Technical Textiles	Manufacturing Capability at Scale	Amplify (2030–2035)
F3-12	Nonwoven Production Systems	Technical Textiles	Manufacturing Capability at Scale	Amplify (2030–2035)
F3-13	Smart Functional Textile Systems	Technical Textiles	Innovation & Technology Origination	Accelerate (2035–2047)

*Illustrative innovation priorities rather than prescribed technologies.

3.5.2. ALIGN (2026–2030)

The Align horizon focuses on eliminating India's largest productivity and digital capability gaps in weaving and knitting. The priority is to modernise core manufacturing infrastructure while establishing real-time production visibility. Productivity improvements and digital traceability must progress together, as modern machinery without operational data cannot deliver the manufacturing intelligence required for future competitiveness.

Rapier Looms are prioritised because they provide the broadest transition pathway for India's MSME weaving base with 2-3x productivity advantage vs shuttle.^{12,34} Rapier technology supports diverse fibre types and fabric constructions, making it suitable for mixed-product clusters. The rapid expansion of rapier adoption in clusters such as Bhiwandi demonstrates commercial viability at scale.^{12,34}

Airjet Looms are prioritised for high-volume cotton and synthetic fabric production where maximum productivity justifies higher capital investment and compressed-air infrastructure.

Waterjet Looms remain a strategic priority for synthetic filament clusters such as Surat, where replacing the remaining shuttle-based capacity delivers immediate productivity gains.¹²

Real-Time Loom Monitoring is prioritised alongside machinery modernisation because digital visibility is becoming as important as mechanical capability. Machine-level production data improves operational efficiency today while creating the digital records required for traceability, lifecycle assessment, and future Digital Product Passport compliance. India's loom-monitoring adoption remains approximately 15–20% compared to 60–70% in competing textile economies such as China and Turkey.¹²

3.5.3. AMPLIFY (2030–2035)

The Amplify horizon focuses on expanding manufacturing flexibility, automation, and higher-value production capabilities. The technologies within this horizon are commercially established. Their wider deployment depends primarily on investment, workforce capability, digital integration, and market development rather than technology maturity.

Electronic Jacquard and Servo Dobby enable economically viable short-run, design-led manufacturing, allowing Indian manufacturers to respond more effectively to changing market demand while increasing product differentiation. India's electronic Jacquard adoption remains approximately 20–25% compared to 50–60% in organized global weaving systems.¹⁰

High-Speed Sizing Machine and Warp Beam Preparation and Warping strengthen process consistency by improving warp preparation, sizing quality, and compatibility with high-speed shuttleless weaving systems.³⁵

³⁴Textile Engineering. Shuttleless Looms Techno-Economics. Textile Engineering Journal, 2024

³⁵Karl Mayer Group. Warp Preparation, Sizing and Beam Preparation Technologies for High-Speed Weaving. Karl Mayer, 2025

Circular Knitting Modernisation focuses on upgrading India's established knitting base through energy-efficient machinery, intelligent controls, and integrated production monitoring rather than large-scale equipment replacement.

WHOLEGARMENT Flatbed Knitting expands India's capability in seamless garment manufacturing, reducing material waste while supporting premium knitwear production. Wider adoption depends equally on digital programming capability and specialised workforce development.

Warp Knitting (DRY-⁹) and **Nonwoven Production Systems** strengthen India's position in technical textiles, supporting growing demand across medical, industrial, automotive, sports, and infrastructure applications.

3.5.4. ACCELERATE (2035–2047)

The Accelerate horizon focuses on building India's long-term capability in advanced textile manufacturing rather than prescribing specific technologies. Beyond 2035, the pace of technological change makes it impractical to predict which manufacturing systems will define future competitiveness. Instead, the priority is to strengthen the research, demonstration, and commercialisation ecosystem required to evaluate and scale emerging production technologies.

Strategic investment should focus on four innovation priorities:

- Intelligent Manufacturing Systems - Develop highly connected manufacturing environments that integrate artificial intelligence, digital twins, autonomous process control, advanced robotics, and real-time analytics to optimise production, quality, and resource efficiency across weaving and knitting operations.
- Advanced Technical Textile Manufacturing -Strengthen capability in manufacturing systems for high-performance fabrics serving medical, mobility, defence, aerospace, industrial, and protective textile applications, enabling India to expand beyond conventional apparel production.
- Advanced Fabric Engineering - Develop capabilities in engineered fabric structures, three-dimensional textile architectures, functional surfaces, and multi-material textile systems that support next-generation composite and technical applications.
- Smart and Functional Textile Systems - Build capability to manufacture textiles incorporating sensing, responsive materials, embedded electronics, and advanced functional finishes, positioning India for emerging markets in intelligent and high-value textile products.

These priorities should be supported through sustained investment in research infrastructure, pilot manufacturing facilities, demonstration centres, and stronger collaboration between industry, academia, Textile Research Associations, and technology providers. Rather than preparing for one specific technology, India should build the institutional capability to identify, evaluate, and commercialise successive generations of advanced textile manufacturing systems.

³⁶ Shima Seiki Mfg. Ltd. WHOLEGARMENT® Seamless Flatbed Knitting Technology. Shima Seiki, Japan, 2025

Current developments such as 3D textile preforms, electrospun nanofibre structures, AI-enabled manufacturing, robotic weaving, and advanced digital production systems illustrate the direction of travel. These examples are indicative rather than exhaustive and should be viewed as emerging innovation pathways rather than prescribed technology choices.

3.5.5. STAGE LINKAGE

Fabric formation quality sets the performance ceiling for wet processing. Grey fabric with inconsistent dimensional structure leads to uneven dye uptake, higher shade variation, and lower right-first-time performance in dyeing and finishing operations. These structural inconsistencies cannot be corrected downstream in the dyehouse.

Investments in advanced wet-processing systems such as LLR dyeing therefore deliver full value only when supported by consistent grey fabric quality at the Factory Dry stage.



3.6 FACTORY – WET (F3): DYEING, PRINTING AND FINISHING

Wet processing is the single most important intervention point in India's textile value chain. It is the stage where water, energy, chemistry, emissions, cost, and compliance converge, making it central to both environmental performance and manufacturing competitiveness.

Unlike other manufacturing stages, wet processing depends on tightly interconnected resource systems. Water consumption influences thermal energy demand. Liquor ratio determines chemical use, salt loading, and wastewater generation. Process control affects product quality, reprocessing, and operating costs. As a result, improvements in one part of the process often deliver multiple performance gains across the entire production system.

The technologies presented in this chapter contribute primarily to **Resource-Intelligent Manufacturing**, while also strengthening **Manufacturing Capability at Scale** and **Digital Infrastructure & Traceability**.

Wet processing is India’s highest-leverage intervention point and and of the sector’s highest-risk stages for competitive exclusion.

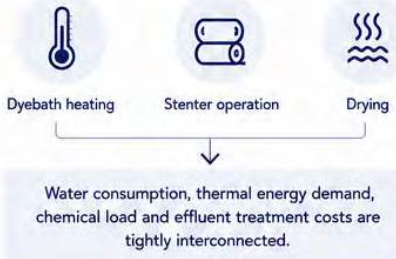


Act here, and gains compound.
Delay here, and risks multiply.

01 THE UNIQUE CHALLENGE OF WET PROCESSING

Unlike other 5F stages where energy demand is primarily electrical and substitutable with renewable sources, wet processing depends on **thermal energy — steam** for dyebath heating, stenter operation, and drying.

THERMAL ENERGY DEPENDENCY CANNOT BE SWITCHED. IT CAN ONLY BE REDUCED BY CUTTING PROCESS DEMAND.



WHY THIS STAGE DRIVES COMPETITIVENESS

- Highest share of operating cost
- Largest environmental footprint
- Most exposed to compliance risk
- Greatest potential for multi-parameter improvement

02 THE CENTRAL STRATEGIC ISSUE: LIQUOR RATIO

High liquor-ratio dyeing increases water use, steam demand, salt consumption, and effluent load simultaneously.

REDUCING LIQUOR RATIO CREATES COMPOUNDING GAINS



03 RISING CHEMICAL MANAGEMENT PRESSURES

Conventional processing chemistries face increasing restrictions under evolving buyer and regulatory frameworks.



REGULATORY LANDSCAPE IS TIGHTENING

- ZDHC MRSL compliance
- EU chemical regulations
- National and regional norms evolving rapidly



BUYER EXPECTATIONS ARE RISING

- Process transparency
- Better wastewater performance
- Lower-carbon manufacturing systems

04 THE NARROWING STRATEGIC WINDOW

Compliance expectations are rapidly becoming baseline export conditions — not premium differentiators.



CARBON DISCLOSURE REQUIREMENTS
Moving from voluntary to mandatory



CHEMICAL COMPLIANCE EXPECTATIONS
Becoming stricter, buyer- and law-driven



TRACEABILITY-LINKED BUYER STANDARDS
Now integral to market access



Mills that defer investment in liquor ratio optimisation, chemical management-data systems risk:

Rising compliance costs

Reduced buyer competitiveness

Growing barriers in regulated export markets



STRATEGIC IMPERATIVE FOR F3 WET

Optimise liquor ratio. Strengthen chemical management. Build process-data systems.

DELIVER LOWER COSTS. STRONGER COMPLIANCE. SUSTAINABLE COMPETITIVENESS.

3.6.1. F3 WET TECHNOLOGY PRIORITY STACK

The Factory (Wet) technologies in Table 8 is organised around three implementation horizons

- **Align (2026–2030):** Establish resource-efficient, compliant, and digitally monitored wet-processing systems.
- **Amplify (2030–2035):** Scale advanced processing technologies, circular water systems, and higher-value manufacturing capability.
- **Accelerate (2035–2047):** Build long-term capability in next-generation low-impact processing technologies.

Together, these priorities strengthen India's transition towards resource-intelligent, low-carbon, and globally competitive wet processing.

Table 8 - Technology Priority Stack for Factory (Wet) Stage

Card No	Technology Name	Technology Focus	Transformation Direction	Roadmap Horizon
F3-14	Low-Liquor Ratio Dyeing	Resource Efficiency	Resource-Intelligent Manufacturing	Align (2026–2030)
F3-15	Automated Dye & Chemical Dispensing Systems	Resource Efficiency	Resource-Intelligent Manufacturing	Align (2026–2030)
F3-16	Right-First-Time Dyeing	Resource Efficiency	Resource-Intelligent Manufacturing	Align (2026–2030)
F3-17	Continuous Bleaching	Resource Efficiency	Resource-Intelligent Manufacturing	Align (2026–2030)
F3-18	Wastewater Heat Recovery	Resource Efficiency	Resource-Intelligent Manufacturing	Align (2026–2030)
F3-19	Stenter Heat Recovery	Resource Efficiency	Resource-Intelligent Manufacturing	Align (2026–2030)
F3-20	Digital Waterless Dyeing Systems	Resource Efficiency	Resource-Intelligent Manufacturing	Amplify (2030–2035)
F3-21	Foam Dyeing	Resource Efficiency	Resource-Intelligent Manufacturing	Amplify (2030–2035)
F3-22	Supercritical CO ₂ Dyeing	Resource Efficiency	Resource-Intelligent Manufacturing	Amplify (2030–2035)
F3-23	Nano-Bubble Dyeing	Resource Efficiency	Innovation & Technology Origination	Accelerate (2035–2047)
F3-24	Ultrasound-Assisted Dyeing	Resource Efficiency	Innovation & Technology Origination	Accelerate (2035–2047)

F3-25	Microwave-Assisted Textile Processing	Resource Efficiency	Innovation & Technology Origination	Accelerate (2035-2047)
F3-26	Enzymatic Pre-treatment & Bio-Scouring	Advanced Sustainable Chemistry	Resource-Intelligent Manufacturing	Align (2026–2030)
F3-27	Cellulase Bio-Polishing	Advanced Sustainable Chemistry	Resource-Intelligent Manufacturing	Align (2026–2030)
F3-28	Nitrogen-Assisted Indigo Dyeing	Advanced Sustainable Chemistry	Resource-Intelligent Manufacturing	Align (2026–2030)
F3-29	Salt-Free Reactive Dyeing	Advanced Sustainable Chemistry	Resource-Intelligent Manufacturing	Amplify (2030–2035)
F3-30	PFAS-Free Durable Water Repellent Finishes	Advanced Sustainable Chemistry	Resource-Intelligent Manufacturing	Amplify (2030–2035)
F3-31	Precision Spray Finishing Systems	Advanced Sustainable Chemistry	Resource-Intelligent Manufacturing	Amplify (2030–2035)
F3-32	Electrochemical Indigo Reduction	Advanced Sustainable Chemistry	Innovation & Technology Origination	Accelerate (2035–2047)
F3-33	Sol-Gel PFAS-Free Finishing	Advanced Sustainable Chemistry	Innovation & Technology Origination	Accelerate (2035–2047)
F3-34	Plasma Surface Treatment	Advanced Sustainable Chemistry	Innovation & Technology Origination	Accelerate (2035–2047)
F3-35	Plasma Wool Shrink-Resist Treatment	Advanced Sustainable Chemistry	Innovation & Technology Origination	Accelerate (2035–2047)
F3-36	Zero Liquid Discharge (ZLD) Systems	Circular Resource Recovery	Resource-Intelligent Manufacturing	Align (2026–2030)
F3-37	Reverse Osmosis (RO)	Circular Resource Recovery	Resource-Intelligent Manufacturing	Align (2026–2030)
F3-38	Caustic Soda Recovery	Circular Resource Recovery	Resource-Intelligent Manufacturing	Align (2026–2030)
F3-39	Primary Effluent Treatment Plants (ETP)	Circular Resource Recovery	Resource-Intelligent Manufacturing	Align (2026–2030)

F3-40	Membrane Bioreactor (MBR)	Circular Resource Recovery	Resource-Intelligent Manufacturing	Amplify (2030–2035)
F3-41	Advanced Oxidation Processes (AOP)	Circular Resource Recovery	Resource-Intelligent Manufacturing	Amplify (2030–2035)
F3-42	UASB Biogas Recovery	Circular Resource Recovery	Resource-Intelligent Manufacturing	Amplify (2030–2035)
F3-43	Sludge Drying Technologies	Circular Resource Recovery	Resource-Intelligent Manufacturing	Amplify (2030–2035)
F3-44	Closed-Loop Process Water Recycling Systems	Circular Resource Recovery	Resource-Intelligent Manufacturing	Amplify (2030–2035)
F3-45	Closed-Loop Water & Chemical Systems	Circular Resource Recovery	Resource-Intelligent Manufacturing	Accelerate (2035–2047)
F3-46	Laser & Ozone Denim Finishing	Specialty Processing	Resource-Intelligent Manufacturing	Align (2026–2030)
F3-47	Digital Inkjet Textile Printing	Specialty Processing	Resource-Intelligent Manufacturing	Amplify (2030–2035)
F3-48	Nanotechnology Functional Coatings (Nano-Silver, Nano-TiO2, Nano-Silica)	Advanced Sustainable Chemistry	Resource-Intelligent Manufacturing	Amplify (2030–2035)
F3-49	Radio-Frequency Drying for Yarn and Technical Textiles	Specialty Processing	Resource-Intelligent Manufacturing	Amplify (2030–2035)

3.6.2. ALIGN (2026–2030)

The **Align** horizon focuses on technologies that deliver the greatest immediate improvements in resource efficiency, process stability, and regulatory compliance. The priority is to reduce water, energy, chemical, and wastewater intensity at source while establishing the operational data required for digital process management and future traceability.

LLR and Airflow Jet Dyeing is prioritized because liquor ratio is the single largest determinant of water consumption, thermal energy demand, chemical use, and effluent generation. Reducing liquor ratio therefore delivers simultaneous improvements across cost, environmental performance, and compliance. India's average liquor ratio of approximately 1:10-1:12 versus global best-available practice of roughly 1:2.3-1:4 means significantly higher water, steam, chemical, salt, and effluent-treatment loads per batch.^{10,37} Reducing liquor ratio therefore lowers multiple resource burdens simultaneously.

Automated Dye and Chemical Kitchen improve process consistency by eliminating manual dosing variability, reducing reprocessing, and improving right-first-time dyeing performance. Considering high re-dyeing rates in India^{10,38} result in entire batches repeating water, energy, and chemical consumption.

ZLD System ETP plus RO plus MEE/MVR and Reverse Osmosis for ZLD Feed establish the wastewater treatment infrastructure increasingly required for regulatory compliance in major processing clusters while improving long-term water reuse.

India's Draft Liquid Waste Management Rules,²⁰²⁴ strengthen wastewater reuse obligations for high-water-use sectors including textiles and formalize stricter compliance, monitoring, reuse, and reporting requirements under an Extended User Responsibility framework^{39,40}.

ETP coagulation and flocculation systems represent the mandatory primary-treatment baseline for dyehouse effluent management.

Enzymatic Pre-treatment and Bio-scouring replaces several conventional scouring and bleaching chemistries increasingly face restrictions under ZDHC MRSL frameworks, with limited safer substitution pathways available. Enzyme-based pre-treatment systems reduce alkali intensity, processing severity, and chemical load while improving compatibility with lower-impact wet-processing systems.^{18,41}

³⁷European Commission. Best Available Techniques Reference Document for the Textiles Industry (EU TXT BREF 2023). Publications Office of the European Union, EUR 30695 EN, 2023

³⁸Datacolor. Right-First-Time Dyeing and Automated Chemical Dispensing Systems in Textile Processing. Datacolor Technical Series, 2025

³⁹Ministry of Environment, Forest and Climate Change (MoEFCC). Draft Liquid Waste Management Rules, 2024. Gazette of India, Government of India, 2024

⁴⁰Down To Earth. India's 2024 Liquid Waste Management Rules: Wastewater Reuse and Compliance Framework. Down To Earth, 2024

⁴¹Novozymes. Enzymatic Pretreatment Solutions for Sustainable Textile Wet Processing. Novozymes Textile Processing Solutions, 2025

Right-First-Time Dyeing with Spectrophotometry are prioritized as the systematic elimination of re-dyeing depends on accurate shade prediction, colour matching, and process control before dyeing begins. Stable low-liquor-ratio dyeing performance is not achievable without high first-pass shade accuracy. Digital spectrophotometric colour-management systems enable dyehouse-level process standardization, reduce reprocessing rates, and significantly improve right-first-time dyeing performance.⁴²

Wastewater Heat Recovery Systems are added here because textile effluent typically leaves the process stream at high temperatures of 60-95 °C, representing recoverable thermal energy that would otherwise be lost during treatment.¹⁴ Heat-exchanger and thermal-recovery systems reduce steam demand, improve energy efficiency, and shorten thermal payback periods in continuous wet-processing operations.⁴³

Laser and Ozone Denim Finishing systems - With tightening EU chemical restrictions on potassium permanganate-based denim finishing create a direct transition requirement toward alternative finishing technologies.⁴⁴

Cellulase Enzyme Bio-Polishing is a value-add quality enhancement rather than a foundational compliance or resource-efficiency intervention. The technology improves knitwear surface smoothness, softness, and pilling resistance for premium export applications, with medium adoption already present across India's organized knitwear sector. Commercial enzyme systems are widely available from suppliers such as Novozymes and AB Enzymes.⁴³

Caustic Soda Recovery in Mercerisation builds on existing mercerisation infrastructure to reduce chemical purchase cost and effluent TDS through sodium hydroxide recovery and reuse. The technology is recognized as Best Available Technique (BAT) under the EU Textile BREF framework³⁹ but delivers maximum value only after baseline wet-processing efficiency and wastewater systems are already established.

Continuous Bleaching with H₂O₂ and Catalase improves process efficiency within existing continuous bleaching systems rather than replacing the bleaching platform itself. Catalase-assisted peroxide decomposition eliminates the conventional hot peroxide kill-wash stage, reducing steam demand and lowering hydrogen peroxide conSalt-free reactive dyeing Cold Pad-Batch systems reduces or eliminates

3.6.3. AMPLIFY (2030–2035)

The **Amplify** horizon focuses on expanding resource efficiency beyond compliance while strengthening manufacturing flexibility, circular water management, and sustainable chemistry. These technologies are commercially proven. The principal challenge is scaling adoption through investment, operational capability, and integration with existing production systems.

Salt-free reactive dyeing Cold Pad-Batch systems reduces or eliminates salt dosing directly lowers effluent TDS, chemical load, and downstream ZLD operating cost while improving manufacturing flexibility for increasingly design-driven markets. Commercial salt-free and low-salt dyeing systems can eliminate

⁴²X-Rite Pantone. Spectrophotometric Colour Control and Right-First-Time Textile Dyeing Systems. X-Rite Technical Solutions, 2025

⁴³GEA Group. Heat Recovery Systems for Textile Wastewater and Process Energy Optimization. GEA Industrial Technologies, 2025

⁴⁴Khalil E. et al. Advanced Technology in Textiles. Springer, 2023. ISBN 978-981-19-7759-7

sodium sulphate (approx. 50–100 g/L per bath) while reducing effluent TDS by an estimated 30–50%.^{45,46} . However, stable low-liquor-ratio dyeing systems and controlled process chemistry must already be in place before salt-free dyeing can deliver reliable industrial-scale performance.⁴⁷

Continuous dyeing systems reduces water and thermal energy consumption per metre of fabric during long-run continuous processing operations. India already has medium-level adoption across organized processing mills, while jigger and pad-batch systems continue to serve as lower-resource alternatives for reactive dyeing applications.

Digital inkjet printing eliminates screen preparation and washing while making short-run and design-led production commercially viable. The technology delivers approximately 70% water savings versus rotary screen printing.^{48,49,50}

Stenter Heat Recovery and Moisture Control is prioritized as the stenter exhaust streams contain 180-220 °C, a substantial recoverable thermal energy that continues to be discharged unused across many textile-processing facilities, despite commercially mature retrofit solutions being widely available. Industrial suppliers in India already offer integrated air-to-air heat recovery, exhaust-air filtration, and thermal recovery systems specifically designed for textile stenters, including retrofit integration into existing exhaust infrastructure.^{51,52} . The strategic gap in India is therefore not technology availability but retrofit adoption across installed stenter capacity.

TexCoat G4 Precision Spray Finishing improves chemical-application efficiency within existing finishing operations rather than replacing the finishing platform itself. Non-contact precision spray systems apply chemistry only where required, significantly reducing water, chemical, and energy consumption while improving process control and minimizing overspray waste.^{53,54}

MBR Secondary Biological Treatment, AOP Colour Removal, UASB Anaerobic Biogas Recovery, ETP Sludge Dewatering Paddle Dryers, and Solar Sludge Drying Beds completes the advanced wastewater-treatment and resource-recovery sequence required for stable long-term ZLD operation. Together, these technologies shift wastewater systems from compliance-only infrastructure toward integrated water, energy, and waste-resourc

PFAS-Free DWR Substitution Systems involves fluorinated chemistries that increasingly face regulatory and buyer-driven restrictions under evolving EU and ZDHC frameworks.e recovery platforms.

⁴⁵Benninger Group. BEN-Colour Cold Pad Batch (CPB) Dyeing Systems with Salt-Free Dyeing Capability. Benninger AG, 2025

⁴⁶Texintel. Benninger-Küstners Promote CPB Salt-Free Dyeing System to Save Water and Energy. Texintel, 2019

⁴⁷Nallathambi, A., and Rengaswami, G.D.V. Industrial-Scale Salt-Free Reactive Dyeing of Cationized Cotton Fabric with Different Reactive Dye Chemistry. Carbohydrate Polymers, Elsevier, 2017

⁴⁸TMMA. 65th Annual Report 2024-25. Textile Machinery Manufacturers Association, 2025

⁴⁹ColorJet India Ltd. Digital Textile Printing Systems and Industrial Inkjet Solutions. ColorJet India, 2025

⁵⁰SPGPrints. Sustainable Textile Printing: digitally reducing the ecological footprint. SPGPrints, November 2021

⁵¹InspirOn Engineering Pvt. Ltd. KAPrec HRU Heat Recovery Unit for Textile Stenters. InspirOn, 2025

⁵²KMA Umwelttechnik GmbH. ULTRAVENT® Heat Recovery and Air Filtration Systems for Stenter Frames. KMA Umwelttechnik, 2025

⁵³BW Converting. TexCoat® G4 Precision Spray Finishing Technology. BW Converting, 2025

⁵⁴Apparel Impact Institute. Precision Spray Finishing Technology Assessment – TexCoat® G4. Apparel Impact Institute, 2025

3.6.4. ACCELERATE (2035–2047)

The **Accelerate** horizon shifts from scaling today's processing technologies to building India's capability to originate the next generation of sustainable wet-processing systems. Beyond 2035, advances in artificial intelligence, materials science, biotechnology, and process engineering are expected to significantly shorten technology development and commercialisation cycles. Technologies currently emerging may reach industrial maturity much sooner than anticipated, while entirely new processing solutions are likely to emerge over the same period. The strategic priority is therefore not to predict a fixed set of future technologies, but to strengthen India's capability to identify, develop, validate, and commercialise successive generations of low-impact textile processing technologies.

Strategic investment should focus on four innovation priorities.

Near-Waterless Processing Systems - Develop next-generation processing platforms that substantially reduce or eliminate conventional water-intensive dyeing and finishing while maintaining commercial productivity, product quality, and process reliability.

Next-Generation Sustainable Chemistry - Strengthen indigenous capability in advanced dyes, enzymes, bio-based auxiliaries, fluorine-free functional finishes, and low-impact processing chemistries that reduce environmental impact while meeting evolving global regulatory requirements.

Intelligent Wet Processing - Integrate artificial intelligence, advanced sensing, digital twins, autonomous process optimisation, and predictive process control into wet-processing operations to continuously improve resource efficiency, product quality, and manufacturing performance.

Circular Water and Chemical Systems - Advance technologies that maximise water reuse, recover chemicals and thermal energy, minimise waste generation, and enable highly circular processing systems with significantly lower environmental footprints.

These priorities should be supported through long-term investment in research infrastructure, pilot facilities, demonstration projects, and stronger collaboration between industry, academia, Textile Research Associations, and technology providers. Rather than preparing for one specific technology, India should build the capability to identify, validate, and commercialise successive generations of low-impact processing technologies.

Current developments such as **supercritical CO₂ dyeing, foam dyeing, digital dye application, nanobubble processing, electrochemical dye reduction, plasma treatment, and ultrasound-assisted processing** illustrate the direction of travel. These examples are indicative rather than exhaustive and should be viewed as emerging innovation pathways rather than prescribed technology choices.

- **Supercritical CO₂ Dyeing** uses CO₂ at its critical point as the dyeing medium, eliminating water consumption and recycling CO₂ in a closed loop.¹⁹ Earlier commercial systems were primarily limited to polyester applications, but newer platforms support multiple natural and synthetic fibres including cotton, viscose, wool, nylon, acrylic, linen, and blends using conventional dyes.⁵⁵ India's first commercial-scale installation was commissioned at Arvind Limited in Ahmedabad in

partnership with H&M Group and Deven Supercriticals in 2025.⁵⁶ Capital cost remains significantly higher than conventional dyeing systems, limiting near-term scalability despite substantial reductions in water use, chemical consumption, effluent generation, and thermal demand.

- **Foam Dyeing and Waterless Application** represents a fundamental process shift away from conventional bath-based wet processing toward near-waterless chemical application. Unlike incremental low-liquor-ratio improvements, foam systems minimize water use at the point of application itself while also reducing drying energy demand, chemical consumption, and effluent generation. The technology is commercially demonstrated for continuous finishing applications but remains at limited industrial adoption scale globally, with TRL estimated around 7.⁵⁷
- **Endeavour Digital Dyeing Alchemie** represents one of the most significant documented multi-parameter process shifts in the Compendium, with reported reductions of up to 95% in water use, 85% in energy consumption, 35% in chemical use, and 50% in operating cost versus conventional dyeing.^{14,58,59} As of 2026, the technology remains at demonstration stage.
- **Nano-Bubble Dyeing** is laboratory and pilot-scale systems that has demonstrated liquor ratios approaching 1:1 through enhanced dye diffusion and wetting efficiency^{19,60}. Commercial deployment remains limited, although platforms such as Jeanologia H2Zero are entering early commercial application within denim processing.⁶¹
- **Plasma Treatment Systems, Ultrasound-Assisted Dyeing, Microwave Processing, Nano-Dye and Cationic Cotton Systems**, and sol-gel PFAS-free DWR systems represent emerging process-substitution pathways that move beyond incremental wet-processing optimization toward fundamentally lower-water, lower-chemical, and lower-emission textile processing architectures. These technologies target elimination of salt dosing, reduction or replacement of conventional wet chemistry, near-waterless chemical application, fluorine-free finishing, and lower thermal-energy intensity. However, most remain at pilot-scale, niche commercial, or early-industrial deployment globally, wit technical barriers related to durability, process uniformity, scale integration, or production economics still limiting mainstream adoption.

⁵⁵Deven Supercriticals Pvt. Ltd. SUPRAUNO® Waterless Dyeing Technology. Deven Supercriticals, 2025

⁵⁶Arvind Limited, H&M Group and Deven Supercriticals. Launch of India's First Commercial Supercritical CO₂ Dyeing Installation. Textile Industry Reports, 2025

⁵⁷Gaston Systems. Foam Finishing and Waterless Textile Chemical Application Technologies. Gaston Systems, 2025

⁵⁸Alchemie Technology. Endeavour™ Low Carbon Digital Textile Dyeing Production. Alchemie Technology Ltd., 2025

⁵⁹IEEE Spectrum. U.K. Startup's Digital Dyeing Printers Save Energy and Water. IEEE, 2023

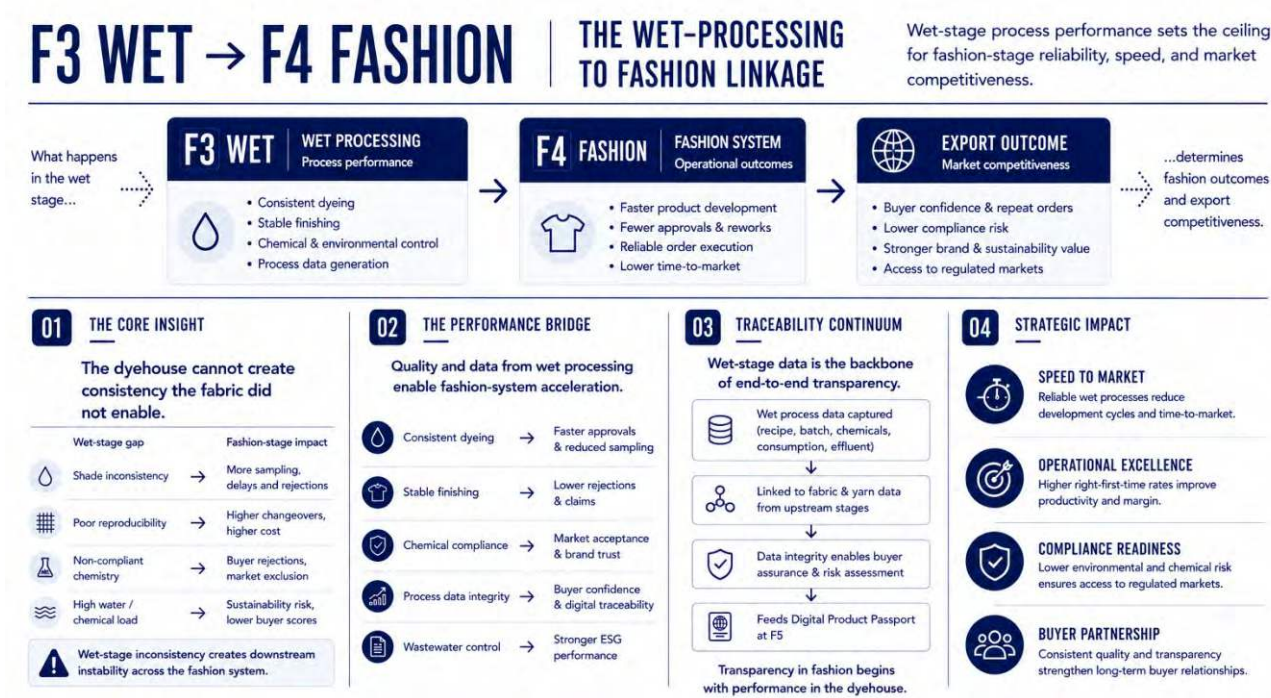
⁶⁰Rezaei, J., et al. Nanobubbles in Textile Wet Processing: Applications and Resource Reduction Potential. Cellulose, Springer Nature, 2020

⁶¹Jeanologia. H2Zero Water-Saving Dyeing Technology for Denim Processing. Jeanologia S.L., 2025

3.6.5. STAGE LINKAGE

Wet-processing compliance and process-data integrity form the foundation for Fashion-stage export readiness. Garment manufacturing depends on receiving fabric with compliant chemistry, documented processing records, and consistent dimensional quality to support buyer requirements, traceability, and Digital Product Passport issuance.

Failures in wet processing cannot be corrected downstream through garment-stage technology investments. F4 competitiveness therefore depends directly on compliance and process consistency established at F3 Wet.



3.7. Fashion (F4): Garmenting and Apparel Manufacturing

Fashion is India's highest-employment textile stage and one of its most under-leveraged technology opportunities. The gap assessment identifies garmenting as delivering some of the highest returns per rupee of technology investment across the value chain. The core constraints are structural and solvable: 8–12 week lead times versus Turkey's 4–6 weeks,^{12,15} 10–15% cutting waste from manual marker making, physical sampling cycles adding 3–4 weeks per iteration, and largely manual sewing operations with minimal production-data visibility.¹²

Unlike upstream textile stages, most T1 interventions in garmenting involve software integration, process redesign, automation upgrades, and digital production systems rather than heavy industrial infrastructure. Capital intensity is therefore comparatively low, while productivity, speed, traceability, and export competitiveness gains are disproportionately high.d at F3 Wet.

Technology can unlock step-change gains in speed, quality, cost and compliance – with the highest return on investment across the entire value chain.



F4-10	RFID Tagging, Warehouse Management and EDI Buyer Integration	Supply Chain Traceability	Digital Infrastructure & Traceability	Align (2026–2030)
F4-11	Automated Pattern Matching for Plaid and Check Fabric Cutting	Manufacturing Automation	Manufacturing Capability at Scale	Align (2026–2030)

3.7.2. ALIGN (2026–2030)

The **Align** horizon focuses on reducing lead times, improving material utilisation, and establishing digital production visibility across garment manufacturing. Unlike upstream manufacturing stages, most interventions combine software, automation, and production management systems rather than heavy industrial infrastructure. Together, these technologies improve productivity while creating the operational data required for traceability, Digital Product Passports, and export competitiveness.

CAD/CAM And Automated Cutting represents the largest cost component in garment manufacturing, while manual marker making continues to generate approximately 10–15% cutting waste.¹⁰ CAD-based optimization and automated cutting are already standard across organized export-oriented garment systems globally. India's gap lies primarily in MSME adoption reach rather than technology availability.

3D Virtual Prototyping is prioritized as physical sampling remains one of the largest hidden drivers of India's lead-time disadvantage. Each sampling round involving design iteration, cutting, stitching, photography, international shipment, buyer review, and revision typically adds 3–4 weeks to product development timelines. Eliminating two to three physical sample cycles through digital prototyping can remove 6–10 weeks from development lead time. Competing sourcing destinations such as Turkey increasingly differentiate themselves through faster sampling responsiveness rather than sewing speed alone.^{10,63}

IoT Production Monitoring and MES Systems simultaneously improve operational efficiency and establish the machine-level production records required for future DPP compliance. Real-time monitoring enables same-shift line balancing and bottleneck correction, while MES infrastructure captures machine ID, operator data, timestamps, and production records required for traceability-linked export systems from 2027 onward.

Unit Production Systems reduces idle movement and work-in-progress accumulation through continuous flow production models, with global implementations documenting 15-25% productivity improvements.⁶⁴

Automated CNC Sewing Units - Since repetitive sewing operations can achieve substantially higher productivity and consistency under automation compared to manual execution.³⁰ These systems are already standard across many organized garment-export facilities in competing manufacturing economies, while adoption within India's MSME garment base remains comparatively limited.

⁶²Textile World. Game-Changing Benefits of 3D Digital Sampling. Textile World, March 2024

⁶³FashionatingWorld. Turkey Report 2024. FashionatingWorld, 2024

⁶⁴Sarkar J. et al. Advanced Technology in Apparel Manufacturing. Springer, 2023

3.7.3. AMPLIFY (2030–2035)

The **Amplify** horizon expands garment manufacturing capability through flexible production systems, energy-efficient operations, advanced quality assurance, and higher-value apparel manufacturing. These technologies are commercially proven. The primary challenge is scaling adoption across the broader industry while integrating digital manufacturing, advanced inspection, and new production models into everyday operations.

Automatic Fabric Spreading Systems - Manual spreading can introduce ply tension variations, which may subsequently result in cut-part dimensional inconsistencies and downstream sewing defects. Automated spreading is already standard across organized export-oriented garment manufacturing globally.

DTG Printing Systems - The growth of India's D2C, customized, and small-batch fashion ecosystem has increased demand for single-piece on-demand printing without the screen preparation and minimum-order constraints of conventional printing systems. The technology enables zero-minimum-order production, faster design iteration, and commercially viable short-run apparel manufacturing.

Servo Sewing Machine Conversion delivers approximately 60–70% energy savings versus conventional clutch-motor systems at comparatively low capital cost with payback periods typically below two years.⁶⁵ Despite short payback periods, adoption is often overlooked because the intervention improves energy efficiency rather than directly increasing production throughput.

Ultrasonic Welding and Sew-Free Bonding Systems are waterproof and sealed seam construction is a functional requirement in performance wear, protective garments, and medical textile applications rather than simply a product-quality enhancement. Ultrasonic welding eliminates needle perforation and improves seam sealing performance for technical tecreate xtile applications where conventional stitched seamStrategic investment during this horizon should focus on four innovation priorities.

3.7.4. ACCELERATE (2035–2047)

The **Accelerate** horizon focuses on building India's long-term capability in intelligent apparel manufacturing. Beyond 2035, advances in artificial intelligence, robotics, computer vision, and advanced automation are expected to reshape garment production, shortening technology development cycles and expanding the range of operations that can be automated. Rather than predicting a fixed set of future technologies, the priority is to strengthen India's capability to evaluate, develop, validate, and commercialise successive generations of apparel manufacturing technologies.

⁶⁵Partnership for Cleaner Textile. Installation of Energy Efficient Servo Motor-based Sewing Machines: Hamza Clothing Ltd. PaCT, 2023

⁶⁶Eryuruk, S.H., Kalaoglu, F., and Kayaoglu, B. Ultrasonic Welding Technology for Waterproof and Technical Textile Seam Applications. Journal of Industrial Textiles, SAGE Publications, 2021

Strategic investment during this horizon should focus on four innovation priorities

Intelligent Apparel Manufacturing - Develop highly automated production systems that combine robotics, artificial intelligence, adaptive material handling, and autonomous production control to improve productivity, flexibility, and manufacturing resilience.

Advanced Digital Manufacturing - Expand the integration of digital twins, machine vision, real-time production analytics, and predictive quality management to create connected garment manufacturing systems capable of continuously optimising production performance.

Next-Generation Garment Construction - Strengthen capabilities in innovative garment assembly methods, seamless construction, advanced bonding technologies, and functional apparel manufacturing that reduce material waste while enabling higher-value products.

Apparel Manufacturing Innovation Ecosystem - Build research infrastructure, pilot facilities, demonstration centres, and industry-academia partnerships that accelerate the development, testing, and commercialisation of emerging garment manufacturing technologies.

These priorities should be supported through sustained investment in research infrastructure, pilot production facilities, demonstration projects, and stronger collaboration between industry, academia, technology providers, and start-ups. Rather than preparing for one specific technology, India should build the institutional capability to identify, evaluate, and commercialise successive generations of apparel manufacturing technologies as they emerge.

Current developments such as robotic sewing, **AI-guided garment assembly, adaptive fabric handling, autonomous quality inspection, and intelligent production systems** illustrate the direction of technological progress. These examples are indicative rather than exhaustive and should be viewed as emerging innovation pathways rather than prescribed technology choices.

- **Robotic Sewing** remains at approximately TRL 5–6 globally despite more than a decade of development effort[L8].^{10,30} SoftWear Automation's SEWBOT® platform has demonstrated automated T-shirt assembly using machine vision, robotic handling, and real-time fabric tracking systems under controlled production conditions.⁶⁷

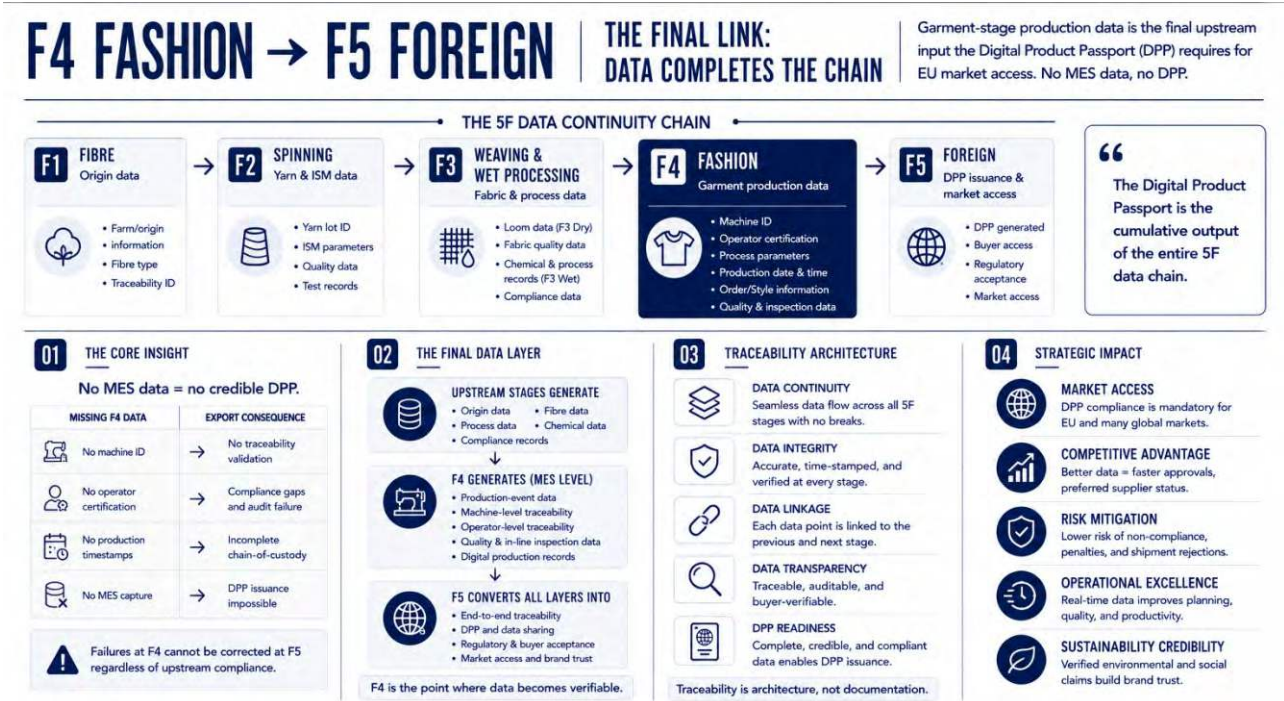
At India's current labour-cost position, the economic case for large-scale robotic sewing deployment remains weak before 2035.³⁰ Future investment decisions should be triggered by ones of two developments: a significant increase in commercial technology readiness demonstrated through credible scaled deployment, or a material shift in India's relative labour-cost competitiveness.

⁶⁷SoftWear Automation. SEWBOT® Automated Apparel Manufacturing Platform. SoftWear Automation Inc., 2025

3.7.5. STAGE LINKAGE

Garment-stage production data forms the final upstream layer required for Digital Product Passport compliance. Machine ID, operator records, production timestamps, and process parameters are generated at F4 and complete the traceability chain established across earlier stages.

Without MES-level data capture at the garment stage, DPP issuance cannot be credibly completed regardless of compliance achieved upstream across F1 to F3. The effectiveness of the 5F traceability system is therefore determined by the weakest data link in the chain.



3.8. FOREIGN (F5): TRACEABILITY, COMPLIANCE AND EXPORT READINESS

The Foreign stage no longer represents the endpoint of the textile value chain. It is the stage where production, sustainability, and traceability information generated across **5F** is verified and translated into market access.

As this report highlights, export readiness depend on operational data generated continuously throughout the value chain. The technologies presented in this chapter therefore do not create these datasets; they verify, integrate, and communicate them in forms recognised by regulators, buyers, and international markets.

The Foreign stage determines whether value created across F1 to F4 can be realised in global export markets.

From 2026, EU market access depends on three converging requirements: carbon emissions transparency under **CBAM**, **ZDHC MRSL**-compliant chemical management, and **Digital Product Passport** capability under the Ecodesign for Sustainable Products Regulation with enforcement from approximately 2027.

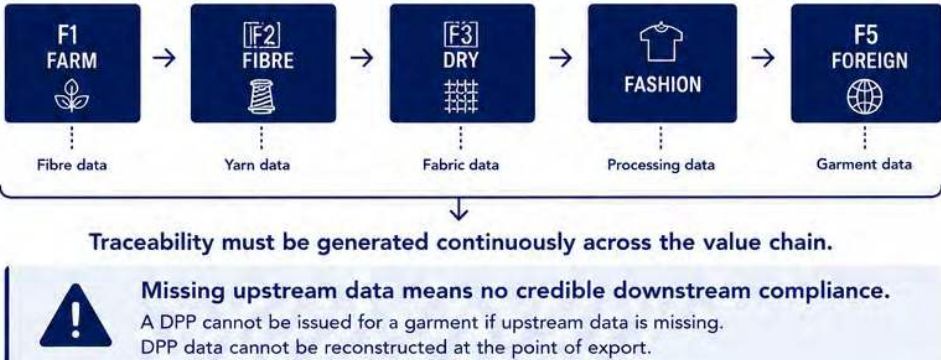
01
THE NEW
EXPORT
GATEWAY

From 2026 onward, export access increasingly depends on compliance infrastructure.



02
THE CORE
INSIGHT

DPP is not created at export.



03
THE READINESS
GAP

India's current readiness is near zero in the MSME sector.

CAPABILITY	CURRENT STATE IN INDIA (MSME)	OBSERVATION
DPP Awareness	Near zero	Awareness and understanding are minimal in MSME clusters.
ZDHC Adoption	Limited to large exporters	Most MSMEs outside ZDHC value chain.
Carbon Footprint Measurement	~10–20 mills nationally ¹	Very limited measurement coverage.

India's MSME export base is approaching a compliance cliff.

04
THE STRATEGIC
VERDICT



1. Based on industry estimates and stakeholder interviews. Source: FOR-5 card.

3.8.1. F5 TECHNOLOGY PRIORITY STACK

The Foreign stage no longer functions only as the export endpoint of the value chain. It has become the verification and compliance layer through which upstream production, sustainability, and traceability data are translated into market access.

The technologies in Table 10 focuses on three priorities:

- **Align (2026–2030):** Establish the digital and compliance infrastructure required for trusted market access.
- **Amplify (2030–2035):** Scale advanced traceability, product verification, and lifecycle reporting systems.
- **Accelerate (2035–2047):** Build long-term capability in intelligent trade infrastructure and next-generation digital verification systems.

Together, these priorities strengthen India's transition towards a transparent, data-driven, and globally trusted textile export ecosystem.

Table 10 - Technology Priority Stack for Foreign Compliance

Card No	Technology Name	Technology Focus	Transformation Direction	Roadmap Horizon
F5-01	Digital Product Passport (DPP) Platform	Product Compliance	Digital Infrastructure & Traceability	Align (2026–2030)
F5-02	ZDHC-Compliant Chemical Management Systems	Product Compliance	Resource-Intelligent Manufacturing	Align (2026–2030)
F5-03	Spectrophotometric Quality Control & Accredited Laboratory Testing	Product Compliance	Manufacturing Capability at Scale	Align (2026–2030)
F5-04	Life Cycle Assessment (LCA) Platforms	Product Compliance	Digital Infrastructure & Traceability	Amplify (2030–2035)
F5-05	Science-Based Target (SBT) Management Platforms	Product Compliance	Resource-Intelligent Manufacturing	Amplify (2030–2035)
F5-06	Future Digital Compliance Ecosystems	Product Compliance	Digital Infrastructure & Traceability	Accelerate (2035–2047)
F5-07	Blockchain-Based Supply Chain Traceability	Supply Chain Traceability	Digital Infrastructure & Traceability	Align (2026–2030)
F5-08	Product Carbon Footprint (PCF) Platforms	Supply Chain Traceability	Digital Infrastructure & Traceability	Align (2026–2030)
F5-09	Fibre-Level Physical Traceability Technologies	Supply Chain Traceability	Digital Infrastructure & Traceability	Amplify (2030–2035)

3.8. 2. ALIGN (2026–2030)

The Align horizon establishes the digital infrastructure required for export competitiveness. These technologies do not operate as standalone systems; they aggregate, verify, and communicate production, sustainability, and traceability data generated across the upstream value chain. Their effectiveness therefore depends on the quality and completeness of operational data generated from Farm through Fashion.

Digital Product Passport Platform (FOR-2) is prioritised because Digital Product Passports are expected to become a central requirement under the EU Ecodesign for Sustainable Products Regulation. Establishing the digital architecture and integrating upstream production data requires significant preparation, making early adoption essential for export readiness.¹¹

ZDHC Gateway Chemical Compliance (FOR-3) strengthens continuous chemical management by moving beyond periodic certification towards operational compliance systems increasingly expected by global brands.^{68,69}

Blockchain Supply Chain Traceability (FOR-6) provides secure chain-of-custody records that strengthen transparency and support emerging due-diligence requirements across international supply chains.⁷⁰

Product Carbon Footprint and Emissions-Accounting Platforms (FOR-5) enable product-level emissions accounting that supports buyer reporting, sustainability disclosures, and future carbon-related trade requirements.

Spectrophotometric QC and NABL Lab Certification (FOR-4) establish internationally recognised verification systems that support restricted-substance compliance and strengthen buyer confidence.

⁶⁸H&M Group. Chemicals and ZDHC Wastewater Management in the Supply Chain. H&M Group Sustainability Disclosure, 2025
⁶⁹Inditex. Innovation, Collaboration and Continuous Improvement for Chemical Safety. Inditex Sustainability Documentation, 2025
⁷⁰TextileGenesis. Fibre-to-Retail Blockchain Traceability Platform for Fashion Supply Chains. TextileGenesis, 2025

3.8.3. Amplify (2030–2035)

The **Amplify** horizon strengthens verification, transparency, and environmental reporting beyond baseline compliance. The technologies in this horizon are commercially available, with the principal challenge being wider industry adoption, interoperability, and integration into routine business operations.

Fibre-Level Physical Traceability (FOR-1) strengthens documentary traceability by enabling independent verification of fibre origin through isotope analysis, DNA markers, and spectroscopic techniques, supporting premium provenance claims and buyer confidence.^{71,72,73} As Digital Product Passport enforcement and due-diligence verification requirements strengthen, physical traceability is expected to become increasingly important for validating premium fibre-origin and sustainability claims.⁷⁴

AI Vision Fabric Inspection extends quality assurance beyond the practical limitations of manual inspection by enabling continuous, high-speed defect detection and classification using artificial intelligence.⁷⁵

LCA Tools and SBTi Target-Setting Platforms convert operational environmental data into product-level lifecycle assessments and science-based emissions reporting, strengthening sustainability disclosures, buyer reporting, and Strategic investment during this horizon should focus on four innovation priorities.

3.8.4. ACCELERATE (2035–2047)

The **Accelerate** horizon shifts from deploying today's compliance technologies to building India's capability to lead the next generation of trusted digital trade systems. Beyond 2035, advances in artificial intelligence, distributed data systems, environmental intelligence, and digital identity are expected to fundamentally reshape how product authenticity, sustainability, and compliance are verified across global value chains. Rather than prescribing a fixed set of future technologies, the priority is to strengthen India's capability to develop, validate, and commercialise successive generations of digital trade and traceability technologies.

Strategic investment during this horizon should focus on four innovation priorities.

Intelligent Traceability Systems -Develop integrated digital ecosystems capable of continuously capturing, verifying, and sharing trusted product and supply-chain information throughout the textile value chain.

⁷¹Oritain. Scientific Isotope Testing for Fibre Origin Verification and Supply Chain Traceability. Oritain Global Ltd., 2025
⁷²Haelixa. DNA Marker-Based Textile and Fibre Traceability Solutions. Haelixa AG, 2025
⁷³FibreTrace. Luminescent Pigment and Spectroscopic Fibre Traceability Technology. FibreTrace B.V., 2025
⁷⁴Textile Exchange. Traceability Technologies and Physical Verification Systems in Textile Supply Chains. Textile Exchange, 2024
⁷⁵Smartex. AI-Enabled Real-Time Quality Control. Apparel Impact Institute, 2024

Environmental Intelligence - Strengthen capabilities in lifecycle assessment, digital carbon accounting, product-level environmental analytics, and automated sustainability reporting to support evolving international disclosure requirements.

Advanced Product Authentication - Develop next-generation physical and digital authentication technologies that strengthen provenance verification, sustainability claims, and buyer confidence.

Trusted Digital Trade Infrastructure - Build interoperable digital platforms that connect Digital Product Passports, customs documentation, certification systems, sustainability reporting, and international compliance requirements into secure digital trade ecosystems.

These priorities should be supported through sustained investment in digital infrastructure, standards development, pilot programmes, industry collaboration, and international interoperability initiatives. Rather than preparing for one specific technology, India should build the institutional capability to continuously identify, evaluate, and commercialise emerging digital trade technologies as they evolve.

Current developments such as AI-enabled supply chain analytics, digital twins, environmental intelligence platforms, advanced fibre authentication, distributed traceability systems, and intelligent compliance platforms illustrate the direction of technological progress. These examples are indicative rather than exhaustive and should be viewed as emerging innovation pathways rather than prescribed technology choices.

- **IoT Sensors and Digital Twin for Supply Chain** extend traceability beyond static shipment records by integrating production-condition and operational-performance data into DPP-linked information systems.⁷⁶
- **LCA Tools and SBTi Target-Setting Platform** convert facility-level environmental datasets such as Higg FEM into product-level lifecycle assessments required for ESG disclosure, BRSR Core reporting, and science-based target validation. Brands are cascading these requirements as well to Tier 1 and 2 suppliers

3.8.5. THE DATA THREAD: HOW TECHNOLOGY INVESTMENTS CONNECT TO EXPORT ACCESS

Every T1 technology recommendation in this chapter has been selected on two criteria: it closes a competitiveness gap, and it generates data. The two criteria are not separate considerations. The EU Digital Product Passport, CBAM compliance, and ZDHC Gateway requirements all depend on verified data generated continuously across the value chain from Farm to Fashion. This section makes that dependency visible.

⁷⁶Deloitte. Digital Twin Applications in Supply Chain Traceability and Manufacturing Systems. Deloitte Insights, 2024

FROM FACTORY DATA TO EXPORT READINESS

HOW TRACEABILITY AND COMPLIANCE DATA IS GENERATED ACROSS THE 5F VALUE CHAIN

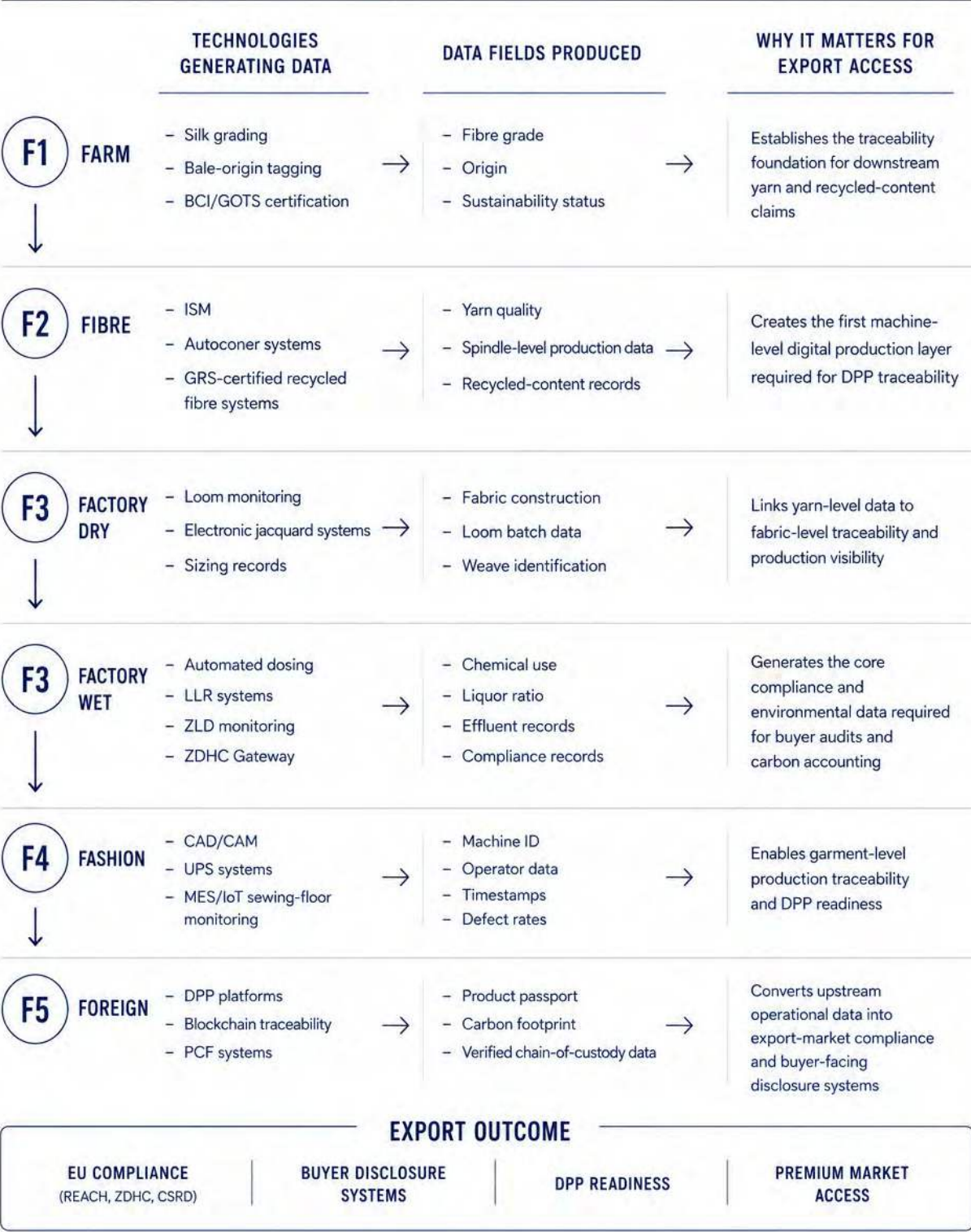


Figure 3 - The 5F Data Thread - from T1 technology investment to DPP issuance

Key implication

A mill that invests only in a DPP platform (FOR-2) without building upstream data infrastructure will have no credible operational data to populate it. In contrast, mills implementing ISM at F2 (SP-1 plus EMG-1), loom monitoring at F3 Dry (EMG-1), automated dosing records at F3 Wet (WET-16), and MES integration at F4 (EMG-1) generate DPP-ready production data automatically through routine operations. In that model, DPP compliance becomes a low incremental reporting layer rather than a separate compliance system. This makes the data-thread architecture the most important investment-sequencing framework in the chapter for management level decision-making.

04

IMPLEMENTATION
FRAMEWORK

The Technology Compendium identifies priority technologies across India's textile value chain. This chapter translates those technology pathways into implementation logic by explaining what different parts of the sector should do, when interventions are required, what enabling conditions must be established, and what risks emerge if transformation is delayed.

The chapter is designed for both government and industry stakeholders. It connects strategic technology priorities with practical modernization pathways across the 5F framework.

The six sections together form an integrated implementation framework. The transformation imperative establishes the urgency for action. The technology pathway defines sequencing across short-, medium-, and long-term horizons. The transition logic explains how these phases connect to one another. The value-chain action plans translate the pathway into stage-specific guidance across the textile ecosystem. The brownfield upgradation framework supports existing units in identifying appropriate modernization pathways. Finally, the enabling conditions register outlines the institutional, policy, financing, infrastructure, and market mechanisms required to support sector-wide transformation.

4.1. THE TRANSFORMATION IMPERATIVE

India's textile sector is at a strategic inflection point. While it remains one of the world's largest textile ecosystems in terms of scale, employment, and value-chain integration, the sector is not yet fully aligned with the emerging drivers of global competitiveness, including automation, sustainability, digitalization, traceability, and speed-to-market.

The challenge is not one of ambition or manufacturing presence. It is the pace of technology adoption, the level of ecosystem integration, and the speed at which the sector can transition toward globally competitive production systems.

Competing textile economies are rapidly modernizing through integrated investments in advanced manufacturing, sustainability infrastructure, digital production systems, and export-compliance capabilities. As global supply chains increasingly prioritize traceability, resource efficiency, responsiveness, and value addition, delayed modernization risks not only limiting future growth, but also weakening existing export competitiveness.

Table 11 - 5F Cost vs Opportunity

5F Stage	Cost of not acting	Opportunity if India acts
F1 Farm	Contamination at the ginning stage propagates through the value chain, setting an irreversible quality ceiling at source	Contamination detection and control at gin eliminates the most expensive downstream quality failure
F2 Fibre	Majority of spinning capacity operates below energy efficiency frontier; high dependence on imported advanced machinery (autoconer, draw-texturing) limits value addition	Shuttleless transition combined with production monitoring enables consistent fabric quality and unlocks downstream value
F3 Dry	Large share of shuttle-based looms results in inconsistent fabric quality and limits downstream processing efficiency	Shuttleless transition + digital monitoring unlocks full value of every downstream investment

F3 Wet	High water intensity (80–150 L/kg) drives energy, chemical, and effluent treatment costs, creating the largest compliance burden in the value chain	Low liquor ratio (LLR) and process optimisation reduce water, energy, chemicals, and ZLD costs simultaneously, delivering multi-parameter gains
F4 Fashion	Long lead times (8–12 weeks) and limited integration with compliance systems restrict access to high-value, fast-cycle markets	Reduced lead times and compliance integration enable participation in premium sourcing shifts driven by traceability and transparency requirements
F5 Foreign	Increasing exposure to carbon pricing and traceability-linked compliance requirements with limited current readiness	Early investment in compliance infrastructure positions India as a preferred sourcing destination for sustainability-driven global buyers

"The current approach remains largely reactive, addressing challenges as they arise rather than anticipating future needs. Moving forward, the sector requires long-term, forward-looking strategic planning."- **Gokaldas Images Pvt Ltd**

"Textile processing represents the weakest link in terms of standardisation of processes, resource consumption, and technologies throughout the entire value chain."- **IIT Delhi**

4.2 UPGRADATION PATHWAY

India's existing textile base is not a constraint to be bypassed; it is the **foundation of transformation**. The sector's scale is embedded in its current clusters with power looms in Bhiwandi and Surat, spinning hubs in Coimbatore and Ludhiana, recycling in Panipat, knitting in Ludhiana, and garment manufacturing across Bengaluru, National Capital Region, and Tirupur.

These are not legacy systems to be replaced; they are **the platforms on which upgrading must occur**. The transformation pathway therefore centres on **modernising existing capacity at scale**, rather than relying primarily on new capacity creation.

Greenfield developments such as PM MITRA Parks Scheme will play an important role in adding integrated, next-generation capacity. However, the **primary lever of transformation remains brownfield modernisation** is upgrading technology, processes, and systems within the existing industrial base.

Three upgrade pathways - self-identification for existing mills

Every brownfield unit can be mapped to one of three pathways based on its current **technology and compliance position**. The selected pathway determines **priorities, sequencing, and financing instruments**, independent of scale, fibre type, or location. The below presented table is illustration for the industry step wise upgrade pathways.

COMPLY Mills below the regulatory baseline	COMPETE Mills at compliance baseline, seeking efficiency gains	TRANSFORM Mills ready to differentiate and lead
You are here if:  • LLR above 1:80 in dyeing • No ZLD or ETP compliance • Clutch motors still in use • No energy audit conducted • Chemical management undocumented 	You are here if:  • ZLD/ETP compliant • LLR between 1:30 and 1:80 • Servo machines partially deployed • Basic MES or ERP in place • Buyer quality audit passed 	You are here if:  • LLR below 1:30 in dyeing • Traceability system operational • SBTi or equivalent commitment made • Buyer sustainability tier qualification • R&D or pilot investment underway 
Your priority:  Energy: VFDs, IE3 motors, LED. Water: LLR machines, basic ETP. Compliance: servo motors, ZDHC chemical audit. All fundable under TUFs/BEE/SIDBI with simplified DPR.	Your priority:  RFT dyeing, auto dispensing, CAD/CAM, digital printing, compact spinning or autoconer upgrade, IoT monitoring. Blended finance and sustainability-linked loans. Buyer programme eligibility.	Your priority:  Waterless dyeing, DPP, blockchain traceability, warp knitting, seamless 3D, scCO₂ pilot participation, chemical recycling PPP. Green bonds and DFI co-investment.

Upgrade sequencing - what to do first

Regardless of pathway, sequencing matters. Investing in traceability before achieving ZLD compliance creates data that cannot be verified. Similarly, investing in spray dyeing before establishing the LLR baseline risks misallocating capital to a system that the mill is not yet equipped to operate effectively. The sequencing logic is:

#	STEP	ACTION AND RATIONALE
1	 AUDIT FIRST	Conduct energy audit (BEE), water audit, and chemical audit (ZDHC gateway). This establishes the baseline data without which no financing application is bankable, and no technology investment can be correctly sized.
2	 ENERGY BASELINE	VFDs, IE3/IE4 motors, LED, PM compressors. These pay for themselves in 2–3 years, free up cash flow for the next step, and satisfy BEE compliance requirements simultaneously.
3	 WATER COMPLIANCE	LLR machines, ETP/ZLD, enzymatic pre-treatment. In regulated states this is non-negotiable. In others it is the buyer compliance requirement arriving by 2028.
4	 PROCESS QUALITY	RFT dyeing, auto dispensing, CAD/CAM, in-line inspection. These reduce rework, improve first-pass yield, and directly improve margin per unit — the financial case for the next investment.
5	 DIGITAL LAYER	MES, IoT monitoring, RFID, traceability. Build on the quality process foundation. Data captured from Step 4 is the input that makes Step 5 meaningful.
6	 DIFFERENTIATION	Waterless processing, DPP, blockchain, warp knitting, seamless, chemical recycling. This step requires the operational discipline built in Steps 1–5 to be commercially viable.

4.3 ENABLING CONDITIONS

Technology adoption depends on more than the availability of equipment. Financing, policy, workforce capability, and market demand determine whether commercially proven technologies are deployed, whether emerging technologies scale, and whether future innovations are developed within India. The India Textile Technology and Innovation Roadmap 2047 sets out the full ecosystem of enabling conditions required for sector-wide transformation. This chapter complements, rather than repeats, that analysis. Its purpose is to connect the technologies presented in this Compendium with the enabling conditions that support their deployment, indicating which instruments, institutions, and stakeholders are most critical for each technology horizon.

4.3.1. EC 1 - FINANCING AND INVESTMENT

Technology adoption across the textile value chain is constrained less by technology availability than by access to finance aligned with different investment profiles. Proven resource-efficiency technologies often require affordable capital for widespread adoption, while emerging technologies demand longer investment horizons and greater risk-sharing.

The financing architecture therefore evolves across the three technology horizons.

Horizon	Financing Priority	Typical Technologies
Align (2026–2030)	Commercial lending, credit guarantees, interest support, MSME finance	Energy efficiency, process modernisation, digital systems, compliance technologies
Amplify (2030–2035)	Blended finance, cluster financing, sustainability-linked finance	Circular systems, advanced manufacturing, traceability infrastructure
Accelerate (2035–2047)	Innovation funding, venture capital, demonstration funding, R&D support	Emerging technologies, pilot facilities, indigenous technology development

Technology deployment therefore depends not only on equipment financing but also on improved project preparation, bankable DPRs, and financing models aligned with techPolicy provides the long-term

4.3.2. EC 2 - Regulatory and policy signals

Policy Instrument	Primary Technology Outcome
Progressive Resource-Efficiency Benchmarks	Low-water, low-energy manufacturing technologies
Renewable Energy Policies	Electrification and renewable integration
Energy Efficiency Programmes	Process optimisation and energy-saving technologies
Circular Economy and EPR Frameworks	Recycling and resource recovery technologies
Digital Product Passport Implementation	Traceability and digital manufacturing systems
Fibre Standards and Labelling	Sustainable and alternative fibre technologies
Chemical Management Regulations	Safer chemistry and cleaner processing technologies

4.3.3. EC 3 - SKILLS AND INSTITUTIONAL CAPACITY

Technology investments create value only when supported by workforce capability. Across every stage of the textile value chain, digital systems, advanced machinery, and sustainability technologies depend on operators, supervisors, engineers, and managers who can interpret operational data and translate it into better decisions.

It identifies workforce capability as one of the most important enabling conditions for technology transformation. The Compendium translates that requirement into the capability needs associated with each technology horizon.

Align (2026–2030): Foundation Capabilities

Capability Area	Primary Outcome
Industry 4.0 and Digital Manufacturing	Higher utilisation of digital production systems
Chemical Management	Safer chemical handling and compliance
Basic MES and Digital Literacy	Improved use of operational data
Technology Financing and DPR Preparation	Improved access to technology finance

Amplify (2030–2035): Advanced Capabilities

Capability Area	Primary Outcome
Digital Product Passport management	Export readiness and traceability
Advanced processing technologies	Operation of next-generation manufacturing systems
Recycling and circular manufacturing	Circular textile operations
Cluster-based technical support	Improved MSME technology adoption
Industry–academia collaboration	Faster commercialisation of innovation

eRather than treating digital capability as a standalone training topic, future programmes should integrate data interpretation, operational decision-making, and continuous improvement throughout technical education, vocational training, and enterprise capability development.

Data literacy is an enabling condition - not a training module

Every enabling condition in this section (financing, regulatory signals, and buyer requirements) will underperform if the workforce cannot **interpret and act on the data generated by deployed technologies**. This is not a short-term training issue. It reflects a broader capability gap that spans education, in-factory practices, management systems, and financing conditions.Addressing this requires **a system-level response**. Curriculum updates across institutions such as ATDC, NIFT, and polytechnics need to incorporate applied data interpretation. Textile Research Associations must extend their role from training to **in-mill coaching**, demonstrating how data informs operational decisions. At the enterprise level, management systems need to shift from volume-based metrics to **data-driven performance indicators**. Financing mechanisms can reinforce this by linking disbursement and performance review to effective use of installed systems.



05

WAY FORWARD TOWARDS
ROADMAP

The technologies presented in this compendium are not a wish list. Each respond to a **specific structural gap**, with a defined causal logic: the gap has an identifiable cause, the technology addresses that cause, and alternative interventions do not deliver the same outcome through equivalent means.

The sequencing across the 5F value chain reflects a **dependency structure**. Farm-stage quality shapes fibre-stage capability; fibre consistency influences factory (dry) performance; fabric quality affects factory (wet) compliance outcomes; and processing data underpins foreign-stage market access. Weakness at any stage propagates downstream. The enabling conditions outlined in Chapter 3.4 are therefore not aspirational. They represent **actionable measures**, mapped to institutions and timelines, required to support this transition. The analysis is complete. Implementation remains.

A small set of decisions in the near term can materially influence the pace of adoption. These actions are independent but mutually reinforcing. Each reduces a specific barrier; taken together, they can significantly accelerate the transition.

Looking toward 2047, the trajectory of India's textile sector will be determined not by the availability of technology, but by the **speed and consistency of adoption**. The technologies are available and, in many cases, already deployed globally. The differentiator will be how quickly existing capacity is upgraded, how effectively enabling conditions are implemented, and how consistently data generated by installed systems is used to improve performance.

06

ANNEXURES

6.1. ANNEXURE I – TECHNOLOGIES AT A GLANCE

The technologies presented in this roadmap are closely aligned with the Government of India's emerging policy direction for transforming the textile sector through modernization, sustainability, and global competitiveness.

In particular, the **Textile Expansion and Employment Mission (TEEM)** is expected to accelerate the adoption of advanced manufacturing, automation, digitalization, and productivity-enhancing technologies across the textile value chain, while the **Tex Eco** initiative provides an enabling framework for resource-efficient production, circularity, cleaner manufacturing, and compliance with evolving global sustainability requirements.

Together, these flagship initiatives complement the technology pathways identified in this compendium by supporting investment, technology deployment, capacity building, and ecosystem development across India's textile industry.

The table below presents an overview of the technologies expected to shape the transformation of India's textile value chain from 2026 to 2047. Technologies are organized by value chain stage and grouped into strategic **technology focus areas**, with each mapped to one of three adoption horizons:

- **Align (2026–2030):** Commercially mature technologies ready for broad industry adoption.
- **Amplify (2030–2035):** Technologies expected to scale across leading enterprises and progressively penetrate the wider industry.
- **Accelerate (2035–2047):** Frontier technologies and next-generation innovations that will redefine manufacturing, circularity, and competitiveness over the long term.

Together, these technologies provide a strategic reference for industry, policymakers, technology providers, investors, and research institutions to guide technology adoption, investment planning, and innovation while supporting the objectives of TEEM, Tex Eco, and India's long-term vision of becoming a globally competitive, sustainable, and technology-driven textile manufacturing hub by 2047.

VALUE CHAIN	TECHNOLOGY FOCUS	ALIGN (2026–2030)	AMPLIFY (2030–2035)	ACCELERATE (2035–2047)
FOUNDATIONAL	Smart Manufacturing	• Industrial Internet of Things (IIoT) Platforms • Manufacturing Execution Systems (MES)	• Artificial Intelligence & Machine Learning for Manufacturing	• Digital Twin Platforms
	Enterprise Systems	• Enterprise Resource Planning (ERP) Systems	–	–
	Asset Management	• Predictive Maintenance Systems	–	–
	Quality Management	• Computer Vision & Automated Quality Inspection	AI-powered Autonomous Quality Management	–
	Energy Management	• Enterprise Energy Management Systems (EMS) • Variable Frequency Drives (VFDs) on Motors • High-Efficiency Motors (IE3/IE4 Class) • Permanent Magnet Screw Air Compressors • LED Lighting Retrofit • Boiler Steam Trap Survey & Condensate Recovery	AI-enabled Energy Optimization Systems	–
	Water Management	• Industrial Water Management & Monitoring Systems	AI-enabled Water Optimization Systems	–
	Digital Infrastructure	• Industrial Cloud Platforms	• Edge Computing Platforms • Industrial Cybersecurity Systems	–
	Industrial Automation	• PLC/SCADA-based Automation Systems	• Industrial Robotics & Collaborative Robots (Cobots)	Autonomous Manufacturing Systems
	Sustainability Management	• Carbon Accounting & ESG Management Platforms	• Digital Product Passport (DPP) & Traceability Platforms	AI-enabled Sustainability Intelligence Platforms
	Clean Energy	• Renewable Energy Integration (Solar, Wind, Rooftop PV)	• Smart Microgrid & Energy Storage Management Systems	–

VALUE CHAIN	TECHNOLOGY FOCUS	ALIGN (2026–2030)	AMPLIFY (2030–2035)	ACCELERATE (2035–2047)
		• Cogeneration & Back-Pressure Steam Turbines • Agro-Waste Briquette Boilers with Automatic Feed Systems	–	–
	Industrial Decarbonization	–	• Waste Heat Recovery & Thermal Energy Optimization	• Green Hydrogen Energy Systems
FARM	Fibre Quality	• NIR/Optical Contamination Detection • Multi-End Automatic Silk Reeling(PV)	–	–
	Digital Traceability	–	• Fibre Identification & IoT Tagging • Digital Fibre Traceability Platform	–
	Future Fibre Materials	–	• Mechanical Decortication	• Mycelium Leather • Bio-based PLA & Emerging Biofibres
FIBRE	Spinning Technologies	• Compact Ring Spinning with Intelligent Monitoring • Open-End Rotor Spinning • Automatic Cone Winding • Draw-Texturing (DTY/POY) • Integrated Blow Room with Contamination Detection • Auto-Doffing Ring Frames, High-Speed (≥1,008 Spindles) • Ring Frame Auto Piecer (India-Made)	• Automated Spinning Preparation • Air-Jet & Vortex Spinning • Draw Frame Auto-Levelling • High-Speed Combing • Two-for-One Twisting	• Advanced Engineered Fibres
	Circular Fibre Systems	• Certified Recycled Polyester Processing • Recycled Cotton Processing • Certified Organic Cotton Processing	• Mechanical Fibre Garneting • Regenerated Cellulosic Fibre Processing (Lyocell & Bamboo) • Chemical Recycling of Polyester • Dope Dyeing & Solution-Dyed Mass Coloration	• Next-Generation Circular Fibre Systems • Advanced Bio-based Fibre Systems

VALUE CHAIN	TECHNOLOGY FOCUS	ALIGN (2026–2030)	AMPLIFY (2030–2035)	ACCELERATE (2035–2047)
FABRIC	Weaving Technologies	• Shuttleless Rapier Looms • Air-Jet Looms • Water-Jet Looms • Real-Time Loom Monitoring	• High-Speed Sizing Systems • Advanced Warping Systems • Electronic Jacquard & Servo Dobby	• Advanced Textile Manufacturing Systems
	Knitting Technologies	–	• Circular Knitting Modernisation • Seamless 3D Flatbed Knitting	–
	Technical Textiles	–	• Warp Knitting • Nonwoven Production Systems	• Smart Functional Textile Systems
	Resource Efficiency	• Low Liquor Dyeing • Automated Dye & Chemical Kitchen • Right-First-Time Dyeing • Continuous Bleaching • Wastewater Heat Recovery • Stenter Heat Recovery	• Digital Waterless Dyeing Systems • Foam Dyeing • Supercritical CO₂ Dyeing Systems	• Nano-Bubble Dyeing • Ultrasound-Assisted Dyeing • Microwave-Assisted Textile Processing
	Advanced Sustainable Chemistry	• Enzymatic Pre-treatment & Bio-scouring • Cellulase Bio-polishing • Nitrogen-Assisted Indigo Dyeing	• Salt-Free Reactive Dyeing • PFAS-Free Durable Water Repellent Finishes • Precision Spray Finishing Systems • Nanotechnology Functional Coatings	• Electrochemical Indigo Reduction • Sol-Gel PFAS-Free Finishing • Plasma Surface Treatment • Plasma Wool Shrink-Resist Treatment
	Circular Resource Recovery	• Zero Liquid Discharge (ZLD) Systems • Reverse Osmosis • Caustic Soda Recovery • Primary Effluent Treatment Plants	• Membrane Bioreactor (MBR) • Advanced Oxidation Processes (AOP) • UASB Biogas Recovery • Sludge Drying Technologies • Closed-Loop Process Water Recycling Systems	• Closed-Loop Water & Chemical Recovery Systems
	Specialty Processing	• Laser & Ozone Denim Finishing	• Digital Inkjet Textile Printing • Radio-Frequency Drying	–

VALUE CHAIN	TECHNOLOGY FOCUS	ALIGN (2026–2030)	AMPLIFY (2030–2035)	ACCELERATE (2035–2047)
GARMENT	Digital Product Development	• CAD/CAM Pattern Making • 3D Virtual Prototyping	• Direct-to-Garment (DTG) Digital Printing	–
	Manufacturing Automation	• Automated CNC Sewing Systems • Automated Pattern Matching for Plaid & Check Fabric Cutting	• Automatic Fabric Spreading • Direct-Drive Servo Sewing Systems	• Robotic Sewing
	Advanced Garment Construction	–	• Ultrasonic Welding & Sew-Free Bonding	• Autonomous Garment Manufacturing
	Supply Chain Traceability	• RFID Tagging, Warehouse Management & EDI Buyer Integration	–	–
FASHION	Product Compliance	• Digital Product Passport (DPP) Platform • ZDHC-Compliant Chemical Management Systems • Spectrophotometric Quality Control & Accredited Lab Testing		
	Supply Chain Traceability	• Blockchain-Based Supply Chain Traceability • Product Carbon Footprint (PCF) Platforms		

6.2 ANNEXURE II – TECHNOLOGY CARDS

The technology cards presented in this annex provide a structured overview of the priority technologies identified through the technology horizon scanning exercise for India's textile value chain, covering the stages from **Farm to Fashion**. Together, the cards provide technical, economic, environmental, and strategic information to support informed decision-making for technology adoption, investment planning, research prioritization, and policy development.

Section	Description
Technology ID & Classification	Provides the technology identifier, value chain stage, technology category, transformation direction, roadmap horizon, Technology Readiness Level (TRL), and current adoption status in India.
Technology Overview & Working Principle	Explains what the technology is, its core operating principle, and how it functions within textile manufacturing.
Primary Applications	Identifies the principal textile processes, products, or manufacturing segments where the technology is typically deployed.
Environmental & Resource Benefits	Summarizes the technology's potential contribution towards reducing energy consumption, water use, chemical inputs, waste generation, emissions, or improving resource efficiency.
Indicative CAPEX (India context)	Provides indicative capital investment ranges for technology deployment. Actual investment requirements vary depending on production scale, equipment specifications, and facility configuration.
OPEX Savings / Payback Period	Summarizes expected operational improvements, productivity gains, quality enhancement, cost savings, and indicative investment payback periods where applicable.
Key Performance Indicators (KPIs)	Lists measurable indicators that can be used to monitor technology performance and operational outcomes after implementation.
Reference Industries	Highlights representative industry applications, textile clusters, or reference installations demonstrating current adoption within India or internationally, where relevant.
Key Adoption Challenges	Identifies common technical, financial, operational, infrastructure, skills, or ecosystem barriers affecting technology deployment.
Technology Developers & Solution Providers	Lists representative technology developers, equipment manufacturers, or solution providers active in the respective technology area.
Key References	Provides selected technical standards, industry publications, research literature, and authoritative references supporting the technology assessment.
Cross-Media Effects	Highlights potential trade-offs across environmental media, including energy, water, chemicals, waste, emissions, or resource consumption that should be considered during implementation.
India Context & Strategic Considerations	Describes the technology's strategic relevance within India's textile sector, including applicability across industry segments, competitiveness, policy priorities, and long-term modernization objectives.



F0-01Enterprise Resource Planning (ERP) Systems		
Transformation DirectionManufacturing Capability at Scale	TRL9	Technology TypeDigital Technology
Technology Focus AreaEnterprise Systems	Roadmap HorizonAlign (2026–2030)	India Adoption (2026)Align (2026–2030)
Technology Overview & Working Principle : Enterprise Resource Planning (ERP) systems provide a centralized platform for managing core business functions, including procurement, inventory, production planning, finance, sales, maintenance, quality, logistics, and human resources. The system consolidates information from multiple departments into a common database, enabling standardized workflows and consistent data management across the organization. Integration with Manufacturing Execution Systems (MES), Warehouse Management Systems (WMS), Supply Chain Management (SCM) platforms, and Industrial Internet of Things (IIoT) systems enables seamless information exchange between business and production operations.		
Primary Applications: Production planning and scheduling; procurement and supplier management; inventory and warehouse management; sales and order management; financial accounting and cost control; quality management; maintenance management; human resource management; demand forecasting; supply chain coordination; enterprise reporting; regulatory and statutory compliance.		
Environmental & Resource Benefits: Optimizes inventory levels, minimizes material overstocking and waste, improves production planning to reduce energy and resource losses, enhances procurement efficiency, and supports digital monitoring of resource consumption, waste generation and sustainability performance across operations.		
Indicative CAPEX (India context) : Basic cloud-based ERP: Rs 2 to 10 lakh per year, SaaS model. [Validated by GA Morgan Dynamics Pvt Ltd via TMMA, May 2026, garment-sector specific]	OPEX Savings / Payback Period: Improves inventory accuracy, production planning, order fulfilment, procurement efficiency, financial control and decision-making while reducing manual processes, data duplication and operational inefficiencies. Enhances customer service and supply chain responsiveness. Typical payback period: 2–5 years, depending on implementation scope and organizational maturity.	
Key Performance Indicators (KPIs): Inventory Turnover Ratio; Inventory Accuracy; Order Fulfilment Rate; On-Time Delivery; Production Schedule Adherence; Procurement Lead Time; Overall Equipment Effectiveness (OEE); Cost of Goods Sold (COGS); Working Capital; Forecast Accuracy; Order Cycle Time; Customer Service Level.	Reference Industries: To be completed later based on verified company reports, technology provider case studies and government or industry publications.	
Key Adoption Challenges: Inventory Turnover Ratio; Inventory Accuracy; Order Fulfilment Rate; On-Time Delivery; Production Schedule Adherence; Procurement Lead Time; Overall Equipment Effectiveness (OEE); Cost of Goods Sold (COGS); Working Capital; Forecast Accuracy; Order Cycle Time; Customer Service Level.		
Technology Developers & Solution Providers: Global: SAP, Oracle, Microsoft, Infor, Epicor, IFS, Sage, QAD, Dassault Systèmes, Aptean. India: Ramco Systems, Tally Solutions, Focus Softnet, Marg ERP, Uneecops Technologies, Godrej Infotech, Intellect Design Arena, Datatex India.	Key References: Ministry of Textiles, Government of India; United Nations Industrial Development Organization (UNIDO); APICS/Association for Supply Chain Management (ASCM); ISO 9001 (Quality Management Systems); ISO 55000 (Asset Management); International Textile Manufacturers Federation (ITMF); World Economic Forum (WEF); Gartner ERP Market Guides. Cross-validated by GA Morgan Dynamics Pvt Ltd for the garment sector, TMMA industry consultation, May 2026.	

Cross Media Effects: No significant cross-media trade-offs identified. ERP systems require additional computing infrastructure and data storage but generally improve material planning, inventory optimization and operational efficiency, resulting in lower resource consumption and waste generation.	
India Context & Strategic ConsiderationsERP systems form the digital backbone for modern textile enterprises by integrating manufacturing, supply chain and business operations. They are particularly valuable for Indian exporters seeking improved traceability, inventory visibility, regulatory compliance and supply chain coordination. Cloud-based ERP solutions are expanding access for MSMEs by reducing upfront capital requirements while supporting digital transformation, export competitiveness and integration with emerging digital compliance frameworks such as Digital Product Passports (DPPs).	

F0-02	Industrial Internet of Things (IIoT) Platforms	
Transformation Direction Digital Infrastructure & Traceability	TRL 9	Technology Type Digital Technology
Technology Focus Area Smart Manufacturing	Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Industrial Internet of Things (IIoT) platforms connect production equipment, utility systems, sensors, and enterprise applications through an integrated digital communication network. Real-time operational data from machines and processes are continuously collected, transmitted, and analysed to provide visibility into equipment performance, process conditions, and resource utilization. The platform integrates with Manufacturing Execution Systems (MES), Enterprise Resource Planning (ERP), Energy Management Systems (EMS), and Quality Management Systems (QMS), creating a unified digital infrastructure for monitoring, automation, and data-driven manufacturing operations.		
Primary Applications: Shop-floor production monitoring and process control; predictive maintenance and asset management; process optimization and quality assurance; energy, water and utility management; production planning and scheduling; inventory and material traceability; integration with ERP, MES, EMS and QMS; Environmental, Social and Governance (ESG) reporting.		
Environmental & Resource Benefits: Reduces energy consumption by 5–15% through process optimization and unplanned equipment downtime by 5–20% through predictive maintenance. Minimizes process losses, rework and utility consumption while enabling continuous monitoring of energy, water, carbon emissions and other sustainability indicators.		
Indicative CAPEX (India context): IoT machine monitoring for a 20-machine garment line: Rs 5 to 15 lakh. [Validated by GA Morgan Dynamics Pvt Ltd via TMMA, May 2026, garment-sector specific]		OPEX Savings / Payback Period: Improves Overall Equipment Effectiveness (OEE), asset utilization, production efficiency, process consistency and product quality while reducing maintenance costs and production disruptions. Typical payback period: 1–3 years.
Key Performance Indicators (KPIs): Overall Equipment Effectiveness (OEE); Machine Availability; Production Throughput; First-Pass Quality (FPQ); Energy Consumption per Unit of Production; Water Consumption per Unit of Production; Unplanned Downtime; Mean Time Between Failures (MTBF); Mean Time to Repair (MTTR).		Reference Industries: Reference plants confirmed by validator for IoT-integrated cutting room: Arvind, Kitex, Rupa, Best Corp Lux, Meenu Creation, Savi Global
Key Adoption Challenges: Overall Equipment Effectiveness (OEE); Machine Availability; Production Throughput; First-Pass Quality (FPQ); Energy Consumption per Unit of Production; Water Consumption per Unit of Production; Unplanned Downtime; Mean Time Between Failures (MTBF); Mean Time to Repair (MTTR).		
Technology Developers & Solution Providers: Siemens, Schneider Electric, ABB, Rockwell Automation, Bosch Rexroth, Altizon Systems, Infinite Uptime		Key References: International Society of Automation, ISA-95 Enterprise-Control System Integration standard; World Economic Forum, Global Lighthouse Network reports on Industry 4.0; Ministry of Textiles, Government of India, PM MITRA scheme documentation. Cross-validated by GA Morgan Dynamics Pvt Ltd for the garment sector, TMMA industry consultation, May 2026.
Cross Media Effects: Minimal cross-media impacts. Marginal increase in electricity demand for digital infrastructure is typically offset by improvements in energy efficiency, resource utilization, and waste reduction.		

India Context & Strategic Considerations: Enables phased digitalization across legacy and modern manufacturing assets, improving operational visibility, resource efficiency, traceability and regulatory compliance. Particularly relevant for MSMEs seeking incremental modernization and integrated manufacturers advancing Industry 4.0. Supports India's Vision 2047 through enhanced productivity, export competitiveness and digital supply chain readiness.
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F0-03		Edge Computing & Industrial Cloud Platforms	
Transformation Direction Digital Infrastructure & Traceability		TRL 8	Technology Type Digital Technology
Technology Focus Area Digital Infrastructure		Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Edge computing processes operational data close to production equipment through local computing devices, while industrial cloud platforms provide centralized storage, advanced analytics, and enterprise-wide data management. Time-critical applications are executed at the edge to minimize communication latency, whereas non-time-sensitive information is synchronized with cloud infrastructure for long-term storage, analysis, and cross-site integration. Together, these technologies provide a scalable digital architecture for industrial data management.			
Primary Applications: Real-time machine control and safety interlocks; low-latency quality inspection processing; local data buffering during network outages; centralized multi-site data aggregation and analytics; remote monitoring and management.			
Environmental & Resource Benefits: Enables reliable operation of real-time efficiency and quality systems that depend on low-latency data processing, indirectly supporting the resource-saving benefits of the systems they underpin.			
Indicative CAPEX (India context): Rs 15 to 40 lakh for edge computing infrastructure per production line; ongoing cloud platform subscription costs typically Rs 5 to 20 lakh per year depending on data volume and services used. [Indicative estimate only; not independently verified against a published market source.]		OPEX Savings / Payback Period: Enables reliable functioning of latency-sensitive applications such as real-time defect detection and machine control, indirectly supporting the payback of those systems. Not typically evaluated as a standalone investment.	
Key Performance Indicators (KPIs): System Latency (milliseconds); Network Uptime (%); Data Processing Throughput; Multi-Site Data Aggregation Completeness.		Reference Industries: Large integrated exporters with multi-site operations and advanced digital infrastructure.	
Key Adoption Challenges: System Latency (milliseconds); Network Uptime (%); Data Processing Throughput; Multi-Site Data Aggregation Completeness.			
Technology Developers & Solution Providers Global: Microsoft Azure Edge, Amazon Web Services (AWS) IoT Greengrass, Siemens Industrial Edge, Schneider Electric. India: Tata Communications, Reliance Jio Cloud.		Key References : Industrial Internet Consortium, Edge Computing reference architecture; ISO/IEC 30141, Internet of Things Reference Architecture.	
Cross Media Effects : Computing infrastructure carries an electricity demand that scales with data volume and processing load.			
India Context & Strategic Considerations: Edge and cloud computing infrastructure is a supporting layer for more advanced digital applications rather than a standalone priority. Adoption is currently concentrated in large multi-site exporters building comprehensive Industry 4.0 capability.			

F0-04		Industrial Cybersecurity Systems	
Transformation Direction Digital Infrastructure & Traceability		TRL 8	Technology Type Digital Technology
Technology Focus Area Digital Infrastructure		Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Industrial cybersecurity systems protect operational technology (OT) assets, industrial control systems, connected machinery, and production networks against unauthorized access, cyber threats, and operational disruption. Security measures typically include network segmentation, identity and access management, endpoint protection, continuous monitoring, intrusion detection, and secure communication protocols. These systems safeguard the integrity, availability, and confidentiality of industrial data while supporting secure integration between operational technology and enterprise information technology environments.			
Primary Applications: Network segmentation between IT and OT systems; intrusion detection and prevention for industrial control systems; secure remote access management; data integrity protection for traceability and compliance records.			
Environmental & Resource Benefits: No direct environmental benefit. Indirectly protects the data integrity of energy, water, and resource monitoring systems that depend on secure, uncompromised data flows.			
Indicative CAPEX (India context): Rs 15 to 50 lakh for initial OT security assessment and implementation in a single facility; ongoing costs of Rs 5 to 15 lakh per year for monitoring and updates. [Indicative estimate only; not independently verified against a published market source.]		OPEX Savings / Payback Period: Reduces risk of costly production disruption from cyber incidents. Payback is typically evaluated on a risk-avoidance basis rather than direct cost savings.	
Key Performance Indicators (KPIs) Security Incident Rate; Network Segmentation Completeness; Mean Time to Detect (MTTD) Security Incidents; Patch Compliance Rate.		Reference Industries Large integrated exporters with significant digital infrastructure and international buyer data security requirements.	
Key Adoption Challenges: Security Incident Rate; Network Segmentation Completeness; Mean Time to Detect (MTTD) Security Incidents; Patch Compliance Rate.			
Technology Developers & Solution Providers : Global: Honeywell, Siemens, Fortinet, Palo Alto Networks. India: Tata Consultancy Services, Wipro, Quick Heal Technologies.		Key References : ISA/IEC 62443, Industrial Automation and Control Systems Security standard; National Critical Information Infrastructure Protection Centre, Government of India guidelines.	
Cross Media Effects: No material environmental trade-off; a data and operational integrity function only.			
India Context & Strategic Considerations: Cybersecurity is an emerging consideration in Indian textile manufacturing as digital connectivity increases. Buyer requirements for data security, particularly among exporters serving global brands, are increasing the relevance of formal OT security programmes.			

F0-05		Manufacturing Execution Systems (MES)	
Transformation Direction Digital Infrastructure & Traceability		TRL 9	Technology Type Digital Technology
Technology Focus Area Smart Manufacturing		Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Manufacturing Execution Systems (MES) bridge enterprise planning systems and shop-floor operations by capturing and managing real-time production data. The system records machine status, work-order execution, material consumption, operator activities, and quality inspections throughout the manufacturing process. MES coordinates production scheduling, monitors manufacturing progress, maintains batch genealogy and product traceability, and exchanges information with Enterprise Resource Planning (ERP), Industrial Internet of Things (IIoT), and quality management systems to ensure synchronized production execution.			
Primary Applications: Real-time production tracking and line balancing; work order and batch genealogy; operator and machine performance monitoring; in-process quality checkpoint recording; work-in-progress visibility; shift and downtime reporting; production data capture for traceability.			
Environmental & Resource Benefits: Reduces work-in-progress inventory and material handling losses. Enables early detection of process deviations that would otherwise result in off-spec production and rework. Supports energy and material consumption tracking at the work-order level, allowing targeted efficiency interventions.			
Indicative CAPEX (India context): Shopfloor MES (examples cited: Worknc, Garmex, STR): Rs 20 to 50 lakh implementation. [Validated by GA Morgan Dynamics Pvt Ltd via TMMA, May 2026, garment-sector specific]		OPEX Savings / Payback Period: Improves on-time delivery, reduces work-in-progress and idle time through real-time bottleneck visibility, and strengthens quality traceability by linking defects to specific machines, operators, and material batches. Typical payback period: 2 to 4 years.	
Key Performance Indicators (KPIs): Overall Equipment Effectiveness (OEE); Work-in-Progress (WIP) Days; On-Time Delivery; First-Pass Yield; Downtime by Cause Code; Batch/Lot Traceability Completeness; Line Efficiency (%).		Reference Industries: Arvind Limited; Vardhman Textiles; Welspun Living; Trident Group.	
Key Adoption Challenges: Overall Equipment Effectiveness (OEE); Work-in-Progress (WIP) Days; On-Time Delivery; First-Pass Yield; Downtime by Cause Code; Batch/Lot Traceability Completeness; Line Efficiency (%).			
Technology Developers & Solution Providers: Global: Siemens (Opcenter), AVEVA, Rockwell Automation, SAP MES, Dassault Systemes (DELMIA), Honeywell. India: Altizon Systems, Infinite Uptime, Tata Consultancy Services, L&T Technology Services.		Key References: International Society of Automation, ISA-95 Enterprise-Control System Integration standard; Ministry of Textiles, Government of India, PM MITRA scheme documentation; International Textile Manufacturers Federation, Annual Report. Cross-validated by GA Morgan Dynamics Pvt Ltd for the garment sector, TMMA industry consultation, May 2026.	
Cross Media Effects: Requires additional computing and networking infrastructure with associated electricity demand.			
India Context & Strategic Considerations: MES adoption in India lags competing textile economies at the shop-floor data layer. It is a near-term structural priority because it generates the machine-level production records needed for EU Digital Product Passport compliance from 2027.			

F0-06		PLC and SCADA Industrial Control Systems	
Transformation Direction Manufacturing Capability at Scale		TRL 9	Technology Type Automation Technology
Technology Focus Area Industrial Automation		Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Programmable Logic Controllers (PLCs) provide real-time machine-level control by receiving sensor inputs and controlling motors, valves, drives and other actuators. SCADA provides supervisory monitoring and control across multiple machines/processes, enabling centralised visibility, alarms and data collection. Together, they form a core control and data layer for automated textile manufacturing.			
Primary Applications: Looms, spinning and winding machines, dyeing and finishing equipment, boilers, utilities, water/ETP systems and other process equipment; centralised monitoring of machine status, process parameters, alarms and production conditions.			
Environmental & Resource Benefits: tighter process control can reduce energy, water, chemical and material losses. The control system itself has negligible energy consumption relative to the machinery it controls.			
Indicative CAPEX (India context): PLC retrofit: ₹1–5 lakh/machine. Facility SCADA: ₹15–60 lakh, depending on machines, data points and integration scope. Indicative estimates; site-specific vendor quotations required.		OPEX Savings / Payback Period: 2–4 years, depending on machine utilisation, baseline automation, downtime, process losses and scope of integration.	
Key Performance Indicators (KPIs): PLC-enabled machines (%); SCADA-connected processes (%); machine uptime; process parameter deviation; unplanned downtime; mean time to fault diagnosis; manual intervention frequency; rework/process loss.		Reference Industries: Standard equipment in organised spinning, weaving, and processing mills; largely absent in the mechanically controlled equipment still dominant in India's powerloom and MSME base.	
Key Adoption Challenges: PLC-enabled machines (%); SCADA-connected processes (%); machine uptime; process parameter deviation; unplanned downtime; mean time to fault diagnosis; manual intervention frequency; rework/process loss.			
Technology Developers & Solution Providers: Siemens; Rockwell Automation; Schneider Electric; Mitsubishi Electric; ABB; Honeywell; Omron; Indian system integrators and machinery OEMs.		Key References: IEC 61131 – Programmable Controllers; ISA-95 / IEC 62264 – Enterprise-Control System Integration; IEC 62443 – Industrial Automation and Control Systems Security.	
Cross Media Effects: No material environmental trade-off; the control system itself consumes negligible electricity relative to the machinery it governs. Networking PLC and SCADA systems introduces a cybersecurity exposure that is a distinct risk category rather than an environmental one, addressed in Industrial Cybersecurity Systems (F0-10).			
India Context & Strategic Considerations: Provides the machine/process-control and data foundation for IIoT, MES, predictive maintenance, energy management, water monitoring and advanced analytics. Higher-level systems can also use sensors/gateways where PLCs are absent, but the absence of machine-level control can limit the depth and reliability of integration.			

F0-07	Enterprise Energy Management Systems (EMS)	
Transformation Direction Resource-Intelligent Manufacturing	TRL 9	Technology Type Energy Technology
Technology Focus Area Energy Management	Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Enterprise Energy Management Systems (EMS) monitor, analyse, and manage energy consumption across manufacturing facilities through a network of smart meters, sensors, and centralized software. The system continuously records electricity, steam, fuel, compressed air, and other utility consumption, compares performance against established baselines, and identifies operational deviations. Integration with production and utility systems enables comprehensive monitoring of energy performance and supports structured energy management programmes aligned with recognized management standards.		
Primary Applications: Plant-wide electricity and utility monitoring; automated deviation alerts; energy benchmarking across production lines or sites; support for ISO 50001 energy management certification; verification of savings from efficiency retrofits such as variable frequency drives and heat recovery systems.		
Environmental & Resource Benefits: Enables continuous identification and correction of energy waste across electricity, steam, and compressed air systems, supporting measurable reductions in specific energy consumption per unit of production.		
Indicative CAPEX (India context): Basic 50-point monitoring system: Rs 5 to 25 lakh. Cloud-connected full system for a medium-sized mill: Rs 30 to 80 lakh. [Validated by TMMA General cross-cutting consultation, May 2026]	OPEX Savings / Payback Period: Payback 3 to 5 years from utility savings, with additional strategic value in export compliance.	
Key Performance Indicators (KPIs): Specific Energy Consumption (kWh or GJ per kg of production); Power Factor; Peak Demand; Energy Cost per Unit of Output; ISO 50001 Certification Status.	Reference Industries: Arvind Limited; Vardhman Textiles; Welspun Living; Trident Group.	
Key Adoption Challenges: Specific Energy Consumption (kWh or GJ per kg of production); Power Factor; Peak Demand; Energy Cost per Unit of Output; ISO 50001 Certification Status.		
Technology Developers & Solution Providers: Global: Siemens, Schneider Electric (EcoStruxure), Honeywell, ABB. India: Thermax, Forbes Marshall.	Key References: Bureau of Energy Efficiency, Perform Achieve and Trade (PAT) Scheme documentation; ISO 50001, Energy Management Systems standard; Ministry of Power, Government of India. Validated by TMMA cross-cutting general technology consultation, May 2026.	
Cross Media Effects: No significant trade-off; the monitoring infrastructure itself consumes negligible electricity relative to the consumption it helps reduce.		
India Context & Strategic Considerations: The Bureau of Energy Efficiency's PAT scheme designates large energy-consuming textile units as Designated Consumers with mandatory reporting obligations, making EMS infrastructure an increasingly standard compliance requirement rather than a discretionary investment.		

F0-08	Industrial Water Management & Monitoring Systems	
Transformation Direction Resource-Intelligent Manufacturing	TRL 8	Technology Type Digital Technology
Technology Focus Area Water Management	Roadmap Horizon Align (2026–2030)	India Adoption (2026)Align (2026–2030)
Technology Overview & Working Principle: Industrial water management and monitoring systems integrate flow meters, water quality sensors, level indicators, and centralized software platforms to continuously monitor water abstraction, consumption, recycling, treatment, and discharge across manufacturing facilities. Real-time monitoring of process water, wastewater, and treatment systems enables comprehensive tracking of water flows and quality parameters. The system interfaces with Effluent Treatment Plants (ETPs), Zero Liquid Discharge (ZLD) systems, and utility infrastructure to support integrated water resource management.		
Primary Applications: Plant-wide water consumption tracking by process stage; effluent quality monitoring including chemical oxygen demand, total dissolved solids, and colour; water recycling rate verification; leak detection; support for water stewardship certification.		
Environmental & Resource Benefits: Enables identification of high water-consuming process stages for targeted intervention, supports verification of water recycling and reuse rates, and provides the data foundation for water stewardship reporting and regulatory compliance.		
Indicative CAPEX (India context): Individual meter: Rs 5,000 to 50,000 depending on pipe size and type. Full plant metering: Rs 2 to 10 lakh. [Validated by TMMA General cross-cutting consultation, May 2026]	OPEX Savings / Payback Period: Payback 1 to 2 years from water savings, with additional value from associated electricity savings.	
Key Performance Indicators (KPIs): Water Consumption per kg of Production; Water Recycling Rate (%); Effluent Chemical Oxygen Demand (mg/L); Effluent Total Dissolved Solids (mg/L); Leak Detection Response Time.	Reference Industries: Tirupur, Surat, and Ahmedabad wet processing clusters with Zero Liquid Discharge obligations.	
Key Adoption Challenges: Water Consumption per kg of Production; Water Recycling Rate (%); Effluent Chemical Oxygen Demand (mg/L); Effluent Total Dissolved Solids (mg/L); Leak Detection Response Time.		
Technology Developers & Solution Providers: Global: Veolia, SUEZ, Xylem, Endress+Hauser. India: Thermax, Ion Exchange India, Va Tech Wabag.	Key References: Central Pollution Control Board, Zero Liquid Discharge guidelines; Gujarat Pollution Control Board, industry effluent standards; ISO 14046, Water Footprint standard. Validated by TMMA cross-cutting general technology consultation, May 2026.	
Cross Media Effects: Metering and sensor infrastructure has a negligible resource footprint relative to the facility it monitors.		
India Context & Strategic Considerations: Water-stressed textile clusters including Tirupur and Surat operate under Zero Liquid Discharge mandates enforced by state pollution control boards, making continuous water monitoring infrastructure a practical necessity for regulatory compliance and license retention.		

F0-09	Predictive Maintenance Systems	
Transformation Direction Manufacturing Capability at Scale	TRL 9	Technology Type Digital Technology
Technology Focus Area Asset Management	Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Predictive maintenance systems continuously monitor the operating condition of production equipment using sensors that measure parameters such as vibration, temperature, acoustic emissions, electrical current, and lubrication condition. Data analytics and machine learning algorithms identify abnormal operating patterns and estimate the remaining useful life of critical components before failure occurs. The system enables maintenance activities to be scheduled based on actual equipment condition rather than fixed maintenance intervals.		
Primary Applications: Condition monitoring of motors, gearboxes, compressors, and pumps; vibration and thermal analysis of spinning and weaving machinery; boiler and steam system health monitoring; early bearing and belt failure detection; maintenance scheduling optimization.		
Environmental & Resource Benefits: Extends equipment operating life, reducing the embodied resource impact of premature replacement. Prevents energy-intensive failure modes such as bearing seizure and motor burnout. Reduces material waste from unplanned production stoppages that generate off-spec output.		
Indicative CAPEX (India context) : Rs 10 to 30 lakh for sensor retrofit and monitoring software on a single production line; Rs 30 lakh to 1.5 crore for plant-wide deployment across spinning, weaving, or wet processing sections. [Indicative estimate only; not independently verified against a published market source.	OPEX Savings / Payback Period: Reduces unplanned downtime and emergency repair costs, extends mean time between failures, and lowers spare parts inventory requirements. Typical payback period: 1 to 3 years.	
Key Performance Indicators (KPIs): Mean Time Between Failures (MTBF); Mean Time to Repair (MTTR); Unplanned Downtime (%); Maintenance Cost per Unit of Production; Equipment Availability (%).	Reference Industries: Arvind Limited; Vardhman Textiles; Trident Group; Raymond Limited.	
Key Adoption Challenges: Mean Time Between Failures (MTBF); Mean Time to Repair (MTTR); Unplanned Downtime (%); Maintenance Cost per Unit of Production; Equipment Availability (%).		
Technology Developers & Solution Providers Global: SKF, Siemens, Honeywell, Bosch Rexroth, GE Digital. India: Infinite Uptime, Altizon Systems, Presage Insights, Flutura Business Solutions.	Key References ISO 55000, Asset Management standard; ISO 13374, Condition Monitoring and Diagnostics of Machines; Bureau of Energy Efficiency, Government of India.	
Cross Media Effects Sensor and monitoring hardware adds modest electricity demand and electronic waste at end of life.		
India Context & Strategic Considerations India's textile machinery base includes a large share of aging equipment, making predictive maintenance particularly valuable for extending asset life and reducing breakdown-related production losses in both organized mills and larger MSME units.		

F0-10	Computer Vision & Automated Quality Inspection	
Transformation Direction Digital Infrastructure & Traceability	TRL 9	Technology Type Digital Technology
Technology Focus Area Quality Management	Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle : Computer vision systems automate visual inspection using high-resolution cameras, advanced imaging technologies, and artificial intelligence-based image analysis algorithms. Images captured during production are compared against predefined quality parameters to identify defects, dimensional variations, colour inconsistencies, and surface irregularities in textiles and garments. The system performs continuous inspection at production speed while generating digital inspection records that support quality assurance and process monitoring.		
Primary Applications: In-line fabric defect detection on looms and finishing ranges; garment seam and assembly inspection; yarn quality monitoring; colour and shade consistency verification; automated grading and classification of inspected material.		
Environmental & Resource Benefits: Earlier defect detection prevents further processing, dyeing, or finishing being applied to material that will ultimately be rejected, reducing water, chemical, and energy waste embedded in defective output.		
Indicative CAPEX (India context): Rs 15 to 40 lakh per inspection line for fabric inspection systems; Rs 10 to 25 lakh per station for garment-level inspection systems, depending on camera resolution, coverage width, and defect classification complexity. [Indicative estimate only; not independently verified against a published market source.]	OPEX Savings / Payback Period: Reduces manual inspection labour, improves defect detection consistency compared with human sampling, and lowers buyer claim and rework rates. Typical payback period: 2 to 4 years.	
Key Performance Indicators (KPIs): Defect Detection Rate (%); False Positive Rate (%); Inspection Throughput (metres or garments per hour); First-Pass Quality; Buyer Claim Rate.	Reference Industries: Arvind confirmed as reference plant for both AI-based fabric inspection and AI-based final garment inspection systems [validated by GA Morgan Dynamics Pvt Ltd]	
Key Adoption Challenges: Defect Detection Rate (%); False Positive Rate (%); Inspection Throughput (metres or garments per hour); First-Pass Quality; Buyer Claim Rate.		
Technology Developers & Solution Providers: Global: Uster Technologies, Cognex, Elbit Imaging, Smartex. India: Visiotex, in-house systems developed by large integrated mills.	Key References: AATCC, Fabric Inspection and Grading Standards; ASTM International, Textile Testing Standards; Apparel Impact Institute, technology assessment publications. Validated by GA Morgan Dynamics Pvt Ltd, TMAA industry consultation, May 2026, with Arvind cited as reference plant for both fabric- and garment-level applications.	
Cross Media Effects: Camera and processing infrastructure adds modest electricity demand; no water or chemical trade-off.		
India Context & Strategic Considerations: India's textile and garment quality control remains largely manual and sampling-based. Computer vision inspection reduces defect escape rates below the practical floor achievable through visual sampling alone, supporting both domestic quality improvement and export compliance.		

F0-11	Industrial Robotics & Collaborative Robots (Cobots)	
Transformation Direction Manufacturing Capability at Scale	TRL 8	Technology Type Manufacturing Equipment
Technology Focus Area Industrial Automation	Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle :Industrial robots and collaborative robots (cobots) automate repetitive production and material handling tasks using programmable multi-axis robotic systems. Conventional industrial robots operate within dedicated safety enclosures for high-speed automated operations, while collaborative robots incorporate force-limiting sensors, machine vision, and advanced safety controls that enable safe interaction with human operators. Both systems can be programmed for flexible manufacturing tasks and integrated with digital production control systems.		
Primary Applications: Material handling and palletizing; fabric roll handling; garment folding and packing; simple pick-and-place operations; assistance with repetitive assembly tasks alongside human operators.		
Environmental & Resource Benefits: Improves consistency of material handling, reducing product damage and associated material waste. No direct resource or emissions benefit beyond productivity and quality improvements.		
Indicative CAPEX (India context): Rs 15 to 40 lakh per cobot unit including integration; Rs 50 lakh to 2 crore for multi-unit industrial robotic material handling systems. [Indicative estimate only; not independently verified against a published market source.]	OPEX Savings / Payback Period: Reduces labour cost for repetitive tasks and improves handling consistency. Typical payback period: 3 to 6 years, depending on labour cost baseline and task complexity.	
Key Performance Indicators (KPIs): Units Handled per Hour; Material Damage Rate; Labour Hours Displaced; Uptime (%).	Reference Industries: Large garment export units in Bengaluru, Delhi NCR, and Chennai; large integrated spinning and weaving mills for material handling.	
Key Adoption Challenges: Units Handled per Hour; Material Damage Rate; Labour Hours Displaced; Uptime (%).		
Technology Developers & Solution Providers: Global: ABB, KUKA, Universal Robots, FANUC, Yaskawa. India: no significant domestic cobot manufacturer identified; systems integration provided by local automation firms.	Key References: International Federation of Robotics, World Robotics Report; ISO 10218, Robots and Robotic Devices Safety Requirements.	
Cross Media Effects: Robotic systems draw continuous electricity during operation, comparable to or somewhat higher than the manual process displaced.		
India Context & Strategic Considerations: India's comparatively low labour cost, relative to competing manufacturing economies where robotics adoption is more advanced, shapes cobot deployment toward specific high-value material handling tasks rather than broad-based factory floor automation.		

F0-12	Artificial Intelligence & Machine Learning for Manufacturing	
Transformation Direction Innovation & Technology Origination	TRL 8	Technology Type Digital Technology
Technology Focus Area Smart Manufacturing	Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Artificial Intelligence (AI) and Machine Learning (ML) systems analyse large volumes of historical and real-time manufacturing data to identify patterns, generate predictions, and optimize industrial processes. Using statistical models and self-learning algorithms, these systems continuously improve prediction accuracy as additional operational data become available. AI and ML platforms can be integrated with enterprise systems, production equipment, sensors, and quality management systems to support advanced manufacturing decision-making across the textile value chain.		
Primary Applications: Demand and sales forecasting; production scheduling and capacity optimization; dye recipe prediction and shade matching; yield and quality prediction from process parameters; energy and resource consumption optimization.		
Environmental & Resource Benefits : Improved forecasting accuracy reduces overproduction and inventory write-offs. Dye recipe prediction reduces the trial dyeing and re-dyeing cycles that consume water, chemicals, and energy without producing saleable output.		
Indicative CAPEX (India context) : Rs 30 lakh to 1 crore for point-solution AI applications such as dye recipe prediction; Rs 1 to 5 crore for broader production planning and forecasting AI platforms integrated across multiple business functions. [Indicative estimate only; not independently verified against a published market source.]	OPEX Savings / Payback Period ; Reduces planning error costs, trial dyeing waste, and inventory carrying costs. Payback varies significantly by application; dye recipe prediction and forecasting applications typically show payback within 2 to 4 years.	
Key Performance Indicators (KPIs) : Forecast Accuracy (%); Right-First-Time Dyeing Rate (%); Production Schedule Adherence; Inventory Write-Off Rate; Yield Improvement (%).	Reference Industries : Large integrated exporters with established digital infrastructure and historical production data.	
Key Adoption Challenges : Forecast Accuracy (%); Right-First-Time Dyeing Rate (%); Production Schedule Adherence; Inventory Write-Off Rate; Yield Improvement (%).		
Technology Developers & Solution Providers : Global: Microsoft Azure AI, Google Cloud AI, IBM Watson, SAP AI. India: Fractal Analytics, Mu Sigma, Tata Consultancy Services.	Key References : World Economic Forum, Global Lighthouse Network reports on AI in manufacturing; NITI Aayog, National Strategy for Artificial Intelligence.	
Cross Media Effects : Requires computing infrastructure for model training and inference, with associated electricity demand scaling with data volume.		
India Context & Strategic Considerations : AI adoption in India's textile sector is currently concentrated among a small number of large integrated exporters, positioning it as a second-wave capability that follows, rather than accompanies, foundational ERP, MES, and IIoT investment.		

F0-13	Digital Twin Platforms	
Transformation Direction Innovation & Technology Origination	TRL 7	Technology Type Digital Technology
Technology Focus Area Smart Manufacturing	Roadmap Horizon Accelerate (2035–2047)	India Adoption (2026) Accelerate (2035–2047)
Technology Overview & Working Principle : Digital twin platforms create dynamic virtual representations of physical equipment, production processes, or manufacturing facilities using continuously updated operational data from sensors, automation systems, and enterprise applications. The digital model replicates the operating behaviour of physical assets and enables simulation, performance analysis, and scenario evaluation under different operating conditions. Continuous synchronization between physical and virtual systems provides an integrated environment for monitoring and operational analysis.		
Primary Applications: Virtual process simulation and optimization before physical changes; predictive scenario planning for capacity and layout decisions; production-condition-aware supply chain traceability; training simulation for new operators.		
Environmental & Resource Benefits: Enables testing of efficiency interventions virtually before physical implementation, reducing trial-and-error resource consumption; supports identification of energy and material optimization opportunities through simulation.		
Indicative CAPEX (India context): IoT sensors and connectivity: Rs 5 to 20 lakh. Digital twin platform (Siemens, Dassault Systemes): Rs 50 lakh to 2 crore for a full factory model. [Validated by GA Morgan Dynamics Pvt Ltd via TMMA, May 2026]	OPEX Savings / Payback Period: Payback 5 to 8 years — described by the validator as strategic value that is hard to quantify in purely financial terms.	
Key Performance Indicators (KPIs): Model Prediction Accuracy (%); Simulation-to-Actual Variance; Number of Process Changes Validated Virtually Before Implementation.	Reference Industries: Large integrated exporters piloting advanced digital manufacturing capability; not yet widespread in India.	
Key Adoption Challenges: Model Prediction Accuracy (%); Simulation-to-Actual Variance; Number of Process Changes Validated Virtually Before Implementation.		
Technology Developers & Solution Providers: Global: Siemens (Digital Industries Software), Dassault Systemes, AVEVA, Microsoft Azure Digital Twins. India: no significant domestic digital twin platform specific to textiles identified.	Key References: Deloitte, Digital Twin applications in supply chain and manufacturing systems, Deloitte Insights; International Society of Automation, digital twin reference frameworks. Validated by GA Morgan Dynamics Pvt Ltd, TMMA industry consultation, May 2026.	
Cross Media Effects: Computing infrastructure for real-time simulation carries an electricity demand proportional to model complexity.		
India Context & Strategic Considerations: Digital twin capability is best understood as a later-stage layer in India's digital manufacturing roadmap, building on and only becoming valuable after IoT, MES, and machine monitoring systems are already generating reliable production data.		

F0-14	Variable Frequency Drives on Motors	
Transformation Direction Resource-Intelligent Manufacturing	TRL 9	Technology Type Energy Technology
Technology Focus Area Energy Management	Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Variable Frequency Drives (VFDs) regulate the speed and torque of alternating current (AC) motors by controlling the frequency and voltage of the electrical supply. Electronic power converters continuously adjust motor output to match process demand rather than operating at constant speed. The system is particularly suited to variable-load equipment such as pumps, fans, compressors, and conveyors, and can be integrated with automation and process control systems for dynamic motor operation.		
Primary Applications: Pumps, fans, and compressors across all textile manufacturing stages, including effluent treatment plant aerators, dyehouse exhaust fans, and stenter drives.		
Environmental & Resource Benefits: Energy saving through variable-speed operation matched to actual load, eliminating the throttling losses inherent in fixed-speed motor operation controlled by mechanical means.		
Indicative CAPEX (India context): Rs 2 to 5 lakh per installation, depending on motor kW rating. [Validated by three independent TMMA members via TMMA, May 2026, with consistent figures across all three]		OPEX Savings / Payback Period: Payback 2 to 3 years.
Key Performance Indicators (KPIs): Energy saving (kWh per year) relative to fixed-speed operation; power factor improvement; motor operating temperature.		Reference Industries: Medium — adopted in organised mills; low penetration in MSMEs. [TMMA-validated, consistent across three respondents]
Key Adoption Challenges: Energy saving (kWh per year) relative to fixed-speed operation; power factor improvement; motor operating temperature.		
Technology Developers & Solution Providers: Global and India-based suppliers of variable frequency drives across major electrical equipment manufacturers; no single supplier named by validators, reflecting the widespread commercial availability of this technology.		Key References: Validated independently by three separate TMMA members via TMMA industry consultation, May 2026, with consistent CAPEX and payback figures across all three.
Cross Media Effects: No cross-media trade-off; pure energy saving with no offsetting water, chemical, or other resource impact.		
India Context & Strategic Considerations: This technology was validated by three separate TMMA members with essentially identical figures, indicating strong industry consensus on its cost and payback profile, yet it had no standalone card in this compendium prior to validation — a notable structural gap given VFDs are among the most universally applicable and well-proven energy efficiency interventions available to Indian textile manufacturers of any size.		

F0-15	High-Efficiency Motors (IE3/IE4 Class)	
Transformation Direction Resource-Intelligent Manufacturing	TRL 9	Technology Type Energy Technology
Technology Focus Area Energy Management	Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: E3 and IE4 premium efficiency motors are high-performance electric motors designed to minimize electrical and mechanical losses through improved magnetic materials, optimized winding configurations, precision manufacturing, and enhanced cooling systems. They deliver the required mechanical output with lower electrical input while maintaining compatibility with standard industrial drive systems. These motors comply with internationally recognized energy efficiency classifications established under IEC 60034-30.		
Primary Applications: All motor-driven textile equipment across spinning, weaving, wet processing, and garment manufacturing, wherever a motor requires replacement or a new installation is specified.		
Environmental & Resource Benefits: Reduces electricity consumption for a given mechanical output compared with lower-efficiency motor classes, and lowers the associated carbon footprint of grid electricity use.		
Indicative CAPEX (India context): 10 to 25 percent premium over standard motors, equivalent to Rs 15,000 to 80,000 per motor depending on kW rating. [Validated by three independent TMMA members via TMMA, May 2026]		OPEX Savings / Payback Period: Payback 2 to 3 years from energy savings alone.
Key Performance Indicators (KPIs): Motor efficiency (%) at rated load relative to IE1/IE2 baseline; energy consumption (kWh) relative to prior motor class; carbon dioxide emissions avoided.		Reference Industries: Medium — installed capacity in organised mills; lower in MSMEs. [TMMA-validated]
Key Adoption Challenges: Motor efficiency (%) at rated load relative to IE1/IE2 baseline; energy consumption (kWh) relative to prior motor class; carbon dioxide emissions avoided.		
Technology Developers & Solution Providers: Global and India-based electrical motor manufacturers; no single supplier named by validators, reflecting broad commercial availability across the market.		Key References: Validated independently by three separate TMMA members via TMMA industry consultation, May 2026.
Cross Media Effects: No cross-media trade-off; pure energy saving with no offsetting resource impact.		
India Context & Strategic Considerations: India's Bureau of Energy Efficiency mandates IE3 as the minimum efficiency class for new motor installations above a threshold rating, making this technology increasingly a compliance baseline rather than a discretionary upgrade, though the large existing installed base of older motors represents a multi-year replacement cycle rather than an immediate transition.		

F0-16	Permanent Magnet Screw Air Compressors	
Transformation Direction Resource-Intelligent Manufacturing	TRL 9	Technology Type Energy Technology
Technology Focus Area Energy Management	Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle : Permanent magnet air compressor systems integrate high-efficiency permanent magnet synchronous motors with variable-speed screw compressors to supply compressed air according to real-time process demand. Electronic drive systems continuously regulate compressor speed, eliminating inefficient load-unload cycling associated with conventional fixed-speed compressors. Integrated controllers monitor pressure, airflow, and operating conditions to optimize compressed air generation across industrial facilities.		
Primary Applications: Compressed air generation for air-jet looms, pneumatic textile machinery, and general factory compressed air systems.		
Environmental & Resource Benefits: Reduces electricity consumption for compressed air generation specifically at part-load operating conditions, which represent the majority of actual operating time for most factory compressed air systems.		
Indicative CAPEX (India context): Rs 2 to 5 lakh per installation, depending on motor kW rating. [Validated by TMMA General cross-cutting consultation, May 2026]		OPEX Savings / Payback Period L Payback 3 to 5 years for compressor replacement.
Key Performance Indicators (KPIs): Compressed air energy consumption (kWh per normal cubic metre delivered) relative to fixed-speed compressor baseline; part-load efficiency.		Reference Industries: Low — very few installations to date. [TMMA-validated]
Key Adoption Challenges: Compressed air energy consumption (kWh per normal cubic metre delivered) relative to fixed-speed compressor baseline; part-load efficiency.		
Technology Developers & Solution Providers: No specific commercial supplier named by validator.		Key References: Validated by TMMA cross-cutting general technology consultation, May 2026.
Cross Media Effects: No cross-media trade-off; pure energy saving specific to compressed air generation with no offsetting resource impact.		
India Context & Strategic Considerations: Compressed air is among the most expensive utilities per unit of useful energy delivered in a textile mill, and air-jet weaving in particular depends heavily on compressed air; this technology's very low current adoption despite meaningful payback suggests an awareness gap rather than an economic or technical barrier.		

F0-17	High-Efficiency LED Lighting Systems	
Transformation Direction Resource-Intelligent Manufacturing	TRL 9	Technology Type Energy Technology
Technology Focus Area Energy Management	Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: High-efficiency Light Emitting Diode (LED) lighting systems replace conventional industrial lighting with semiconductor-based luminaires that convert electrical energy directly into visible light. Modern systems incorporate electronic drivers, optical controls, and intelligent lighting management to provide uniform illumination while enabling automated switching, dimming, occupancy sensing, and daylight harvesting. The systems are designed to meet industrial lighting requirements across production, inspection, warehouse, and utility areas.		
Primary Applications: Universal application across production floor, quality inspection areas, offices, and warehouse space in any textile manufacturing facility.		
Environmental & Resource Benefits: Substantially lower electricity consumption than the lighting technologies it replaces for equivalent illumination, resulting in a correspondingly lower associated carbon footprint from reduced grid electricity demand.		
Indicative CAPEX (India context): Rs 200 to 500 per fitting; a typical full mill retrofit totals Rs 5 to 25 lakh. [Validated by TMMA General cross-cutting consultation, May 2026]	OPEX Savings / Payback Period: Payback 1 to 3 years depending on operating hours and the specific lamp technology being replaced.	
Key Performance Indicators (KPIs): Lighting electricity consumption (kWh per year) relative to prior lighting technology; illumination level maintained (lux); colour rendering index for quality inspection areas.	Reference Industries: Growing, driven by Energy Efficiency Services Limited bulk procurement programmes and declining LED costs. [TMMA-validated]	
Key Adoption Challenges: Lighting electricity consumption (kWh per year) relative to prior lighting technology; illumination level maintained (lux); colour rendering index for quality inspection areas.		
Technology Developers & Solution Providers: No specific commercial supplier named by validator; validator notes individual machines are increasingly supplied with LED-based indicator and alarm lighting as standard equipment from original equipment manufacturers.	Key References: Validated by TMMA cross-cutting general technology consultation, May 2026.	
Cross Media Effects: No cross-media trade-off; pure energy saving with no offsetting resource impact.		
India Context & Strategic Considerations: This is among the most basic, universally applicable, and fastest-payback energy interventions available to any textile manufacturer regardless of size, yet had no standalone card in this compendium prior to TMMA validation — a striking omission given how frequently it is cited as a baseline recommendation in energy efficiency programmes generally.		

F0-18	Intelligent Steam Management & Heat Recovery Systems	
Transformation Direction Resource-Intelligent Manufacturing	TRL 9	Technology Type Resource Efficiency Technology
Technology Focus Area Resource Management	Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Intelligent Steam Management & Heat Recovery Systems optimize the generation, distribution, utilization, recovery, and monitoring of industrial steam to maximize thermal efficiency and minimize energy losses. The system combines digital steam monitoring with steam trap diagnostics, condensate recovery, flash steam recovery, heat exchanger optimization, and heat integration techniques to improve overall steam system performance. Integrated with Enterprise Energy Management Systems (EMS), Industrial Internet of Things (IIoT) platforms, and process automation systems, these solutions enable continuous monitoring of steam quality, pressure, flow, condensate recovery, and equipment performance, supporting predictive maintenance and real-time optimization of industrial utility networks.		
Primary Applications: Steam generation and distribution; steam trap monitoring; condensate and flash steam recovery; boiler feedwater preheating; heat exchanger optimisation; wastewater heat recovery; process heat integration; utility performance monitoring.		
Environmental & Resource Benefits: Reduces fuel consumption, steam losses, freshwater demand, boiler make-up water, and greenhouse gas emissions through improved condensate recovery and waste heat utilisation. Improves boiler efficiency while reducing water treatment chemicals and thermal energy losses.		
Indicative CAPEX (India context): Steam trap monitoring systems: ₹5–20 lakh; condensate recovery upgrades: ₹10–75 lakh; integrated steam management systems: ₹25 lakh–₹2 crore, depending on plant size and steam network complexity.	OPEX Savings / Payback Period: Typical fuel savings of 5–20% and condensate recovery of 70–90%, depending on existing system performance. Typical payback period: 1–3 years.	
Key Performance Indicators (KPIs): Boiler efficiency (%); steam generation intensity (kg steam/kg product); condensate recovery rate (%); steam distribution losses (%); steam trap health (% operational); thermal energy intensity; fuel consumption per tonne of steam; heat recovery rate (%).	Reference Industries	
Key Adoption Challenges: Boiler efficiency (%); steam generation intensity (kg steam/kg product); condensate recovery rate (%); steam distribution losses (%); steam trap health (% operational); thermal energy intensity; fuel consumption per tonne of steam; heat recovery rate (%).		
Technology Developers & Solution Providers: Global: Spirax Sarco, Armstrong International, TLV, Emerson, Siemens, ABB. India: Forbes Marshall, Thermax, Spirax Sarco India, Armstrong India.	Key References: ISO 50001:2018 Energy Management Systems; U.S. Department of Energy – Steam System Best Practices; Spirax Sarco Steam Engineering Guidelines; Apparel Impact Institute (AII) Low-Carbon Thermal Energy Roadmap; Cross-validated through literature review and international steam management best practices.	
Cross Media Effects: No significant cross-media trade-offs. Reduced fuel consumption also lowers water consumption, wastewater generation, and greenhouse gas emissions associated with steam production.		

India Context & Strategic Considerations: Steam accounts for the majority of thermal energy demand in textile wet processing, making steam system optimisation one of the fastest-payback energy efficiency interventions available. Many Indian textile facilities continue to operate with low condensate recovery rates and limited steam monitoring. Intelligent Steam Management & Heat Recovery Systems provide a commercially mature pathway to improve utility performance while establishing the thermal efficiency foundation for future deployment of renewable bioenergy, industrial heat pumps, solar thermal systems, and other low-carbon process heat technologies.
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F0-19	Renewable Energy Integration & Microgrid Management	
Transformation Direction Resource-Intelligent Manufacturing	TRL 8	Technology Type Energy Technology
Technology Focus Area Clean Energy	Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Renewable energy integration and microgrid management systems coordinate on-site renewable energy generation, energy storage, grid connectivity, and facility electricity demand through intelligent control platforms. The system continuously balances electricity supply and consumption by managing power flows between renewable generation sources, battery storage, captive generation, and the utility grid. Advanced controllers optimize energy dispatch, maintain power quality, and support resilient operation during grid disturbances or planned islanded operation.		
Primary Applications: Rooftop and ground-mounted solar photovoltaic integration; battery energy storage management; captive power optimization; grid outage islanding; renewable energy self-consumption maximization.		
Environmental & Resource Benefits: Reduces grid electricity purchase and associated Scope 2 emissions; reduces diesel generator use during outages; supports renewable energy targets under state Renewable Purchase Obligation frameworks.		
Indicative CAPEX (India context): TMMA member validation (2024 pricing): rooftop solar PV Rs 45,000 to 55,000 per kW; 500 kW rooftop system Rs 250 to 300 lakh; solar thermal collector Rs 3,000 to 6,000 per square metre. This is consistent with, though slightly higher than, the independently verified 2026 commercial and industrial market pricing of Rs 35,000 to 41,000 per kW already cited below, reflecting the decline in solar costs between 2024 and 2026. Battery storage adds Rs 8 to 15 lakh per 100 kilowatt-hour of storage capacity; microgrid controller integration adds Rs 20 to 60 lakh depending on system complexity, not independently verified.		OPEX Savings / Payback Period: Payback 4 to 6 years for photovoltaic systems, 3 to 5 years for solar thermal, at current electricity tariffs. TMMA validators confirm rooftop solar adoption is growing rapidly, with an estimated 10 percent of processing units in textile parks having adopted rooftop solar as of the 2024-25 period.
Key Performance Indicators (KPIs): Renewable Energy Self-Consumption (%); Grid Electricity Displacement (kWh per year); Diesel Generator Run-Hours Avoided; Carbon Dioxide Emissions Avoided (tonnes per year).		Reference Industries: Textile mills across Gujarat, Tamil Nadu, and Maharashtra with adequate roof or land area for solar installation.
Key Adoption Challenges: Renewable Energy Self-Consumption (%); Grid Electricity Displacement (kWh per year); Diesel Generator Run-Hours Avoided; Carbon Dioxide Emissions Avoided (tonnes per year).		
Technology Developers & Solution Providers: Global: Schneider Electric, ABB. India: Tata Power Solar, Adani Solar, Vikram Solar, Waaree Energies, Fourth Partner Energy, Amplus Solar, Cleantech Solar.		Key References: Ministry of New and Renewable Energy, Government of India, PM Surya Ghar and rooftop solar benchmark cost circulars, FY 2025-26; Bluebird Solar, 50 kW and 100 kW Solar Panel System Price in India (2026), market-referenced commercial and industrial pricing. Cross-validated by TMMA cross-cutting general technology consultation, May 2026 (2024 pricing basis).
Cross Media Effects: Solar panel and battery manufacturing carry an upstream embodied carbon and mineral footprint, recovered over the operational lifetime through avoided grid emissions; battery end-of-life disposal requires management.		

India Context & Strategic Considerations: India's textile mill rooftops, particularly in Gujarat and Tamil Nadu with high solar irradiance, represent strong candidates for renewable energy integration, supported by national solar mission targets and state renewable purchase obligation frameworks.

F0-20	Cogeneration & Industrial Energy Recovery Systems	
Transformation Direction Resource-Intelligent Manufacturing	TRL 9	Technology Type Energy Technology
Technology Focus Area Clean Energy	Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Cogeneration & Industrial Energy Recovery Systems simultaneously generate electricity and useful thermal energy from a single fuel source while recovering waste heat that would otherwise be lost. Technologies include Combined Heat and Power (CHP) systems, back-pressure steam turbines, waste heat recovery boilers, Organic Rankine Cycle (ORC) systems, and industrial energy recovery units. These systems maximise overall fuel utilisation by supplying electricity and process steam or hot water for textile manufacturing operations.		
Primary Applications: Combined heat and power generation; process steam generation; waste heat recovery; electricity generation from excess steam pressure; boiler efficiency improvement; industrial utility optimisation.		
Environmental & Resource Benefits: Improves overall fuel utilisation from approximately 35–45% in conventional power generation to 70–90% through combined production of electricity and useful heat. Reduces primary fuel consumption, greenhouse gas emissions, and operating costs while improving energy resilience.		
Indicative CAPEX (India context): Back-pressure steam turbine systems: ₹2–10 crore; medium-scale CHP systems: ₹5–25 crore, depending on plant size, steam demand, and power generation capacity.		OPEX Savings / Payback Period: Reduces purchased electricity and improves overall energy efficiency. Typical payback period: 3–6 years, depending on fuel costs, electricity tariffs, plant load factor, and steam demand.
Key Performance Indicators (KPIs): Overall energy efficiency (%); electricity generated (kWh); steam generated (TPH); specific fuel consumption; boiler efficiency (%); waste heat recovery rate (%); CO ₂ emissions reduction; annual energy cost savings.		Reference Industries: Low — limited to large integrated mills with boiler capacity above 10 tonnes per hour. [TMMA-validated]
Key Adoption Challenges: Overall energy efficiency (%); electricity generated (kWh); steam generated (TPH); specific fuel consumption; boiler efficiency (%); waste heat recovery rate (%); CO ₂ emissions reduction; annual energy cost savings.		
Technology Developers & Solution Providers: No specific commercial supplier named by validator.		Key References: Validated by TMMA cross-cutting general technology consultation, May 2026.
Cross Media Effects: Improves overall fuel-to-useful-energy conversion efficiency relative to generating steam and electricity separately; no water or chemical trade-off beyond standard boiler operation.		
India Context & Strategic Considerations: Textile wet processing requires simultaneous demand for electricity and process steam, making cogeneration particularly suitable for integrated textile facilities. While already deployed in several large textile clusters, significant opportunities remain to improve efficiency through modern CHP systems, waste heat recovery, and industrial energy recovery technologies		

F0-21		Renewable Bioenergy Process Heat Systems	
Transformation Direction Resource-Intelligent Manufacturing		TRL 9	Technology Type Clean Energy Technology
Technology Focus Area Clean Energy & Industrial Decarbonization		Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Renewable Bioenergy Process Heat Systems generate industrial steam and thermal energy using sustainably sourced solid biomass and renewable gaseous biofuels as alternatives to coal and furnace oil. The technology encompasses high-efficiency biomass combustion systems, biomass gasification, and biomethane utilisation, hybrid biomass-electric systems, and advanced combustion controls. Typical feedstocks include agricultural residues, biomass pellets, briquettes, bagasse, rice husk, cotton stalk, groundnut shell, and biomethane.			
Primary Applications: Process steam generation; thermal oil heating; hot water generation; boiler fuel substitution; Combined Heat & Power (CHP); hybrid renewable thermal systems.			
Environmental & Resource Benefits: Reduces dependence on fossil fuels, lowers lifecycle greenhouse gas emissions, utilises agricultural and agro-industrial residues, and supports circular bioeconomy principles. Sustainable biomass and renewable gaseous biofuels can substantially reduce Scope 1 emissions while diverting agricultural residues from open-field burning.			
Indicative CAPEX (India context): High-efficiency biomass boiler systems: ₹1–10 crore; biomass fuel handling and storage systems: ₹20 lakh–₹2 crore; biogas or biomethane integration costs vary depending on fuel supply infrastructure and plant capacity.		OPEX Savings / Payback Period: Operating costs depend on biomass or biomethane availability and local fuel prices. Typical payback period: 3–6 years, with shorter payback where low-cost agricultural residues are readily available and coal or furnace oil prices are high.	
Key Performance Indicators (KPIs): Renewable fuel substitution (%); steam generation efficiency (%); specific fuel consumption (kg fuel/tonne steam); renewable energy share (%); CO ₂ emissions reduction; boiler efficiency (%); ash generation; thermal energy intensity.		Reference Industries	
Key Adoption Challenges: Renewable fuel substitution (%); steam generation efficiency (%); specific fuel consumption (kg fuel/tonne steam); renewable energy share (%); CO ₂ emissions reduction; boiler efficiency (%); ash generation; thermal energy intensity.			
Technology Developers & Solution Providers: Global: Babcock & Wilcox, Valmet, ANDRITZ, Sugimat. India: Thermax, ISGEC Heavy Engineering, Cheema Boilers, Balkrishna Boilers, Forbes Marshall, VYNCKE India, AtmosPower.		Key References: Apparel Impact Institute (AII) & Global Efficiency Intelligence – Low-Carbon Thermal Energy Roadmap for the Textile Industry; International Energy Agency (IEA); MNRE National Bioenergy Programme; Bureau of Energy Efficiency (BEE); UNIDO Industrial Decarbonization initiatives.	
Cross Media Effects: Environmental performance depends on sustainable biomass sourcing and effective emissions control. Biomass combustion generates ash requiring appropriate management, while poor-quality fuels can increase particulate emissions. Sustainable sourcing and modern combustion technologies minimise these impacts and maximise lifecycle carbon benefits.			

India Context & Strategic Considerations: India's large agricultural economy provides a significant competitive advantage for renewable industrial process heat through abundant agricultural residues and an expanding biomethane ecosystem. Renewable Bioenergy Process Heat Systems provide a practical transition pathway for textile manufacturers seeking to reduce dependence on coal and furnace oil while maintaining high-temperature steam generation. These systems are particularly relevant for textile clusters with strong access to agricultural residues and complement longer-term electrification pathways such as industrial heat pumps and green hydrogen for deep industrial decarbonization.

F0-22		Industrial Process Heat Electrification Systems	
Transformation Direction Resource-Intelligent Manufacturing		TRL 9	Technology Type Clean Energy Technology
Technology Focus Area Clean Energy & Industrial Decarbonization		Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Industrial Process Heat Electrification Systems replace fossil fuel-based thermal energy with electricity for industrial heating applications. The technology portfolio includes high-temperature industrial heat pumps, steam-generating heat pumps, electric boilers, electric thermal oil heaters, electrode boilers, hybrid electric-steam systems, and waste heat upgrading technologies. These systems utilise renewable electricity and recovered waste heat to generate process steam, hot water, and thermal energy for textile manufacturing with significantly higher energy efficiency than conventional fossil fuel-based heating			
Primary Applications: Process steam generation; hot water generation; thermal oil heating; boiler replacement or hybridisation; wastewater heat recovery; boiler feedwater preheating; low- and medium-temperature textile wet processing.			
Environmental & Resource Benefits: Reduces fossil fuel consumption and direct greenhouse gas emissions while improving thermal efficiency. High-temperature heat pumps can achieve 2–4 times higher energy efficiency than conventional electric resistance heating by upgrading waste heat. When powered by renewable electricity, these systems significantly reduce the carbon footprint of industrial process heat.			
Indicative CAPEX (India context): Industrial heat pumps and electric process heating systems typically range from ₹50 lakh to ₹10 crore, depending on capacity, operating temperature, and integration requirements. Retrofit costs vary according to existing steam infrastructure and process configuration.		OPEX Savings / Payback Period: Operating costs depend on electricity tariffs, renewable electricity availability, and fuel prices. Typical payback period: 3–7 years, with shorter payback where waste heat recovery and low-cost renewable electricity are available.	
Key Performance Indicators (KPIs): Process heat electrification rate (%); Coefficient of Performance (COP); renewable electricity utilisation (%); thermal energy efficiency (%); specific thermal energy consumption; CO ₂ emissions reduction; fossil fuel displacement (%); process temperature stability.		Reference Industries	
Key Adoption Challenges: Process heat electrification rate (%); Coefficient of Performance (COP); renewable electricity utilisation (%); thermal energy efficiency (%); specific thermal energy consumption; CO ₂ emissions reduction; fossil fuel displacement (%); process temperature stability.			
Technology Developers & Solution Providers: Global: GEA, MAN Energy Solutions, Johnson Controls, Siemens Energy, Danfoss, Mayekawa, Mitsubishi Heavy Industries. India: Thermax, Kirloskar Chillers, Blue Star, Voltas, Danfoss India, Trane India.		Key References: Apparel Impact Institute (AII) & Global Efficiency Intelligence – Low-Carbon Thermal Energy Roadmap for the Textile Industry; International Energy Agency (IEA) – The Future of Heat Pumps; UNIDO Industrial Decarbonization initiatives; IRENA Industrial Electrification publications.	
Cross Media Effects: Increased electricity demand may require grid upgrades and renewable electricity integration. Environmental performance depends on the carbon intensity of the electricity supply, with the greatest benefits achieved when coupled with renewable energy generation or low-carbon electricity.			

India Context & Strategic Considerations: Industrial process heat accounts for the largest share of thermal energy demand in textile wet processing. As renewable electricity becomes increasingly available and industrial heat pump technologies mature, electrification offers a long-term pathway for replacing coal and furnace oil in low- and medium-temperature applications. Hybrid configurations combining heat pumps, electric boilers, renewable electricity, and thermal storage are expected to play an increasingly important role in India's industrial decarbonization strategy, particularly in export-oriented textile manufacturing responding to tightening global climate and carbon regulations.

F0-23		Industrial Solar Thermal Systems	
Transformation Direction Resource-Intelligent Manufacturing		TRL 9	Technology Type Clean Energy Technology
Technology Focus Area Clean Energy & Industrial Decarbonization		Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Industrial Solar Thermal Systems capture solar radiation to generate hot water, process heat, steam, or thermal oil for industrial applications. The technology includes flat-plate collectors, evacuated tube collectors, concentrating solar thermal (CST) systems, thermal oil heating systems, and thermal energy storage integrated with conventional boilers or process heating systems. Solar thermal energy can operate as a standalone renewable heat source or in hybrid configurations with biomass, heat pumps, or conventional boilers to improve energy reliability			
Primary Applications: Boiler feedwater preheating; hot water generation; textile washing and dyeing; thermal oil heating; process steam preheating; hybrid renewable thermal systems; thermal energy storage integration.			
Environmental & Resource Benefits: Reduces fossil fuel consumption and greenhouse gas emissions by replacing conventional fuels with renewable solar heat. Improves boiler efficiency through feedwater preheating while reducing operating costs and supporting industrial decarbonization. When integrated with thermal storage, solar thermal systems increase renewable heat utilisation and improve energy resilience.			
Indicative CAPEX (India context): Industrial solar thermal systems typically range from ₹20 lakh to ₹5 crore, depending on collector type, thermal capacity, process temperature, storage requirements, and plant integration.		OPEX Savings / Payback Period: Reduces fossil fuel consumption for hot water and low- to medium-temperature process heating. Typical payback period: 3–7 years, depending on solar resource availability, fuel prices, process heat demand, and utilisation rates.	
Key Performance Indicators (KPIs): Solar thermal energy generated (kWhth/year); solar fraction (%); fossil fuel displacement (%); process heat supplied (GJ/year); CO ₂ emissions reduction; collector efficiency (%); renewable thermal energy share (%); thermal storage utilisation (%).		Reference Industries	
Key Adoption Challenges: Solar thermal energy generated (kWhth/year); solar fraction (%); fossil fuel displacement (%); process heat supplied (GJ/year); CO ₂ emissions reduction; collector efficiency (%); renewable thermal energy share (%); thermal storage utilisation (%).			
Technology Developers & Solution Providers: Global: Absolicon, TVP Solar, Soltigua, Aalborg CSP, Industrial Solar GmbH. India: Megawatt Solutions, SunMaxx Solar, Gadhia Solar, Inter Solar Systems, Bosch Thermotechnology India, Thermax.		Key References: International Renewable Energy Agency (IRENA) – Solar Heat for Industrial Processes; International Energy Agency (IEA) Solar Heating & Cooling Programme; MNRE National Solar Mission; Apparel Impact Institute (AII) & Global Efficiency Intelligence – Low-Carbon Thermal Energy Roadmap for the Textile Industry.	
Cross Media Effects: Minimal cross-media impacts. Installation requires roof or land area and periodic water use for collector cleaning, but significantly reduces fossil fuel consumption and associated greenhouse gas emissions over the system lifecycle.			

India Context & Strategic Considerations: India possesses one of the world's highest solar resources, providing significant opportunities for renewable industrial process heat. Industrial Solar Thermal Systems are particularly suitable for textile wet processing applications requiring hot water and low- to medium-temperature heat, including washing, bleaching, dyeing, and boiler feedwater preheating. Hybrid integration with biomass, industrial heat pumps, thermal energy storage, and conventional boilers can improve reliability while reducing dependence on fossil fuels.

F0-24Green Hydrogen Energy Systems		
Transformation Direction Technology Sovereignty	TRL 6	Technology Type Energy Technology
Technology Focus Area Decarbonization	Roadmap Horizon Accelerate (2035–2047)	India Adoption (2026) Accelerate (2035–2047)
Technology Overview & Working Principle: Industrial green hydrogen systems produce hydrogen through water electrolysis powered by renewable electricity and utilize the hydrogen as a low-carbon energy carrier for industrial thermal applications. The system comprises renewable electricity generation, electrolyzers, hydrogen compression and storage infrastructure, distribution systems, and combustion or process equipment designed for hydrogen utilization. Integration with industrial energy systems enables the substitution of conventional fossil fuels in suitable high-temperature process heating applications.		
Primary Applications: Stenter frame process heating; steam boiler fuel substitution; potential future application in high-temperature dyeing processes requiring thermal energy.		
Environmental & Resource Benefits: Zero carbon dioxide emissions from combustion when produced from renewable electricity, offering a decarbonization pathway for process heat, one of the most difficult textile manufacturing emissions sources to abate through electrification alone.		
Indicative CAPEX (India context): Electrolysis, storage, and delivery infrastructure: Rs 500 to 2,000 lakh at mill level. Burner modification: Rs 5 to 15 lakh per stenter or boiler. [Validated by TMMA General cross-cutting consultation, May 2026]		OPEX Savings / Payback Period: Payback 10 to 15 years at current costs, improving as electrolyser costs fall. Validator identifies San International as a company reportedly planning a hydrogen boiler transition, and cites the Monforts WasserSTOFF programme as the relevant international reference initiative.
Key Performance Indicators (KPIs): Green Hydrogen Purity (%); Nitrogen Oxide Emissions from Combustion (mg/Nm3); Levelized Cost of Hydrogen (Rs per kg).		Reference Industries: No current textile sector application in India; identified as a long-term decarbonization pathway.
Key Adoption Challenges: Green Hydrogen Purity (%); Nitrogen Oxide Emissions from Combustion (mg/Nm3); Levelized Cost of Hydrogen (Rs per kg).		
Technology Developers & Solution Providers: Global: ITM Power, Nel Hydrogen, Siemens Energy. India: Reliance Industries, Adani New Industries, NTPC.		Key References: Ministry of New and Renewable Energy, National Green Hydrogen Mission, Government of India; International Energy Agency, Global Hydrogen Review. Validated by TMMA cross-cutting general technology consultation, May 2026.
Cross Media Effects: Green hydrogen production requires substantial renewable electricity input; combustion at flame temperature can generate nitrogen oxides requiring burner-level control.		
India Context & Strategic Considerations: India's National Green Hydrogen Mission targets 5 million tonnes per year of production capacity by 2030, primarily directed at fertilizer, steel, and refining sectors. Textile sector application remains a long-term, post-2035 consideration rather than a near-term opportunity.		

F0-25	Carbon Accounting & ESG Management Platforms	
Transformation Direction Resource-Intelligent Manufacturing	TRL 8	Technology Type Digital Technology
Technology Focus Area Sustainability Management	Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Carbon accounting and Environmental, Social and Governance (ESG) management platforms collect, consolidate, and analyse environmental and sustainability data from multiple organizational sources. The platforms quantify greenhouse gas emissions across Scope 1, Scope 2, and Scope 3 categories using internationally recognized accounting methodologies while integrating information on energy, water, waste, and other sustainability indicators. Automated reporting functions support regulatory disclosures, customer requirements, and corporate sustainability management.		
Primary Applications: Scope 1, 2, and 3 greenhouse gas emissions calculation and reporting; BRSR Core disclosure preparation; supplier-level emissions data collection for brand reporting; Carbon Border Adjustment Mechanism (CBAM) exposure assessment.		
Environmental & Resource Benefits: Provides the data foundation for identifying highest-impact emissions sources and prioritizing decarbonization investment across energy, transport, and supply chain activities.		
Indicative CAPEX (India context): Rs 10 to 30 lakh per year for platform licensing and data integration for a single facility; larger multi-site groups typically incur Rs 30 lakh to 1 crore per year depending on supply chain complexity. [Indicative estimate only; not independently verified against a published market source.]	OPEX Savings / Payback Period: Primarily a compliance and market-access investment rather than a direct cost-saving measure, though data generated often reveals energy efficiency opportunities with independent payback.	
Key Performance Indicators (KPIs): Scope 1, 2 and 3 Emissions (tonnes CO2 equivalent); Emissions Intensity per Unit of Production; BRSR Core Disclosure Completeness; SBTi Target Alignment Status.	Reference Industries: Large export-oriented mills reporting to brand ESG programmes and preparing for CBAM exposure.	
Key Adoption Challenges: Scope 1, 2 and 3 Emissions (tonnes CO2 equivalent); Emissions Intensity per Unit of Production; BRSR Core Disclosure Completeness; SBTi Target Alignment Status.		
Technology Developers & Solution Providers: Global: Worldly (Higg Index platforms), Carbonfact, Sphera, Persefoni. India: Bureau Veritas India for verification support.	Key References: GHG Protocol Corporate Accounting and Reporting Standard; Securities and Exchange Board of India, Business Responsibility and Sustainability Reporting framework; Science Based Targets initiative, Sectoral Decarbonization Approach.	
Cross Media Effects: No material trade-off from the reporting function itself; underlying data collection requires staff time and system integration.		
India Context & Strategic Considerations: BRSR Core disclosure is mandatory for India's top listed companies and is increasingly cascaded to their supplier base, while EU Carbon Border Adjustment Mechanism exposure makes carbon accounting a near-term market-access requirement for textile exporters.		



F1-01	Near-Infrared (NIR) & Optical Cotton Contamination Detection	
Transformation Direction Natural Fibre Leadership	TRL 9	Technology Type Testing & Quality Technology
Technology Focus Area Fibre Quality	Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Near-infrared (NIR) and optical contamination detection systems automatically identify and remove foreign materials from seed cotton or lint during ginning using high-speed imaging and spectroscopic analysis. Optical cameras detect visible contaminants based on colour, shape, and contrast, while NIR sensors distinguish materials according to their spectral signatures, enabling identification of contaminants that are visually similar to cotton. The system activates high-speed ejectors to remove contaminated material before downstream processing.		
Primary Applications: Cotton ginning line contamination removal; blow room feed preparation for spinning; premium grade cotton segregation for export quality yarn.		
Environmental & Resource Benefits: Prevents contamination introduced at the ginning stage from propagating through spinning, weaving, and dyeing, where it cannot be corrected and results in yarn defects, fabric rejection, and reprocessing waste.		
Indicative CAPEX (India context): Rs 35 to 80 lakh per optical sorting line; Rs 60 to 120 lakh per near-infrared sorting line, depending on throughput capacity. [Indicative estimate only; not independently verified against a published market source.]	OPEX Savings / Payback Period: Reduces yarn rejection and reprocessing costs downstream. Payback period is typically 2 to 4 years based on quality-related cost avoidance.	
Key Performance Indicators (KPIs): Contamination Count per Gram of Lint; Sorting Accuracy (%); Throughput (kg per hour); Downstream Yarn Defect Rate Reduction.	Reference Industries: Punjab and Haryana cotton belt; Vidarbha, Maharashtra; Coimbatore ginning clusters.	
Key Adoption Challenges: Contamination Count per Gram of Lint; Sorting Accuracy (%); Throughput (kg per hour); Downstream Yarn Defect Rate Reduction.		
Technology Developers & Solution Providers: Global: Jossi Systems, Uster Technologies, Sikora. India: Trutzschler India, manufacturing at Sanand, Gujarat.	Key References: International Textile Manufacturers Federation, Cotton Contamination Survey; Textile Commissioner, Government of India, cotton quality reports.	
Cross Media Effects: Minor additional electricity use at the ginning stage; no water or chemical impact.		
India Context & Strategic Considerations: India is the world's largest cotton producer, and contamination introduced at ginning is widely recognized as the primary quality constraint limiting India's access to premium export yarn markets.		

F1-02	Multi-End Automatic Silk Reeling	
Transformation Direction Natural Fibre Leadership	TRL 9	Technology Type Manufacturing Equipment
Technology Focus Area Fibre Quality	Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Multi-end automatic silk reeling machines mechanize the extraction of continuous silk filaments from softened cocoons using synchronized reeling units, automatic thread joining, and controlled winding mechanisms. Process parameters such as cocoon cooking temperature, filament tension, winding speed, and break detection are continuously regulated to maintain uniform yarn formation. Automated stop-motion and monitoring systems improve process control while producing consistent raw silk quality suitable for downstream textile manufacturing.		
Primary Applications: Silk filature and reeling operations converting raw cocoons into reelable raw silk yarn.		
Environmental & Resource Benefits: Improves cocoon-to-silk conversion efficiency, reducing silk waste generated through inconsistent manual reeling. Controlled temperature boiling reduces fuel waste compared with open-fire traditional methods.		
Indicative CAPEX (India context): Rs 8 to 18 lakh per motorized multi-end reeling unit. [Indicative estimate only; not independently verified against a published market source.]	OPEX Savings / Payback Period: Upgrades silk output from 2A commodity grade to 3A premium export grade, improving realized price per kilogram. Relatively low capital cost with rapid payback through quality-linked price improvement.	
Key Performance Indicators (KPIs): Denier Uniformity (Coefficient of Variation %); Raw Silk Grade Achieved (2A to 4A scale); Cocoon Consumption per kg of Reeled Silk; Reeling Efficiency (%).	Reference Industries: Karnataka, including Mysuru and Ramanagara; West Bengal, including Murshidabad; Tamil Nadu silk reeling clusters.	
Key Adoption Challenges: Denier Uniformity (Coefficient of Variation %); Raw Silk Grade Achieved (2A to 4A scale); Cocoon Consumption per kg of Reeled Silk; Reeling Efficiency (%).		
Technology Developers & Solution Providers: Central Silk Technological Research Institute affiliated equipment; Karnataka Silk Industries Corporation supported systems.	Key References: Central Silk Board, Ministry of Textiles, Government of India, silk production statistics; International Sericultural Commission, technical reports.	
Cross Media Effects: Motorized reeling substitutes electricity for the firewood or coal previously used in open-fire cocoon boiling; no water impact change.		
India Context & Strategic Considerations: India is the world's second largest silk producer, and its competitiveness gap relative to China is primarily attributable to reeling-stage processing quality rather than raw cocoon production capacity.		

F1-03	Fibre Identification & IoT Tagging	
Transformation Direction Digital Infrastructure & Traceability	TRL 8	Technology Type Digital Technology
Technology Focus Area Digital Traceability	Roadmap Horizon Amplify (2030–2035)	India Adoption (2026)Amplify (2030–2035)
Technology Overview & Working Principle: Fibre identification and Internet of Things (IoT) tagging systems establish a digital identity for natural fibres and textile products using physical identification technologies such as Quick Response (QR) codes, Radio Frequency Identification (RFID), Near Field Communication (NFC) tags, or embedded material markers. Each identifier is linked to a digital database containing origin, certification, and production information, enabling authenticated product identification throughout the supply chain.		
Primary Applications: Geographical Indication protected handloom textiles, including Kanjivaram silk, Pochampally Ikat, Banarasi brocade, and Chanderi fabric; premium cotton or wool provenance verification.		
Environmental & Resource Benefits: No direct environmental cross-media effect. Indirectly supports the economic sustainability of genuine artisan production by protecting against counterfeit displacement of authentic Geographical Indication products.		
Indicative CAPEX (India context): Rs 5 to 20 lakh per cluster for tagging infrastructure and registry integration. [Indicative estimate only; not independently verified against a published market source.]	OPEX Savings / Payback Period: Payback is realized through counterfeit-loss prevention and premium price protection rather than direct cost saving; not precisely quantifiable from available data.	
Key Performance Indicators (KPIs): Proportion of Geographical Indication Output Digitally Tagged (%); Counterfeit Incidence Rate; Digital Product Passport Field Completeness.	Reference Industries: Kanjivaram, Tamil Nadu; Pochampally, Telangana; Banarasi, Varanasi; Chanderi, Madhya Pradesh.	
Key Adoption Challenges: Proportion of Geographical Indication Output Digitally Tagged (%); Counterfeit Incidence Rate; Digital Product Passport Field Completeness.		
Technology Developers & Solution Providers: National Handloom Development Corporation pilot programmes; FibreTrace; Haelixa.	Key References: Geographical Indications of Goods Registration and Protection Act, Government of India; National Handloom Development Corporation, Ministry of Textiles publications.	
Cross Media Effects: No environmental trade-off; tagging infrastructure has negligible resource footprint.		
India Context & Strategic Considerations: Kanjivaram silk is one of India's most economically significant Geographical Indication products, and legally enforceable, DPP-verifiable provenance would materially strengthen the position of genuine artisan producers against counterfeit competition ahead of 2027 European due diligence requirements.		

F1-04	Digital Fibre Traceability Platform	
Transformation Direction Digital Infrastructure & Traceability	TRL 9	Technology Type Digital Technology
Technology Focus Area Digital Traceability	Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Digital fibre traceability platforms record, manage, and verify the movement of fibres and materials throughout the textile value chain using centralized digital records and chain-of-custody documentation. Information related to sourcing, processing, certification, transportation, and product transformation is securely captured and linked across successive production stages. The platform integrates with enterprise systems and certification databases to provide traceable records from fibre origin to finished product.		
Primary Applications: Chain-of-custody documentation for organic, recycled, or certified fibre; buyer-facing traceability dashboards; supply chain due diligence reporting.		
Environmental & Resource Benefits: Enables verification of sustainable fibre claims, supporting market mechanisms that reward lower-impact fibre production and processing choices.		
Indicative CAPEX (India context): Rs 15 to 40 lakh for platform licensing and integration across a supply chain segment. [Indicative estimate only; not independently verified against a published market source.]	OPEX Savings / Payback Period: Supports premium market access for certified sustainable products rather than direct operational cost savings.	
Key Performance Indicators (KPIs): Supply Chain Node Coverage (%); Data Completeness per Batch; Third-Party Verification Pass Rate.	Reference Industries: Export-oriented spinning and processing mills serving certified organic or recycled fibre supply chains.	
Key Adoption Challenges: Supply Chain Node Coverage (%); Data Completeness per Batch; Third-Party Verification Pass Rate.		
Technology Developers & Solution Providers: Global: TextileGenesis, TrusTrace, Circularise, FibreTrace.	Key References: Textile Exchange, Content Claim Standard documentation; Global Organic Textile Standard, chain of custody requirements.	
Cross Media Effects: No environmental trade-off from the software platform itself.		
India Context & Strategic Considerations: Digital traceability platforms are increasingly required by global brands sourcing certified organic or recycled fibre from India, and will form part of the data infrastructure required for EU Digital Product Passport compliance from 2027.		

F1-05	Mechanical Decortication for Bast, Leaf & Agricultural Residue Fibres	
Transformation Direction Natural Fibre Leadership	TRL 9	Technology Type Manufacturing Equipment
Technology Focus Area Future Fibre Materials	Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Mechanical decortication systems extract bast fibres from agricultural residues such as banana pseudostems, pineapple leaves, hemp, flax, and kenaf using mechanical crushing, scraping, roller separation, or water-assisted extraction processes. The equipment separates fibrous material from the surrounding plant tissue without relying on chemical retting, after which the extracted fibres undergo cleaning, drying, and grading for subsequent textile or technical applications.		
Primary Applications: Geotextiles; technical nonwovens; handicraft-blend yarns; composite reinforcement material.		
Environmental & Resource Benefits: Valorizes agricultural waste that would otherwise be burned or landfilled. Retting-free mechanical extraction avoids the high biochemical oxygen demand effluent associated with water-retting.		
Indicative CAPEX (India context): Rs 5 to 15 lakh per decortication unit. [Indicative estimate only; not independently verified against a published market source.]		OPEX Savings / Payback Period: Payback depends on downstream market development for the extracted fibre; not precisely quantified in available data.
Key Performance Indicators (KPIs): Fibre Extraction Efficiency (%); Fibre Tensile Strength (MPa); Fibre Length Uniformity.		Reference Industries: Tamil Nadu banana belts, including Theni and Dindigul; Kerala; Andhra Pradesh; North-East India for pineapple leaf fibre.
Key Adoption Challenges: Fibre Extraction Efficiency (%); Fibre Tensile Strength (MPa); Fibre Length Uniformity.		
Technology Developers & Solution Providers: ICAR-Central Institute for Research on Cotton Technology, research and equipment development; local fabricators in Coimbatore.		Key References: Indian Council of Agricultural Research, Central Institute for Research on Cotton Technology, technical bulletins; Ministry of Textiles, National Technical Textiles Mission documentation.
Cross Media Effects Retting-free decortication avoids water-retting effluent, but residual pith and fibre sheath require disposal or composting.		
India Context & Strategic Considerations: India generates an estimated 51 million tonnes of banana pseudo-stem residue annually, representing a large untapped domestic fibre resource that mechanical decortication could convert into industrial-grade textile input at meaningful national scale.		

F1-06	Mycelium-Based Leather Materials	
Transformation Direction Innovation & Technology Origination	TRL 6	Technology Type Material Innovation
Technology Focus Area Future Fibre Materials	Roadmap Horizon Accelerate (2035–2047)	India Adoption (2026) Accelerate (2035–2047)
Technology Overview & Working Principle: Mycelium-based leather materials are produced by cultivating fungal mycelium on controlled agricultural biomass substrates under regulated environmental conditions. The interconnected fungal network is harvested, compressed, stabilized, and finished using mechanical and chemical treatments to produce sheet materials with leather-like characteristics. Material properties are controlled through substrate composition, cultivation parameters, and post-processing techniques to meet product-specific performance requirements.		
Primary Applications: Luxury leather alternative applications in bags, footwear, and fashion accessories.		
Environmental & Resource Benefits: Potentially lower lifecycle impact than animal leather when produced from agricultural waste substrate, with no associated animal welfare concerns and biodegradable end-of-life characteristics.		
Indicative CAPEX (India context): Not commercially costed; research and demonstration stage globally with no established production cost benchmarks.		OPEX Savings / Payback Period: Not applicable at current pre-commercial stage.
Key Performance Indicators (KPIs): Tensile Strength Relative to Leather (MPa); Water Resistance; Abrasion Durability Cycles; Production Scalability (square metres per year).		Reference Industries: No current India commercial production; relevant to design research institutions.
Key Adoption Challenges: Tensile Strength Relative to Leather (MPa); Water Resistance; Abrasion Durability Cycles; Production Scalability (square metres per year).		
Technology Developers & Solution Providers: Global: Bolt Threads, Ecovative Design, Modern Meadow. No India commercial producer identified.		Key References: Textile Exchange, Preferred Fiber and Materials Market Report.
Cross Media Effects: Substrate drying and processing require energy input not present in disposal of the underlying agricultural waste.		
India Context & Strategic ConsiderationsGlobal competitors hold significant first-mover advantage in mycelium materials, while India's substantial agricultural residue base, including rice straw and bagasse, remains largely untapped as a substrate resource. Commercial relevance is expected beyond 2035.		

F1-07	Bio-based PLA & Emerging Bio-fibre Production	
Transformation Direction Innovation & Technology Origination	TRL 6	Technology Type Material Innovation
Technology Focus Area Future Fibre Materials	Roadmap Horizon Accelerate (2035–2047)	India Adoption (2026) Accelerate (2035–2047)
Technology Overview & Working Principle: Bio-based Polylactic Acid (PLA) fibre is manufactured by fermenting plant-derived carbohydrates into lactic acid, followed by polymerization and melt spinning into continuous filaments. Emerging bio-based fibre systems extend this approach to alternative renewable feedstocks, including agricultural residues, bio-based polymers, and naturally derived cellulose sources. Fibre production follows conventional polymer processing routes while utilizing renewable raw materials as the primary feedstock.		
Primary Applications: Compostable hygiene nonwovens; limited apparel blend applications; packaging fibre; technical textile research.		
Environmental & Resource Benefits: Bio-based feedstock reduces dependence on petrochemical raw material. Industrially compostable under controlled conditions, though India currently lacks widespread industrial composting infrastructure to realize this benefit at end of life.		
Indicative CAPEX (India context): No established India commercial production; import cost applies for PLA fibre currently. [Indicative estimate only; not independently verified against a published market source.]		OPEX Savings / Payback Period: Not applicable at current pre-commercial stage in India.
Key Performance Indicators (KPIs): Bio-Based Carbon Content (%); Composting Rate Under Industrial Conditions; Thermal Stability Relative to Conventional Synthetics.		Reference Industries: No current India commercial production.
Key Adoption Challenges: Bio-Based Carbon Content (%); Composting Rate Under Industrial Conditions; Thermal Stability Relative to Conventional Synthetics.		
Technology Developers & Solution Providers: Global: NatureWorks (Ingeo brand), TotalEnergies Corbion, Arkema (castor oil-derived polyamide). No India commercial producer identified.		Key References: Textile Exchange, Preferred Fiber and Materials Market Report; Ministry of Textiles, National Technical Textiles Mission documentation.
Cross Media Effects: Realizing the compostability benefit depends on availability of industrial composting infrastructure at end of life, which is largely absent in India.		
India Context & Strategic Considerations: India's sugarcane and citrus processing sectors, and its position as a leading global castor oil producer, represent underutilized structural feedstock advantages for next-generation bio-based fibre production, positioning this as a strategic research and development priority for the 2035 to 2047 horizon.		

F2

FIBRE
TECHNOLOGIES

F2-01	Compact Ring Spinning with Intelligent Monitoring	
Transformation Direction Manufacturing Capability at Scale	TRL 9	Technology Type Manufacturing Equipment
Technology Focus Area Spinning Technologies	Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Compact ring spinning incorporates a fibre condensing system between the drafting unit and the ring-spinning zone to minimize the spinning triangle formed during yarn formation. Pneumatic or mechanical condensing aligns fibres before twist insertion, resulting in improved fibre integration within the yarn structure. Modern compact spinning frames incorporate electronic spindle monitoring, automated process control, and digital performance monitoring to maintain consistent yarn production under varying operating conditions.		
Primary Applications: Fine count combed cotton yarn production for shirting, fine knitwear, and sewing thread.		
Environmental & Resource Benefits: Reduces fibre waste in the blow room and reduces yarn breakage-related reprocessing compared with conventional ring spinning, lowering the associated energy and material waste.		
Indicative CAPEX (India context): Retrofit kit: Rs 27 to 30 lakh per 1,824-spindle frame (Rs 15 to 18 lakh per 1,008-spindle equivalent). New compact ring frame: Rs 120 to 125 lakh per 1,824-spindle frame (Rs 88 to 93 lakh per 1,008-spindle equivalent). [Validated by Truetzschler India Pvt Ltd via TMMMA, May 2026]		OPEX Savings / Payback Period: Improved productivity of 10 to 15 percent, improved yarn strength, improved fabric durability, reduced yarn hairiness, reduced yarn breaks up to 2 percent, and better working environment. Payback 3 to 5 years from price premium and quality improvement. Validator confirms viability extends to domestic markets, not export-only, due to production and quality improvements.
Key Performance Indicators (KPIs): Ends-Down per 1,000 Spindle Hours; Yarn Count Strength Product; Uster Hairiness Index; Individual Spindle Monitoring Coverage (%).		Reference Industries: Coimbatore; Ludhiana; Ahmedabad; Bhilwara spinning mills.
Key Adoption Challenges: Ends-Down per 1,000 Spindle Hours; Yarn Count Strength Product; Uster Hairiness Index; Individual Spindle Monitoring Coverage (%).		
Technology Developers & Solution Providers: Global: Rieter, Marzoli, Toyota Industries. India: Lakshmi Machine Works, holding a leading share of the domestic ring spinning market.		Key References: International Textile Manufacturers Federation, Annual Report; Ministry of Textiles, Government of India, Technology Upgradation Fund Scheme documentation. Validated by Truetzschler India Pvt Ltd, TMMMA industry consultation, May 2026.
Cross Media Effects: No water use; reduced fly fibre generation improves workplace air quality but electricity demand is comparable to conventional ring spinning.		
India Context & Strategic Considerations: Lakshmi Machine Works is India's principal domestic manufacturer of ring spinning frames, competing directly with Swiss and Italian machinery on quality, supported by the Amended Technology Upgradation Fund Scheme for mill modernization.		

F2-02	Open-End Rotor Spinning	
Transformation Direction Manufacturing Capability at Scale	TRL 9	Technology Type Manufacturing Equipment
Technology Focus Area Spinning Technologies	Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Open-end rotor spinning produces yarn directly from drawn sliver without the intermediate roving process. Individual fibres are separated, transported by airflow into a high-speed rotating rotor, and consolidated into yarn through centrifugal forces and controlled twist insertion. Rotor speed, opening roller performance, and yarn withdrawal are electronically controlled to maintain consistent yarn formation. The technology provides a continuous spinning process suitable for a wide range of natural, regenerated, and recycled fibres.		
Primary Applications: Denim yarn; terry towel yarn; industrial yarn; yarn spun from recycled cotton fibre.		
Environmental & Resource Benefits: Compatible with recycled and lower-quality fibre inputs, supporting circular fibre processing pathways. Lower energy consumption per kilogram than ring spinning at coarse counts.		
Indicative CAPEX (India context): Rs 500 to 1,200 lakh per rotor spinning unit (Autocoro-type, 480 rotors). [Validated by Truetzschler India Pvt Ltd via TMMMA, May 2026 — noted as outside LMW's supply scope by second validator]	OPEX Savings / Payback Period: Approximately 60 percent lower labour requirement compared with ring spinning for equivalent output. Payback period: 4 to 6 years.	
Key Performance Indicators (KPIs): Rotor Speed (revolutions per minute); Yarn Coefficient of Variation (%); Ends-Down Rate; Production Speed.	Reference Industries: Ahmedabad denim cluster; Bhilwara; Kolhapur towel manufacturing.	
Key Adoption Challenges: Rotor Speed (revolutions per minute); Yarn Coefficient of Variation (%); Ends-Down Rate; Production Speed.		
Technology Developers & Solution Providers: Global: Saurer (Autocoro), Rieter (R70), Jingwei. India: Lakshmi Machine Works, supplying accessories.	Key References: International Textile Manufacturers Federation, Annual Report; Textile Exchange, Preferred Fiber and Materials Market Report. Validated by Truetzschler India Pvt Ltd, TMMMA industry consultation, May 2026.	
Cross Media Effects: No water use; rotor operation at high speed carries a higher per-machine noise and bearing wear profile than ring spinning.		
India Context & Strategic Considerations: Rotor spinning penetration in India remains lower than in leading textile economies despite strong alignment with the growing man-made fibre and recycled fibre processing trends the sector is moving toward.		

F2-03		Automatic Cone Winding	
Transformation Direction Manufacturing Capability at Scale		TRL 9	Technology Type Manufacturing Equipment
Technology Focus Area Spinning Technologies		Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Automatic cone winding systems transfer yarn from spinning bobbins onto larger packages suitable for downstream weaving, knitting, or dyeing operations. Electronic yarn clearers continuously monitor yarn quality and automatically remove faults before precision splicing reconnects the yarn. Automated package handling, doffing, tension control, and winding parameter management ensure uniform package formation while maintaining consistent yarn quality throughout the winding process.			
Primary Applications: Yarn winding for weaving and knitting package preparation across all fibre types.			
Environmental & Resource Benefits: Electronic yarn clearing reduces downstream fabric defects arising from yarn faults, lowering the material waste associated with defective fabric production.			
Indicative CAPEX (India context): Saurer Autoconer X6: Rs 80 to 150 lakh per unit. Murata 21C: Rs 70 to 120 lakh per unit. LMW LW60 (India-made alternative): Rs 2.5 to 3.0 lakh per drum. Yarn clearer system (Uster Quantum): Rs 2 to 5 lakh per Autoconer; full Uster quality data system Rs 15 to 30 lakh. [Validated by Truetzschler India Pvt Ltd and a second TMMMA member via TMMMA, May 2026]		OPEX Savings / Payback Period: Improved productivity and consistent yarn quality; reduced manpower up to 75 percent for link winder operations. Payback 3 to 5 years from quality improvement and downstream defect reduction. India is currently 100 percent import-dependent for high-end autoconers, though LMW has launched the LW60 automatic winder as a domestic alternative competing directly with imported European machinery.	
Key Performance Indicators (KPIs): Splice Quality Relative to Ring Yarn Strength; Yarn Clearer Cut Rate per Kilometre; Package Weight Consistency.		Reference Industries: LMW (LW60, India-made alternative — direct competitor to imported machines); Saurer and Murata installations in organised export mills	
Key Adoption Challenges: Splice Quality Relative to Ring Yarn Strength; Yarn Clearer Cut Rate per Kilometre; Package Weight Consistency.			
Technology Developers & Solution Providers: Global: Saurer (Autoconer), Savio, Murata. India: Savio operates a joint venture manufacturing presence.		Key References: International Textile Manufacturers Federation, Annual Report. Validated by Truetzschler India Pvt Ltd and a second TMMMA member, TMMMA industry consultation, May 2026.	
Cross Media Effects: No water use; negligible trade-off.			
India Context & Strategic Considerations: Automatic cone winding with electronic yarn clearing is increasingly standard in export-oriented spinning mills, reflecting buyer quality requirements for defect-free yarn packages.			

F2-04	Draw-Texturing (DTY/POY)	
Transformation Direction Manufacturing Capability at Scale	TRL 9	Technology Type Manufacturing Equipment
Technology Focus Area Spinning Technologies	Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Draw-texturing systems convert Partially Oriented Yarn (POY) into Drawn Textured Yarn (DTY) by combining controlled drawing, false-twist texturing, heat setting, and winding within a continuous production line. The process modifies filament orientation and introduces permanent crimp and bulk through thermal and mechanical deformation. Electronic process controls regulate yarn tension, temperature, draw ratio, and spindle speed to achieve consistent yarn characteristics.		
Primary Applications: Polyester DTY for woven and knitted fabric; nylon DTY for hosiery and stretch fabric applications.		
Environmental & Resource Benefits: Single-stage transformation from POY to finished textured yarn eliminates intermediate processing steps and associated energy use compared with multi-stage alternatives.		
Indicative CAPEX (India context): Rs 80 to 200 lakh per machine of 240 position capacity. [Indicative estimate only; not independently verified against a published market source.]		OPEX Savings / Payback Period: High productivity per machine supports rapid capital recovery. Payback period: 4 to 7 years.
Key Performance Indicators (KPIs): Production Speed (metres per minute); Yarn Elongation (%); Crimp Contraction (%); Shrinkage.		Reference Industries: Surat DTY cluster, Gujarat; Silvassa; Bhilwara synthetic yarn sector.
Key Adoption Challenges: Production Speed (metres per minute); Yarn Elongation (%); Crimp Contraction (%); Shrinkage.		
Technology Developers & Solution Providers: Global: Oerlikon Barmag, Murata, SSM. India: Surbhi Engineering, Surat, manufacturing texturing accessories.		Key References: International Textile Manufacturers Federation, Annual Report.
Cross Media Effects: Finish oil applied to yarn during texturing requires management as a minor effluent stream in downstream processing.		
India Context & Strategic Considerations: Surat is India's largest draw-texturing cluster, processing a substantial share of the country's polyester filament yarn production.		

F2-05		Automated Spinning Preparation	
Transformation Direction Manufacturing Capability at Scale		TRL 8	Technology Type Manufacturing Equipment
Technology Focus Area Spinning Technologies		Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Automated spinning preparation systems integrate bale opening, fibre blending, cleaning, carding, draw frame operations, auto-levelling, and material transport into a coordinated production sequence. Automated handling systems transfer material between successive preparation stages while electronic process controls continuously regulate sliver quality, fibre blending, and machine operating parameters. The integrated system establishes consistent feed material for downstream spinning operations.			
Primary Applications: Blow room bale management and contamination control; carding with automatic sliver levelling; automated can transport between preparation stages.			
Environmental & Resource Benefits: Reduces sliver damage and contamination from manual handling, lowering downstream yarn defect rates and associated reprocessing waste. Dust extraction integrated into blow room automation improves workplace air quality.			
Indicative CAPEX (India context): AGV-based automated sliver can transport (T-CAN) system: Rs 150 to 400 lakh per spinning preparation line. [Validated by Truetzschler India Pvt Ltd via TMMA, May 2026]		OPEX Savings / Payback Period: Payback 5 to 7 years from labour savings and quality improvement. Validator notes the technology is 'yet to be commercialised' at the time of validation, with trials presently taking place offshore.	
Key Performance Indicators (KPIs): Sliver Coefficient of Variation (%); Contamination Incidents; Labour Hours per Tonne Processed; Dust Levels (mg per cubic metre).		Reference Industries: Large integrated spinning mills across Coimbatore, Ludhiana, and Gujarat.	
Key Adoption Challenges: Sliver Coefficient of Variation (%); Contamination Incidents; Labour Hours per Tonne Processed; Dust Levels (mg per cubic metre).			
Technology Developers & Solution Providers: Global: Trutzschler, Rieter, Marzoli. India: Lakshmi Machine Works.		Key References: International Textile Manufacturers Federation, Annual Report. Validated by Truetzschler India Pvt Ltd, TMMA industry consultation, May 2026.	
Cross Media Effects: No water or chemical trade-off; dust extraction systems consume modest additional electricity.			
India Context & Strategic Considerations: Automated spinning preparation is increasingly standard in new and modernized mills, while a large legacy base of manually operated preparation equipment remains in the wider MSME spinning sector.			

F2-06	Air-Jet & Vortex Spinning	
Transformation Direction Manufacturing Capability at Scale	TRL 9	Technology Type Manufacturing Equipment
Technology Focus Area Spinning Technologies	Roadmap Horizon Amplify (2030–2035)	India Adoption (2026)Amplify (2030–2035)
Technology Overview & Working Principle: Air-jet and vortex spinning technologies produce yarn by using high-velocity air streams to wrap outer fibres around a parallel fibre core without employing conventional ring-and-traveller twisting mechanisms. Drafted fibres are transported through specially designed air nozzles that generate controlled vortex flow, forming fasciated yarn structures. Electronic control systems regulate airflow, drafting conditions, and yarn formation parameters to ensure stable production across different fibre types and yarn counts.		
Primary Applications: Polyester-cotton blended yarn for shirting, T-shirt fabric, and workwear.		
Environmental & Resource Benefits: Eliminates the roving stage, reducing floor space and material handling per kilogram of yarn produced. Lower fly fibre generation compared with ring spinning.		
Indicative CAPEX (India context): Rs 800 to 1,800 lakh per Murata Vortex Spinning (MVS) machine, 860 spindles. [Validated by Truetzschler India Pvt Ltd via TMMA, May 2026 — noted as outside LMW’s supply scope by second validator]	OPEX Savings / Payback Period: Payback 4 to 7 years. Validator confirms very high capital cost, limited suitable yarn count range for the Indian market since coarser counts are not technically feasible on this technology, and limited domestic service support as key constraints.	
Key Performance Indicators (KPIs): Production Speed (metres per minute); Yarn Coefficient of Variation (%); Imperfections per Kilometre.	Reference Industries: Tirupur; Surat polyester-cotton blend yarn producers; Coimbatore blended yarn exporters.	
Key Adoption Challenges: Production Speed (metres per minute); Yarn Coefficient of Variation (%); Imperfections per Kilometre.		
Technology Developers & Solution Providers: Global: Murata Machinery (Vortex Spinning System), Rieter (J70). India: domestic manufacturing capability in development.	Key References: International Textile Manufacturers Federation, Annual Report. Validated by Truetzschler India Pvt Ltd, TMMA industry consultation, May 2026.	
Cross Media Effects: No water use; capital-intensive equipment carries an embodied manufacturing footprint amortized over a long operating life.		
India Context & Strategic Considerations: Air-jet spinning's productivity advantage is well suited to India's growing polyester-cotton blend export segment, making the current gap between demonstrated global performance and Indian adoption a significant untapped competitiveness opportunity.		

F2-07	Draw Frame Auto-Levelling	
Transformation Direction Manufacturing Capability at Scale	TRL 9	Technology Type Manufacturing Equipment
Technology Focus Area Spinning Technologies	Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Draw frame auto-levelling systems continuously measure sliver mass variation and automatically adjust drafting parameters to maintain uniform linear density. Sensors positioned before and after the drafting zone monitor incoming and outgoing sliver characteristics, while servo-controlled drafting mechanisms compensate for short-term and long-term mass irregularities. Closed-loop control systems provide consistent sliver quality for subsequent spinning operations.		
Primary Applications: Sliver preparation feeding ring, compact, rotor, and air-jet spinning processes.		
Environmental & Resource Benefits: Improved sliver uniformity reduces downstream yarn defects and associated fabric-stage reprocessing and waste.		
Indicative CAPEX (India context): Card with auto-leveller: Rs 34 to 63 lakh (auto-levelling component alone: Rs 2 to 5 lakh). Draw frame with auto-leveller: Rs 24 to 26 lakh (auto-levelling component alone: Rs 10 to 12 lakh). [Validated by Truetzschler India Pvt Ltd via TMMA, May 2026]	OPEX Savings / Payback Period: Improves yarn quality consistency, reducing downstream defect-related costs. Payback period: 3 to 5 years.	
Key Performance Indicators (KPIs): Sliver Coefficient of Variation (%); Autoleveller Response Speed; Draft Ratio Range.	Reference Industries: Truetzschler India Pvt Ltd (validator); adoption confirmed as standard across reputed Indian spinning mills	
Key Adoption Challenges: Sliver Coefficient of Variation (%); Autoleveller Response Speed; Draft Ratio Range.		
Technology Developers & Solution Providers: Global: Trutzschler, Rieter. India: Lakshmi Machine Works.	Key References: International Textile Manufacturers Federation, Annual Report. Validated by Truetzschler India Pvt Ltd, TMMA industry consultation, May 2026.	
Cross Media Effects: No material trade-off; negligible additional electricity for servo control electronics.		
India Context & Strategic Considerations: Electronic auto-levelling is increasingly the default specification in new spinning preparation lines, reflecting buyer requirements for consistent yarn quality in export markets.		

F2-08	High-Speed Combing	
Transformation Direction Manufacturing Capability at Scale	TRL 9	Technology Type Manufacturing Equipment
Technology Focus Area Spinning Technologies	Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: High-speed combing systems remove short fibres, neps, seed coat fragments, and remaining impurities from carded sliver to produce high-quality combed sliver for fine yarn manufacturing. The process combines lap feeding, fibre combing, detaching, and sliver formation within a synchronized mechanical sequence. Modern combers incorporate automated lap handling, electronic timing control, and process monitoring to maintain consistent fibre preparation at high production speeds.		
Primary Applications: Fine count combed cotton yarn for shirting, fine knitwear, and premium export yarn.		
Environmental & Resource Benefits: Removed noil fibre is a recyclable input for open-end spinning, supporting circular fibre utilization rather than pure waste generation.		
Indicative CAPEX (India context): Rs 35 to 65 lakh per combing machine. [Indicative estimate only; not independently verified against a published market source.]	OPEX Savings / Payback Period: Enables production of premium combed yarn commanding higher market prices. Payback period: 5 to 8 years.	
Key Performance Indicators (KPIs): Noil Percentage Removed (typically 12 to 18%); Comber Speed (nips per minute); Sliver Uniformity.	Reference Industries: Coimbatore and Erode fine-count spinning mills; Ludhiana.	
Key Adoption Challenges: Noil Percentage Removed (typically 12 to 18%); Comber Speed (nips per minute); Sliver Uniformity.		
Technology Developers & Solution Providers: Global: Rieter (E80), Trutzschler (TCO21). India: Lakshmi Machine Works (LK69).	Key References: International Textile Manufacturers Federation, Annual Report.	
Cross Media Effects: No water use in the combing process itself; noil fibre stream requires a downstream use pathway to avoid becoming waste.		
India Context & Strategic Considerations: India is notable for having a domestic combing machine manufacturer, Lakshmi Machine Works, competing directly with Swiss machinery quality, an important import substitution capability for the fine-count spinning segment.		

F2-09	Two-for-One Twisting	
Transformation Direction Manufacturing Capability at Scale	TRL 9	Technology Type Manufacturing Equipment
Technology Focus Area Spinning Technologies	Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Two-for-One twisting systems produce twisted yarn by inserting two turns of twist during each spindle revolution through a rotating balloon and stationary package arrangement. The process combines twisting and package formation within a single operation, eliminating intermediate rewinding stages. Electronic spindle drives, tension control systems, and yarn monitoring devices ensure uniform twist insertion and package quality across multiple production positions.		
Primary Applications: Sewing thread; plied yarn; industrial yarn; fancy and effect yarn production.		
Environmental & Resource Benefits: Higher twisting efficiency reduces energy consumption per kilogram of twisted yarn compared with conventional ring twisting.		
Indicative CAPEX (India context): Rs 15 to 40 lakh per machine of 120 spindle capacity. [Indicative estimate only; not independently verified against a published market source.]	OPEX Savings / Payback Period: Approximately double the productivity of ring twisting for equivalent twist insertion. Payback period: 3 to 6 years.	
Key Performance Indicators (KPIs): Twists per Metre; Package Weight; Production Speed (metres per minute).	Reference Industries: Coimbatore sewing thread manufacturing; Surat; Ahmedabad.	
Key Adoption Challenges: Twists per Metre; Package Weight; Production Speed (metres per minute).		
Technology Developers & Solution Providers: Global: Savio, Volkmann (Saurer group). India: Surbhi Engineering, Surat.	Key References: International Textile Manufacturers Federation, Annual Report.	
Cross Media Effect: sNo water use; negligible trade-off relative to conventional ring twisting.		
India Context & Strategic Considerations Surbhi Engineering in Surat is a confirmed Indian manufacturer of two-for-one twisting equipment, representing a domestic manufacturing capability in this segment.		

F2-10	Advanced Engineered Fibre Production	
Transformation Direction Innovation & Technology Origination	TRL 6	Technology Type Process Technology
Technology Focus Area Spinning Technologies	Roadmap Horizon Accelerate (2035–2047)	India Adoption (2026) Accelerate (2035–2047)
Technology Overview & Working Principle: Advanced engineered fibre production systems manufacture high-performance synthetic fibres with specialized mechanical, thermal, chemical, or protective properties through controlled polymer preparation and solution or melt spinning processes. Fibre formation is followed by drawing, heat treatment, surface modification, and winding operations to achieve specified material characteristics. Production systems incorporate precise control of polymer chemistry, spinning conditions, and post-processing parameters to meet demanding technical performance requirements.		
Primary Applications: Ballistic protective clothing; aerospace and defence composite reinforcement; cut-resistant workwear; fire-resistant technical textiles.		
Environmental & Resource Benefits: No specific environmental benefit data identified for this fibre category in available literature.		
Indicative CAPEX (India context): Very high; no India domestic production cost data available given the absence of domestic manufacturing capability. [Indicative estimate only; not independently verified against a published market source.]	OPEX Savings / Payback Period: Not applicable; India currently imports these fibres rather than producing them domestically.	
Key Performance Indicators (KPIs): Tensile Strength (gigapascals); Modulus (gigapascals); Thermal Stability (degrees Celsius); Ballistic Performance Rating.	Reference Industries: Defence and aerospace technical textile converters in India, using imported fibre for downstream fabric and composite production.	
Key Adoption Challenges: Tensile Strength (gigapascals); Modulus (gigapascals); Thermal Stability (degrees Celsius); Ballistic Performance Rating.		
Technology Developers & Solution Providers: Global: DuPont (Kevlar), Teijin (Twaron), DSM and Avient (Dyneema), Toyobo (Zylon). No India domestic producer identified.	Key References: Ministry of Textiles, National Technical Textiles Mission documentation, Government of India.	
Cross Media Effects: No cross-media data identified in available literature for this fibre category.		
India Context & Strategic Considerations: This represents a strategic import-substitution gap rather than a near-term deployment priority. The National Technical Textiles Mission identifies defence and aerospace fibre applications as long-term capability-building priorities extending to 2047.		

F2-11		Certified Recycled Polyester Processing	
Transformation Direction Resource-Intelligent Manufacturing		TRL 9	Technology Type Process Technology
Technology Focus Area Circular Fibre Systems		Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Certified recycled polyester processing converts post-consumer or post-industrial polyethylene terephthalate (PET) waste into recycled polymer feedstock through sorting, cleaning, shredding, melting, filtration, and pelletization. The recycled polymer is subsequently melt-spun into staple fibre or filament yarn using conventional polyester spinning equipment. Material traceability and recycled content are maintained through certified chain-of-custody systems in accordance with recognized recycled material standards.			
Primary Applications: Sportswear and activewear fabric; outerwear; bag fabric; fleece fabric.			
Environmental & Resource Benefits: Recycled polyester production requires substantially lower energy than virgin polyester production and diverts plastic bottle waste from landfill. Textile Exchange data indicates recycled polyester represented approximately 14 percent of global polyester fibre market share in 2022, sourced overwhelmingly from bottle feedstock rather than textile-to-textile recycling.			
Indicative CAPEX (India context): Rs 20 to 50 lakh per bottle-to-flake recycling line. [Indicative estimate only; not independently verified against a published market source.]		OPEX Savings / Payback Period: Recycled polyester fibre typically commands a 10 to 20 percent price premium over virgin polyester, recoverable through Global Recycled Standard certification.	
Key Performance Indicators (KPIs): Recycled Content (%); Global Recycled Standard Certification Status; Energy Consumption per kg Relative to Virgin Polyester; Contamination Rate in Recycled Stream.		Reference Industries: Surat synthetic fabric cluster; Silvassa; Panipat post-consumer polyester recycling.	
Key Adoption Challenges: Recycled Content (%); Global Recycled Standard Certification Status; Energy Consumption per kg Relative to Virgin Polyester; Contamination Rate in Recycled Stream.			
Technology Developers & Solution Providers: Global: Indorama Ventures. India: Reliance Industries, Polygenta Technologies.		Key References: Textile Exchange, Preferred Fiber and Materials Market Report; Global Recycled Standard, certification requirements.	
Cross Media Effects: Mechanical recycling energy input is required; contaminant removal from mixed bottle feedstock generates a residual reject stream.			
India Context & Strategic Considerations: India recycles a substantial volume of PET bottles annually, though the majority is directed to non-textile applications. Textile-grade recycled polyester capacity is growing but remains a minority share of total PET recycling.			

F2-12	Recycled Cotton Processing	
Transformation Direction Resource-Intelligent Manufacturing	TRL 8	Technology Type Process Technology
Technology Focus Area Circular Fibre Systems	Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Recycled cotton processing mechanically converts pre-consumer and post-consumer cotton textile waste into reusable fibre through sorting, cutting, opening, garneting, blending, and cleaning operations. The recovered fibres are prepared for subsequent spinning or nonwoven manufacturing, with process parameters adjusted according to fibre quality and intended end use. Integrated dust extraction and fibre handling systems maintain process stability and material consistency throughout recycling operations.		
Primary Applications: Recycled yarn in the English count 4 to 16 range; shoddy blankets; industrial wiping cloths; nonwoven material.		
Environmental & Resource Benefits: Diverts textile waste from landfill and avoids the water and pesticide footprint associated with virgin cotton cultivation. Mechanical processing is a dry process requiring no water.		
Indicative CAPEX (India context): Rs 40 to 100 lakh per garneting and opening line. [Indicative estimate only; not independently verified against a published market source.]	OPEX Savings / Payback Period: Payback depends on recycled fibre market pricing relative to virgin cotton; typically 3 to 6 years.	
Key Performance Indicators (KPIs): Fibre Recovery Rate (%); Average Fibre Length After Opening; Achievable Open-End Spinning Count; Dust Content.	Reference Industries: Panipat, Haryana, recognized as a global centre for textile recycling; Bhilwara and Tirupur cutting waste collection.	
Key Adoption Challenges: Fibre Recovery Rate (%); Average Fibre Length After Opening; Achievable Open-End Spinning Count; Dust Content.		
Technology Developers & Solution Providers: Global: Laroche, Bonino. India: Bikon, Coimbatore.	Key References: Textile Exchange, Preferred Fiber and Materials Market Report.	
Cross Media Effects: Garneting requires electricity; process generates airborne fibre dust requiring extraction and filtration.		
India Context & Strategic Considerations: Panipat processes a very large volume of recycled textile material annually, making India one of the world's leading centres for mechanical textile recycling, alongside Prato in Italy.		

F2-13	Certified Organic Cotton Processing	
Transformation Direction Natural Fibre Leadership	TRL 9	Technology Type Process Technology
Technology Focus Area Circular Fibre Systems	Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Certified organic cotton processing maintains physical segregation and documented chain-of-custody throughout fibre handling, spinning, weaving, dyeing, and garment manufacturing. Dedicated storage, controlled material movement, transaction certificates, and production records preserve product identity from certified fibre through finished goods. Digital traceability and certification management systems support compliance with recognized organic textile standards.		
Primary Applications: Organic cotton spinning, weaving, and wet processing serving certified supply chains for premium and sustainable apparel brands.		
Environmental & Resource Benefits: Certification protects the integrity of upstream organic farming practices, which avoid synthetic pesticide and fertilizer use, through the processing stages of the supply chain.		
Indicative CAPEX (India context): Rs 5 to 15 lakh for segregated processing line setup and certification audit costs. [Indicative estimate only; not independently verified against a published market source.]	OPEX Savings / Payback Period: Premium pricing for certified organic fabric is generally recoverable against the certification and segregation cost, though not precisely quantified in available data.	
Key Performance Indicators (KPIs): Chain-of-Custody Integrity (Transaction Certificate Audit Trail); Certification Renewal Status; Segregation Compliance Audit Score.	Reference Industries: Vidarbha, Maharashtra, organic cotton spinning; Gujarat certified processing units.	
Key Adoption Challenges: Chain-of-Custody Integrity (Transaction Certificate Audit Trail); Certification Renewal Status; Segregation Compliance Audit Score.		
Technology Developers & Solution Providers: Control Union, Ecocert, providing India-based organic certification services.	Key References: Global Organic Textile Standard, version 7.0; Organic Content Standard, Textile Exchange.	
Cross Media Effects: No processing-stage trade-off; dedicated segregated equipment or batch scheduling adds operational complexity rather than resource burden.		
India Context & Strategic Considerations: Sustainable cotton production reached approximately 27 percent of global cotton output in 2021 to 2022, while India's certified organic cotton share remains below 6 percent, positioning certified organic processing capacity as an increasingly important market access requirement.		

F2-14	Mechanical Fibre Garneting	
Transformation Direction Resource-Intelligent Manufacturing	TRL 9	Technology Type Process Technology
Technology Focus Area Circular Fibre Systems	Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Mechanical fibre garneting systems recover reusable fibres from textile waste using a sequence of opening, tearing, cleaning, blending, and individualization processes performed by rotating pinned or toothed cylinders. The equipment separates compacted textile waste into spinnable fibre while removing impurities and foreign materials. Process settings are adjusted according to fibre composition, waste characteristics, and target fibre quality for downstream processing.		
Primary Applications: Feedstock preparation for recycled cotton and recycled wool spinning; nonwoven fibre preparation.		
Environmental & Resource Benefits: Enables mechanical recycling of textile waste without water or chemical input, avoiding the environmental footprint of virgin fibre production for the recycled portion of output.		
Indicative CAPEX (India context): Rs 30 to 90 lakh per garneting line, depending on capacity and feedstock type. [Indicative estimate only; not independently verified against a published market source.]	OPEX Savings / Payback Period: Payback depends on feedstock cost and recycled fibre market pricing; typically 3 to 6 years.	
Key Performance Indicators (KPIs): Fibre Recovery Rate (%); Throughput (kg per hour); Fibre Length Distribution After Processing.	Reference Industries: Panipat, Haryana, for both cotton and wool garneting.	
Key Adoption Challenges: Fibre Recovery Rate (%); Throughput (kg per hour); Fibre Length Distribution After Processing.		
Technology Developers & Solution Providers: Global: Laroche (Airfeed system), Dell'Orco and Villani. India: local Panipat-based fabricators.	Key References: Textile Exchange, Preferred Fiber and Materials Market Report.	
Cross Media Effects: Garneting requires electricity and generates airborne fibre dust requiring extraction.		
India Context & Strategic Considerations: Garneting equipment underpins Panipat's established position as a global recycling hub for both cotton and wool textile waste.		

F2-15	Regenerated Cellulosic Fibre Processing (Lyocell & Bamboo)	
Transformation Direction Natural Fibre Leadership	TRL 8	Technology Type Process Technology
Technology Focus Area Circular Fibre Systems	Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Regenerated cellulosic fibre production converts purified cellulose into textile fibres through dissolution, fibre formation, regeneration, washing, and drying processes. Depending on the production route, cellulose is dissolved using solvent-based or chemical processes before being extruded through spinnerets to form continuous filaments. Controlled regeneration and post-treatment determine the physical characteristics of the final fibre prior to cutting or winding.		
Primary Applications: Luxury and sustainable apparel; sportswear; intimate wear; knitwear blended with cotton.		
Environmental & Resource Benefits: Closed-loop lyocell solvent spinning achieves near-zero solvent discharge and requires substantially less water than cotton cultivation. Bamboo viscose processed through conventional chemistry carries the same carbon disulphide and sodium hydroxide effluent profile as standard viscose and should not be assumed inherently lower-impact without verification of the specific production route.		
Indicative CAPEX (India context): No established India domestic lyocell production; Aditya Birla produces modal, a related regenerated cellulosic fibre, at its Kharach facility in Gujarat. [Indicative estimate only; not independently verified against a published market source.]	OPEX Savings / Payback Period: Not applicable for lyocell given import dependency; modal production economics are established within Aditya Birla's existing operations.	
Key Performance Indicators (KPIs): Solvent Recovery Rate (%) for lyocell; Water Consumption per kg Fibre; Forest Stewardship Council Certification Status of Wood Pulp Feedstock.	Reference Industries: Aditya Birla, Kharach, Gujarat, for modal fibre production; India's organized apparel exporters for lyocell-based sustainable fashion lines using imported fibre.	
Key Adoption Challenges: Solvent Recovery Rate (%) for lyocell; Water Consumption per kg Fibre; Forest Stewardship Council Certification Status of Wood Pulp Feedstock.		
Technology Developers & Solution Providers: Global: Lenzing AG (Tencel brand). India: Aditya Birla (Birla Excel modal, Liva viscose range).	Key References: Textile Exchange, Preferred Fiber and Materials Market Report.	
Cross Media Effects: Lyocell solvent spinning has minimal discharge; bamboo viscose processed through conventional chemistry retains the carbon disulphide and sodium hydroxide effluent burden of standard viscose production.		
India Context & Strategic Considerations: Aditya Birla's Kharach facility in Gujarat is India's closest domestic equivalent to lyocell-type regenerated cellulosic fibre production, though true closed-loop lyocell capacity remains absent domestically.		

F2-16	Chemical Recycling of Polyester	
Transformation Direction Resource-Intelligent Manufacturing	TRL 7	Technology Type Process Technology
Technology Focus Area Circular Fibre Systems	Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Chemical recycling of polyester depolymerizes polyester waste into its constituent chemical building blocks through glycolysis, methanolysis, hydrolysis, or related chemical processes. Purified monomers or oligomers are subsequently re-polymerized to produce virgin-equivalent polyester suitable for conventional melt spinning. The process accommodates textile waste streams that cannot be effectively recycled through mechanical methods because of contamination or material degradation.		
Primary Applications: Polyester fabric waste feedstock recycling; post-consumer garment recycling into virgin-equivalent polyester fibre.		
Environmental & Resource Benefits Enables genuine textile-to-textile circularity for polyester, reducing dependence on virgin petrochemical feedstock, though the chemical depolymerization process itself is energy intensive and requires life cycle comparison against mechanical recycling and virgin production.		
Indicative CAPEX (India context): Very high; global-scale commercial plants require capital investment in the range of several thousand lakh, with no India domestic facility currently operating. [Indicative estimate only; not independently verified against a published market source.]	OPEX Savings / Payback Period: Not commercially proven at scale; Textile Exchange data confirms textile-to-textile recycling represents less than 1 percent of all recycled polyester globally.	
Key Performance Indicators (KPIs): Monomer Purity (%); Conversion Rate (%); Energy Consumption per kg Monomer Produced; Feedstock Quality Requirements.	Reference Industries: No current India facility; Surat's polyester processing base represents potential future feedstock source.	
Key Adoption Challenges: Monomer Purity (%); Conversion Rate (%); Energy Consumption per kg Monomer Produced; Feedstock Quality Requirements.		
Technology Developers & Solution Providers: Global: Eastman (Polyester Renewal Technology), Loop Industries, Carbios.	Key References: Textile Exchange, Preferred Fiber and Materials Market Report.	
Cross Media Effects: Chemical depolymerization is energy intensive and requires solvent or reagent input, warranting life cycle comparison against mechanical recycling and virgin production before assuming net benefit.		
India Context & Strategic Considerations: Surat's large polyester fabric processing base represents a logical future feedstock source and potential location for textile-to-textile polyester recycling capacity, should the technology achieve commercial maturity.		

F2-17	Next-Generation Circular Fibre Systems	
Transformation Direction Resource-Intelligent Manufacturing	TRL 6	Technology Type Process Technology
Technology Focus Area Circular Fibre Systems	Roadmap Horizon Accelerate (2035–2047)	India Adoption (2026) Accelerate (2035–2047)
Technology Overview & Working Principle: Next-generation circular fibre systems recover cellulose or polymer components from blended and difficult-to-recycle textile waste through advanced dissolution, separation, purification, and fibre regeneration technologies. These processes produce new textile fibres suitable for repeated textile-to-textile recycling while maintaining controlled fibre quality. The technologies combine chemical processing, material separation, and fibre manufacturing within an integrated circular production pathway.		
Primary Applications: Cotton and blended garment waste recycling into new cellulosic textile fibre.		
Environmental & Resource Benefits: If successfully commercialized, avoids the water and pesticide footprint of virgin cotton cultivation for the recycled fibre portion, while requiring solvent recovery infrastructure to manage the chemical dissolution process.		
Indicative CAPEX (India context): Very high; no commercial-scale cost data available given pre-commercial technology status. [Indicative estimate only; not independently verified against a published market source.		OPEX Savings / Payback Period: Not commercially applicable at current technology readiness level.
Key Performance Indicators (KPIs): Cellulose Recovery Rate (%); Fibre Quality Relative to Virgin Cotton; Solvent Recovery Rate.		Reference Industries: Panipat recycling cluster and Tirupur cutting waste represent potential future feedstock sources.
Key Adoption Challenges: Cellulose Recovery Rate (%); Fibre Quality Relative to Virgin Cotton; Solvent Recovery Rate.		
Technology Developers & Solution Providers: Global: Infinited Fiber Company, Re:newcell, Ioncell (Aalto University). India: Renewlane, an early-stage Mumbai-based initiative.		Key References: Textile Exchange, Preferred Fiber and Materials Market Report.
Cross Media Effects: Chemical dissolution of cellulose requires solvent input; solvent recovery infrastructure is essential to avoid a new effluent burden replacing the one eliminated.		
India Context & Strategic Considerations: India's textile recycling ecosystem, centred on Panipat, provides a strong feedstock base should fibre-to-fibre cotton chemical recycling technology mature to commercial scale.		

F2-18	Advanced Bio-based Fibre Systems	
Transformation Direction Innovation & Technology Origination	TRL 6	Technology Type Material Innovation
Technology Focus Area Circular Fibre Systems	Roadmap Horizon Accelerate (2035–2047)	India Adoption (2026) Accelerate (2035–2047)
Technology Overview & Working Principle: Advanced bio-based fibre systems manufacture textile fibres from renewable biological feedstocks using engineered polymer synthesis, bio-based monomer production, and conventional fibre spinning technologies. Feedstocks may include agricultural biomass, bio-derived polymers, or renewable chemical intermediates that are converted into spinnable polymers before fibre formation. Process conditions are controlled to achieve the required physical and mechanical fibre properties.		
Primary Applications: Premium sustainable apparel; technical textile research and development.		
Environmental & Resource Benefits: Bio-based feedstock reduces fossil raw material dependency; specific environmental performance depends on the polymer route and remains an area of active research.		
Indicative CAPEX (India context): Not commercially costed; pre-commercial research and development stage globally.	OPEX Savings / Payback Period: Not applicable at current pre-commercial stage.	
Key Performance Indicators (KPIs): Bio-Based Carbon Content (%); Thermal Stability Relative to First-Generation Bio-Based Fibres; Mechanical Performance Parity with Conventional Synthetics.	Reference Industries: Gujarat, as a potential castor oil feedstock source; sugarcane-producing regions as bio-polymer feedstock sources.	
Key Adoption Challenges: Bio-Based Carbon Content (%); Thermal Stability Relative to First-Generation Bio-Based Fibres; Mechanical Performance Parity with Conventional Synthetics.		
Technology Developers & Solution Providers: Global: Arkema (Rilsan bio-polyamide from castor oil), Avantium (polyethylene furanoate). No India commercial producer identified.	Key References: Textile Exchange, Preferred Fiber and Materials Market Report.	
Cross Media Effects: Polymer conversion processes for next-generation bio-based fibres require chemical and energy input not yet characterized in available literature.		
India Context & Strategic Considerations: India's position as the world's largest castor oil producer, concentrated in Gujarat, represents a structural feedstock advantage for bio-polyamide production that remains undeveloped domestically as of current data.		

F2-19	Integrated Blow Room with Contamination Detection	
Transformation Direction Manufacturing Capability at Scale	TRL 9	Technology Type Manufacturing Equipment
Technology Focus Area Spinning Technologies	Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Integrated blow room systems combine bale opening, fibre cleaning, blending, dust removal, and contamination detection within a continuous automated material preparation line. Optical and spectroscopic sensors identify foreign materials during fibre transport, while automated ejection mechanisms remove contaminants before carding. Centralized process control coordinates material flow and operating parameters across individual machines to ensure consistent fibre preparation.		
Primary Applications: Spinning preparation for all cotton and cotton-blend yarn production, positioned upstream of carding.		
Environmental & Resource Benefits: Contamination entering at blow room stage causes downstream yarn defects, fabric rejection, and reprocessing; integrated detection at this stage prevents that contamination from propagating through the remainder of the value chain.		
Indicative CAPEX (India context): Complete integrated blow room line: Rs 150 to 400 lakh depending on capacity. [Validated by Truetzschler India Pvt Ltd via TMMA, May 2026]	OPEX Savings / Payback Period: Payback 3 to 5 years from raw material savings, quality improvement, and reduced rework.	
Key Performance Indicators (KPIs): Contamination count pre- and post-line (per ITMF Cotton Contamination Survey methodology); sorting accuracy (%); throughput (kg per hour).	Reference Industries: Medium adoption in organised mills above 25,000 spindles; low in MSME spinning units. [TMMA-validated]	
Key Adoption Challenges: Contamination count pre- and post-line (per ITMF Cotton Contamination Survey methodology); sorting accuracy (%); throughput (kg per hour).		
Technology Developers & Solution Providers: Truetzschler India Pvt Ltd, Ahmedabad (validator and confirmed manufacturer).	Key References: Validated by Truetzschler India Pvt Ltd, TMMA industry consultation, May 2026.	
Cross Media Effects: Minor additional electricity use for vision and sorting systems; no water or chemical impact.		
India Context & Strategic Considerations: Truetzschler India identifies the root cause of India's cotton contamination problem as originating in the field: 'contamination is due to wrong picking and storing methods employed in cotton fields; mechanical picking over manual picking is needed to avoid high levels of contamination.' This reframes blow-room detection as a downstream mitigation for an upstream agricultural practice issue rather than a complete solution.		

F2-20	Auto-Doffing Ring Frames, High-Speed (≥1,008 Spindles)	
Transformation Direction Manufacturing Capability at Scale	TRL 9	Technology Type Manufacturing Equipment
Technology Focus Area Spinning Technologies	Roadmap Horizon Align (2026–2030)	India Adoption (2026)Align (2026–2030)
Technology Overview & Working Principle: Automatic doffing systems mechanize the removal of full bobbins and replacement with empty tubes on ring spinning frames without interrupting machine operation. Coordinated mechanical handling systems synchronize spindle stopping, bobbin exchange, tube loading, and machine restart through programmable control systems. The technology integrates with modern ring spinning frames to automate package handling while maintaining production continuity.		
Primary Applications: Cotton and blended yarn spinning in large, organised spinning mills operating at scale.		
Environmental & Resource Benefits: Reduces manual handling and associated ergonomic risk at the doffing stage; supports continuous, higher-utilisation frame operation.		
Indicative CAPEX (India context): Rs 300 to 800 lakh per ring frame, 1,008 spindles, fully equipped. [Validated by Truetzschler India Pvt Ltd via TMMA, May 2026]		OPEX Savings / Payback Period: Payback 4 to 6 years from productivity and labour cost savings.
Key Performance Indicators (KPIs): Doffing cycle time; frame utilisation (%); labour hours per tonne of yarn produced.		Reference Industries: Limited to large organised mills; major gap versus global leaders in adoption scale. [TMMA-validated]
Key Adoption Challenges: Doffing cycle time; frame utilisation (%); labour hours per tonne of yarn produced.		
Technology Developers & Solution Providers: Global manufacturers offering auto-doffing ring frame technology; no India-domestic full-frame equivalent confirmed by validator.		Key References: Validated by Truetzschler India Pvt Ltd, TMMA industry consultation, May 2026.
Cross Media Effects: No water use; electricity demand comparable to conventional ring frames without auto-doffing.		
India Context & Strategic Considerations: This is a distinct technology from compact ring spinning (F2-01): auto-doffing addresses labour and cycle-time efficiency, while compact spinning addresses yarn quality through fibre condensing. India's technology gap here is characterised by very limited domestic manufacturing capability at the high-end, auto-doffing segment specifically.		

F2-21		Ring Frame Auto Piecer (India-Made)	
Transformation Direction Technology Sovereignty		TRL 9	Technology Type Manufacturing Equipment
Technology Focus Area Spinning Technologies		Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Automatic piecing systems detect yarn breaks during ring spinning and restore yarn continuity through automated end location, yarn preparation, and controlled piecing operations. Sensors identify broken ends, while robotic or mechanical piecing units rejoin the yarn without manual intervention. The system integrates with machine monitoring and spindle control to maintain continuous spinning operations across large spindle installations.			
Primary Applications: Cotton and blended ring-spun yarn production in organised spinning mills.			
Environmental & Resource Benefits: Reduces manpower requirement in ring frame operation by up to 50 percent according to the validating manufacturer, lowering the labour intensity of a traditionally very labour-heavy spinning stage.			
Indicative CAPEX (India context): Retrofit unit: Rs 25 to 50 lakh per ring frame. New ring frame with integrated system: Rs 80 to 120 lakh per frame. Validator specifies 2 units per ring frame up to 1,824 spindles, at Rs 25 lakh per unit. [Validated by Truetzschler India Pvt Ltd and a second TMMA member via TMMA, May 2026]		OPEX Savings / Payback Period: Payback 3 to 5 years from labour cost savings according to the manufacturer; a second validator corrected this to a longer 6 to 8 years.	
Key Performance Indicators (KPIs): Manpower reduction (%); piecing consistency versus manual piecing; frame downtime from broken ends.		Reference Industries: Growing — commercially deployed by Lakshmi Machine Works; limited diffusion beyond large organised mills. [TMMA-validated]	
Key Adoption Challenges: Manpower reduction (%); piecing consistency versus manual piecing; frame downtime from broken ends.			
Technology Developers & Solution Providers: Lakshmi Machine Works (India, Coimbatore) — TMMA Innovation Award 2024 winner for this technology, confirmed India-made.		Key References: Validated by Truetzschler India Pvt Ltd and a second TMMA member, TMMA industry consultation, May 2026.	
Cross Media Effects: No water use; reduces manual labour exposure to a repetitive, continuous-walking task; no chemical impact.			
India Context & Strategic Considerations: This technology won the TMMA Innovation Award in 2024 and is confirmed India-made by Lakshmi Machine Works — a notable domestic innovation. The two TMMA validators disagree meaningfully on payback (3 to 5 years versus 6 to 8 years), a discrepancy worth flagging rather than resolving arbitrarily; both figures are retained here.			

F2-22		Dope Dyeing and Solution-Dyed Mass Coloration	
Transformation Direction Resource-Intelligent Manufacturing		TRL 9	Technology Type Process Technology
Technology Focus Area Circular Fibre Systems		Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Solution dyeing, also known as dope dyeing, incorporates pigments or colourants directly into the polymer melt before fibre extrusion. Colour becomes an integral part of the fibre during melt spinning, eliminating the need for subsequent conventional dyeing processes for synthetic fibres. Precise dosing and dispersion systems ensure uniform colour distribution throughout the polymer prior to filament formation and winding.			
Primary Applications: Polyester and nylon staple fibre and filament yarn for apparel, sportswear, home textiles, and technical textiles, in applications where a fixed colour per production batch is acceptable.			
Environmental & Resource Benefits: Eliminates the water, salt, and auxiliary chemical consumption of a separate dyehouse process entirely for the coloured fibre volume produced this way, since colouration occurs within fibre manufacturing rather than as an additional wet processing stage.			
Indicative CAPEX (India context): Pigment dosing and mixing system added to an existing spinning line: Rs 200 to 800 lakh, typically integrated at the fibre manufacturing stage rather than at dyehouse level. [Validated by Yamuna Machine Works Ltd via TMMA, May 2026]		OPEX Savings / Payback Period: Payback 4 to 7 years at dyeing-cost-avoidance value.	
Key Performance Indicators (KPIs): Colour consistency batch to batch; pigment dosing accuracy; dyeing-stage water and chemical avoidance (litres and kilograms per kg fibre, relative to conventional dyeing of the same fibre).		Reference Industries: Growing, particularly for polyester in Surat and in synthetic yarn production more broadly. [TMMA-validated]	
Key Adoption Challenges: Colour consistency batch to batch; pigment dosing accuracy; dyeing-stage water and chemical avoidance (litres and kilograms per kg fibre, relative to conventional dyeing of the same fibre).			
Technology Developers & Solution Providers: Integrated into fibre and filament yarn production lines; no single-machine vendor identified separately from fibre producers themselves in available validation data.		Key References: Validated by Yamuna Machine Works Ltd, TMMA industry consultation, May 2026.	
Cross Media Effects: Eliminates dyehouse-stage water, salt, and chemical consumption entirely for fibre coloured this way; no offsetting trade-off identified for the elimination itself, though colour inflexibility shifts risk from environmental impact to inventory and demand-forecasting risk.			
India Context & Strategic Considerations: This technology sits structurally outside the wet processing stage entirely, since colouration happens during fibre manufacturing rather than fabric or garment processing — a genuinely different intervention point in the value chain than any other dyeing technology in this compendium, and one that eliminates the dyehouse step rather than making it more efficient.			

 **FACTORY (DRY & WET)
TECHNOLOGIES**

F3-01	Shuttleless Rapier Weaving	
Transformation Direction Manufacturing Capability at Scale	TRL 9	Technology Type Manufacturing Equipment
Technology Focus Area Weaving Technologies	Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Shuttleless rapier weaving systems insert weft yarn using one or two rapier heads that transport the yarn across the warp shed without the use of a conventional shuttle. Electronic control systems coordinate shedding, weft insertion, beat-up, and take-up mechanisms to maintain synchronized fabric formation. Modern rapier looms support flexible handling of a wide range of yarn types, counts, and weave structures while integrating with digital machine control and monitoring systems.		
Primary Applications: Shirting; suiting; home textiles; denim; technical fabrics.		
Environmental & Resource Benefits: Approximately 25 to 35 percent lower energy consumption than shuttle looms of equivalent output, with no shuttle oil contamination and reduced noise pollution.		
Indicative CAPEX (India context): Rs 25 to 60 lakh per loom for Chinese-manufactured machines; Rs 80 to 180 lakh per loom for European brands. [Indicative estimate only; not independently verified against a published market source.]	OPEX Savings / Payback Period: Two to three times the productivity of shuttle looms. Payback period: 5 to 8 years for European machines, shorter for lower-cost Chinese alternatives.	
Key Performance Indicators (KPIs): Pick Rate (picks per minute); Weft Waste (%); Loom Efficiency (%); Warp Breakage Rate.	Reference Industries: Bhiwandi, Maharashtra, with a substantial base of Chinese-manufactured rapier looms; Ichalkaranji; Surat; Bhilwara; Erode.	
Key Adoption Challenges: Pick Rate (picks per minute); Weft Waste (%); Loom Efficiency (%); Warp Breakage Rate.		
Technology Developers & Solution Providers: Global: Picanol, Itema Group, Dornier, Toyota Industries. Chinese manufacturers include RIFA and Jingwei. India: Alidhra Weavetech, Premier Looms, Dynamic Autolooms.	Key References: International Textile Manufacturers Federation, Annual Report; Ministry of Textiles, Government of India, Technology Upgradation Fund Scheme documentation.	
Cross Media Effects: No water use; electricity demand per loom is lower than shuttle looms but the aggregate cluster-wide demand rises with productivity gains.		
India Context & Strategic Considerations: Bhiwandi has added a substantial number of rapier looms, predominantly Chinese-manufactured at significantly lower cost than European alternatives, reflecting the price-sensitive nature of India's powerloom modernization pathway.		

F3-02	Air-Jet Weaving	
Transformation Direction Manufacturing Capability at Scale	TRL 9	Technology Type Manufacturing Equipment
Technology Focus Area Weaving Technologies	Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Air-jet weaving systems insert weft yarn across the warp shed using controlled jets of compressed air guided through profiled reeds and auxiliary nozzles. Electronic controllers regulate air pressure, nozzle timing, and yarn insertion parameters according to fabric construction and operating speed. Integrated sensors continuously monitor weft insertion and machine performance to maintain stable weaving under high-speed production conditions.		
Primary Applications: Cotton shirting in light to medium weight; synthetic fabrics; taffeta; lining fabric; dress fabric.		
Environmental & Resource Benefits: Four to six times the productivity of shuttle looms. Programmable air pressure regulation on modern machines reduces compressed air energy consumption compared with older systems.		
Indicative CAPEX (India context): Rs 90 to 200 lakh per loom, plus Rs 50 lakh to 1 crore for supporting compressed air infrastructure. [Indicative estimate only; not independently verified against a published market source.]	OPEX Savings / Payback Period: Payback period: 5 to 8 years, though operating cost is higher than rapier weaving due to compressed air energy consumption.	
Key Performance Indicators (KPIs): Pick Rate (picks per minute); Air Consumption per Pick; Compressor Energy per Shift; Loom Efficiency (%).	Reference Industries: Organized weaving mills in Coimbatore, where shuttleless penetration is more established than in the wider powerloom sector.	
Key Adoption Challenges: Pick Rate (picks per minute); Air Consumption per Pick; Compressor Energy per Shift; Loom Efficiency (%).		
Technology Developers & Solution Providers: Global: Toyota Industries (JAT910), Picanol (Omni Plus), Tsudakoma. Chinese manufacturers include RIFA and Jingwei.	Key References: International Textile Manufacturers Federation, Annual Report.	
Cross Media Effects: Compressed air generation is energy intensive; compressor efficiency and air leak management determine the scale of this trade-off.		
India Context & Strategic Considerations: Air-jet weaving’s productivity advantage is best suited to India’s higher-value cotton shirting and synthetic fabric segments, where the additional infrastructure investment is more readily justified than across the broader price-sensitive powerloom base that has driven rapier loom uptake.		

F3-03		Water-Jet Weaving	
Transformation Direction Manufacturing Capability at Scale		TRL 9	Technology Type Manufacturing Equipment
Technology Focus Area Weaving Technologies		Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Water-jet weaving systems propel hydrophobic filament yarns through the warp shed using a high-pressure water jet as the weft insertion medium. The weaving process integrates water delivery, yarn insertion, shedding, beat-up, drying, and fabric winding within a continuous production sequence. Automated control systems regulate water pressure, nozzle performance, and loom operating parameters to ensure consistent fabric formation.			
Primary Applications: Polyester taffeta; nylon lining fabric; synthetic filament fabric exclusively.			
Environmental & Resource Benefits: Lower operating energy than air-jet weaving due to the use of water rather than compressed air as the weft insertion medium; water can be recycled in a closed loop within the weaving shed.			
Indicative CAPEX (India context): Rs 40 to 80 lakh per loom for India-manufactured machines; higher for imported alternatives. [Indicative estimate only; not independently verified against a published market source.		OPEX Savings / Payback Period: Payback period: 4 to 7 years.	
Key Performance Indicators (KPIs): Pick Rate (picks per minute); Water Consumption per Hour; Fabric Defect Rate; Closed-Loop Water Recovery Rate (%).		Reference Industries: Surat synthetic fabric cluster, where water-jet looms represent approximately 90 percent of the loom base.	
Key Adoption Challenges: Pick Rate (picks per minute); Water Consumption per Hour; Fabric Defect Rate; Closed-Loop Water Recovery Rate (%).			
Technology Developers & Solution Providers: Global: Tsudakoma, established as a leader in water-jet weaving technology. India: Premier Looms, Dynamic Autolooms, both based in Surat.		Key References: International Textile Manufacturers Federation, Annual Report.	
Cross Media Effects: Water use of approximately 5 to 8 litres per hour per loom requires either closed-loop recycling or wastewater treatment if discharged.			
India Context & Strategic Considerations: Surat's water-jet loom base has grown substantially over the past two decades, tracking the growth of India's synthetic fibre fabric production, and Premier Looms and Dynamic Autolooms represent established India-based manufacturers in this segment.			

F3-04	Real-Time Loom Monitoring	
Transformation Direction Digital Infrastructure & Traceability	TRL 9	Technology Type Digital Technology
Technology Focus Area Weaving Technologies	Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Real-time loom monitoring systems collect operational data directly from weaving machines using machine-mounted sensors, programmable controllers, and digital communication networks. The system continuously records production speed, machine efficiency, downtime events, fault conditions, and fabric output, transmitting the information to centralized monitoring platforms. Integration with production management systems enables continuous monitoring of loom performance across manufacturing facilities.		
Primary Applications: Production monitoring across shuttle and shuttleless looms alike; downtime cause analysis; efficiency benchmarking; machine-level production record generation for traceability purposes.		
Environmental & Resource Benefits: No direct environmental cross-media effect. Enables data-driven identification of energy and material waste hotspots on the weaving floor through visibility into machine-level performance.		
Indicative CAPEX (India context): Rs 15 to 40 lakh per loom shed for a multi-loom monitoring system. [Indicative estimate only; not independently verified against a published market source.]	OPEX Savings / Payback Period: Payback period: 3 to 5 years through efficiency and downtime reduction, with additional strategic value through traceability readiness.	
Key Performance Indicators (KPIs): Loom Efficiency (%); Downtime by Cause Code (hours per month); Picks per Minute Relative to Rated Speed; Fabric Metres Produced per Shift.	Reference Industries: Bhiwandi; Surat; Erode; Ichalkaranji; Coimbatore organized weaving mills.	
Key Adoption Challenges: Loom Efficiency (%); Downtime by Cause Code (hours per month); Picks per Minute Relative to Rated Speed; Fabric Metres Produced per Shift.		
Technology Developers & Solution Providers: Global: Uster Technologies (Quantum systems), Rieter (Essential), Loepfe.	Key References: International Textile Manufacturers Federation, Annual Report.	
Cross Media Effects: Sensor and connectivity hardware adds modest electricity demand; no water or chemical trade-off.		
India Context & Strategic Considerations: Mechanical loom modernization and digital monitoring adoption must advance together, since modern shuttleless looms without monitoring cannot generate the machine-level production records required for future Digital Product Passport compliance, while monitoring legacy shuttle looms cannot resolve underlying productivity limitations.		

F3-05		High-Speed Sizing Systems	
Transformation Direction Manufacturing Capability at Scale		TRL 9	Technology Type Manufacturing Equipment
Technology Focus Area Weaving Technologies		Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: High-speed sizing systems apply a controlled layer of protective sizing material onto warp yarns before weaving to improve yarn integrity during loom operation. The process combines size preparation, yarn impregnation, moisture control, drying, and beam winding within a continuous production line. Automated control systems regulate size concentration, application rate, drying conditions, yarn tension, and machine speed to maintain consistent sizing performance.			
Primary Applications: Warp sizing for all woven fabric types, including cotton, blended, and synthetic fabric production.			
Environmental & Resource Benefits: Modern sizing machines with thermal insulation and condensate return achieve 15 to 25 percent steam and energy savings compared with older sizing ranges.			
Indicative CAPEX (India context): Rs 60 to 150 lakh per sizing range. [Indicative estimate only; not independently verified against a published market source.]		OPEX Savings / Payback Period: Energy saving of 15 to 25 percent compared with older sizing equipment. Payback period: 5 to 8 years.	
Key Performance Indicators (KPIs): Size Add-On Percentage (typically 8 to 12% for cotton); Steam Consumption per kg Yarn; Wastewater Chemical Oxygen Demand from Size Removal.		Reference Industries: Surat; Bhiwandi; Ichalkaranji; Bhilwara weaving preparation.	
Key Adoption Challenges: Size Add-On Percentage (typically 8 to 12% for cotton); Steam Consumption per kg Yarn; Wastewater Chemical Oxygen Demand from Size Removal.			
Technology Developers & Solution Providers: Global: Karl Mayer, Benninger. India: Yamuna Textile Machines, Surat, a leading domestic manufacturer.		Key References: International Textile Manufacturers Federation, Annual Report; Gujarat Pollution Control Board, industry guidance.	
Cross Media Effects: Desizing effluent downstream from sized warp remains a significant biochemical oxygen demand contributor regardless of sizing machine efficiency.			
India Context & Strategic Considerations: Yamuna Textile Machines in Surat is India's leading domestic manufacturer of sizing equipment, representing a strong Make in India manufacturing capability in weaving preparation machinery.			

F3-06		Advanced Warping Systems	
Transformation Direction Manufacturing Capability at Scale		TRL 9	Technology Type Manufacturing Equipment
Technology Focus Area Weaving Technologies		Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Advanced warping systems prepare warp yarns by winding multiple yarn ends onto warp beams under precisely controlled tension and alignment conditions. Electronic tension control, automatic yarn break detection, beam building, and yarn distribution systems ensure uniform warp formation throughout the process. Depending on production requirements, the systems support direct warping, sectional warping, and pattern warping for a wide range of fabric constructions.			
Primary Applications: Warp beam preparation for all woven fabric production, including jacquard pattern warp preparation.			
Environmental & Resource Benefits: Consistent warp tension reduces warp breakage during weaving, lowering associated material waste and reprocessing.			
Indicative CAPEX (India context): Rs 20 to 60 lakh per warping machine. [Indicative estimate only; not independently verified against a published market source.]		OPEX Savings / Payback Period: Payback period: 3 to 6 years through productivity gains and reduced warp breakage.	
Key Performance Indicators (KPIs): Winding Speed (metres per minute); Tension Coefficient of Variation (%); Beam Density; Length Wound Consistency.		Reference Industries: Surat; Bhiwandi; Ichalkaranji; Bhilwara; Erode weaving clusters.	
Key Adoption Challenges: Winding Speed (metres per minute); Tension Coefficient of Variation (%); Beam Density; Length Wound Consistency.			
Technology Developers & Solution Providers: Global: Karl Mayer, Benninger, Staubli, Suzuki. India: Prashant Group, Ahmedabad, an established domestic manufacturer.		Key References: International Textile Manufacturers Federation, Annual Report.	
Cross Media Effects: No water or chemical use; modest electricity demand from servo tension control.			
India Context & Strategic Considerations: Prashant Group in Ahmedabad is India's leading indigenous manufacturer of warping machinery, providing a domestic manufacturing alternative to European suppliers.			

F3-07		Electronic Jacquard & Servo Dobby	
Transformation Direction Manufacturing Capability at Scale		TRL 9	Technology Type Manufacturing Equipment
Technology Focus Area Weaving Technologies		Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Electronic jacquard and servo dobby systems digitally control warp yarn selection during weaving through electronically actuated lifting mechanisms. Pattern information generated from computer-aided design (CAD) software is transmitted directly to the loom controller, eliminating mechanical patterning systems. Programmable electronic actuation enables rapid pattern changes and precise control of complex woven structures without physical pattern modifications.			
Primary Applications: Silk brocade; fancy suiting; home textile furnishing; technical woven fabric; upholstery; heritage handloom fabrics including Varanasi silk.			
Environmental & Resource Benefits: Eliminates punched card paper waste and reduces pattern set-up downtime, improving repeat accuracy and enabling short-run design flexibility with minimal material waste from set-up trials.			
Indicative CAPEX (India context): Rs 30 lakh per machine. [Validated by Vandewiele Savio India Pvt Ltd via TMMA, May 2026]		OPEX Savings / Payback Period: Payback 3 to 5 years. High design flexibility and speed confirmed as the primary operational benefits.	
Key Performance Indicators (KPIs): Pattern Changeover Time (minutes); Hook Speed Relative to Loom Compatibility; Warp Break Rate; Pattern Repeat Accuracy.		Reference Industries: RAMCO, Welspun, Kapoor among confirmed reference installations	
Key Adoption Challenges: Pattern Changeover Time (minutes); Hook Speed Relative to Loom Compatibility; Warp Break Rate; Pattern Repeat Accuracy.			
Technology Developers & Solution Providers: Global: Staubli, Grosse. India: TiaTech, Surat, manufacturing electronic jacquard and drop box controllers.		Key References: International Textile Manufacturers Federation, Annual Report. Validated by Vandewiele Savio India Pvt Ltd, TMMA industry consultation, May 2026.	
Cross Media Effects: No water use; moderate electricity demand from electronic actuation compared with mechanical dobby systems.			
India Context & Strategic Considerations: TiaTech in Surat is a notable Indian manufacturer of electronic jacquard equipment, providing import substitution potential for the Varanasi and Surat weaving clusters that rely heavily on complex pattern weaving.			

F3-08		Advanced Textile Manufacturing Systems	
Transformation Direction Innovation & Technology Origination		TRL 6	Technology Type Manufacturing Equipment
Technology Focus Area Weaving Technologies		Roadmap Horizon Accelerate (2035–2047)	India Adoption (2026) Accelerate (2035–2047)
Technology Overview & Working Principle: Advanced textile manufacturing systems produce three-dimensional woven or braided structures by interlacing yarns in multiple directions to create integrated fibre architectures. Computer-controlled yarn handling, tension regulation, and machine coordination enable the production of complex near-net-shape textile preforms for structural and technical applications. Digital process control ensures precise fibre placement and repeatable fabric geometry throughout production.			
Primary Applications: Aerospace composite reinforcement; automotive structural components; wind turbine blade reinforcement; defence applications.			
Environmental & Resource Benefits: Near-net-shape production reduces composite machining waste compared with conventional two-dimensional laminate approaches.			
Indicative CAPEX (India context): Very high; specialized three-dimensional weaving equipment requires substantial capital investment with limited commercial-scale cost benchmarks available. [Indicative estimate only; not independently verified against a published market source.]		OPEX Savings / Payback Period: Not quantified in available data; niche high-value application.	
Key Performance Indicators (KPIs): Fibre Volume Fraction (%); Inter-Laminar Shear Strength; Near-Net-Shape Tolerance; Production Rate.		Reference Industries: Aerospace and defence supply chains; automotive composite component manufacturers; wind energy sector.	
Key Adoption Challenges: Fibre Volume Fraction (%); Inter-Laminar Shear Strength; Near-Net-Shape Tolerance; Production Rate.			
Technology Developers & Solution Providers: Global: Bally Ribbon Mills, Lindauer Dornier. No India commercial supplier identified.		Key References: Ministry of Textiles, National Technical Textiles Mission documentation.	
Cross Media Effects: No water or chemical use in the weaving process itself; specialized equipment carries a higher embodied manufacturing footprint than conventional looms.			
India Context & Strategic Considerations: India's National Technical Textiles Mission specifically targets composite reinforcement textiles for defence, aerospace, and infrastructure applications, with public sector aerospace and defence organizations as potential anchor buyers.			

F3-09		Circular Knitting Modernisation	
Transformation Direction Manufacturing Capability at Scale		TRL 9	Technology Type Manufacturing Equipment
Technology Focus Area Knitting Technologies		Roadmap Horizon Amplify (2030–2035)	India Adoption (2026)Amplify (2030–2035)
Technology Overview & Working Principle: High-speed circular knitting systems produce tubular knitted fabrics using rotating cylinder needle beds synchronized with yarn feeding, stitch formation, take-down, and fabric winding mechanisms. Electronic knitting controls regulate stitch length, yarn feed, pattern selection, and machine speed to achieve consistent fabric construction. Modern machines support computerized pattern programming and automated process monitoring across a wide range of knitted fabric types.			
Primary Applications: T-shirt fabric; knitwear; hosiery; sportswear; underwear fabric.			
Environmental & Resource Benefits: Higher productivity per unit floor space and lower yarn waste compared with older circular knitting equipment.			
Indicative CAPEX (India context): Rs 12 to 30 lakh per machine. [Indicative estimate only; not independently verified against a published market source.]		OPEX Savings / Payback Period: Payback period: 4 to 7 years.	
Key Performance Indicators (KPIs): Production Rate; Fabric Width; Needle Breakage Rate; Defect Count per Roll.		Reference Industries: Tirupur, Tamil Nadu, India's dominant knitwear manufacturing hub; Ludhiana; Delhi National Capital Region hosiery.	
Key Adoption Challenges: Production Rate; Fabric Width; Needle Breakage Rate; Defect Count per Roll.			
Technology Developers & Solution Providers: Global: Mayer and Cie, Precision Fukuhara, Terrot, Pai Lung.		Key References: International Textile Manufacturers Federation, Annual Report.	
Cross Media Effects: No water use; compact footprint reduces land and building energy demand per unit of fabric output.			
India Context & Strategic Considerations: Tirupur operates a very large base of circular knitting machines, and the upgrade opportunity in this cluster is primarily oriented toward quality improvement and automation rather than basic capacity expansion.			

F3-10		Seamless 3D Flatbed Knitting	
Transformation Direction Manufacturing Capability at Scale		TRL 8	Technology Type Manufacturing Equipment
Technology Focus Area Knitting Technologies		Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Seamless three-dimensional flatbed knitting systems manufacture complete garment panels or finished garments directly from yarn through digitally controlled needle selection and stitch formation. Computerized knitting programs coordinate multiple needle beds, yarn carriers, and transfer mechanisms to produce complex three-dimensional structures without conventional cut-and-sew assembly. Integrated software enables direct translation of digital garment designs into automated knitting instructions.			
Primary Applications: Shaped knitwear panels; sweaters; sportswear; fashion knitwear; fully seamless garment production.			
Environmental & Resource Benefits: WholeGarment production mode achieves near-zero cutting waste and eliminates sewing thread and trim waste, representing a significant reduction in pre-consumer textile waste compared with cut-and-sew knitwear production.			
Indicative CAPEX (India context): Rs 50 to 150 lakh per machine. [Indicative estimate only; not independently verified against a published market source.]		OPEX Savings / Payback Period: Payback period: 6 to 10 years, requiring premium product positioning to justify the investment.	
Key Performance Indicators (KPIs): Production Speed (rows per minute); Gauge Range; Cutting Waste (%; target zero in WholeGarment mode); Pattern Complexity.		Reference Industries: Ludhiana sweater manufacturing cluster; Delhi National Capital Region fashion knitwear; premium export knitwear units.	
Key Adoption Challenges: Production Speed (rows per minute); Gauge Range; Cutting Waste (%; target zero in WholeGarment mode); Pattern Complexity.			
Technology Developers & Solution Providers: Global: Shima Seiki (WholeGarment technology), Stoll (Knit and Wear technology).		Key References: International Textile Manufacturers Federation, Annual Report.	
Cross Media Effects: No water use; higher per-machine electricity demand than basic circular knitting given greater mechanical and control complexity.			
India Context & Strategic Considerations: Ludhiana operates India's largest flatbed knitting cluster, though current capability is predominantly oriented toward conventional cut-and-sew production rather than seamless WholeGarment manufacturing, representing a significant upgrade opportunity for premium export positioning.			

F3-11	Warp Knitting	
Transformation Direction Manufacturing Capability at Scale	TRL 9	Technology Type Manufacturing Equipment
Technology Focus Area Technical Textiles	Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Advanced warp knitting, nonwoven, and smart textile manufacturing systems produce specialized textile structures using digitally controlled fibre formation, bonding, or knitting technologies. Warp knitting machines interloop multiple yarn systems supplied from warp beams, while spunbond and meltblown systems form continuous fibre webs directly from polymer extrusion. Smart textile manufacturing integrates conductive materials, sensors, functional yarns, or printed electronic components into textile structures through controlled manufacturing processes to create functional fabrics.		
Primary Applications: Lace; bra fabric; sportswear fabric; automotive technical textiles; mosquito nets; medical mesh fabric.		
Environmental & Resource Benefits: High production speed with minimal waste; digital pattern integration enables lightweight technical fabric production replacing heavier woven alternatives in some applications.		
Indicative CAPEX (India context): Rs 100 to 300 lakh per machine. [Indicative estimate only; not independently verified against a published market source.]	OPEX Savings / Payback Period: Payback period: 7 to 12 years, reflecting the specialized and typically lower-volume nature of warp knit technical fabric markets.	
Key Performance Indicators (KPIs): Production Speed (revolutions per minute); Fabric Defect Count per 100 Metres; Pattern Changeover Time.	Reference Industries: Kutch, Gujarat, lace production; Surat technical fabrics; Mumbai technical textile exporters.	
Key Adoption Challenges: Production Speed (revolutions per minute); Fabric Defect Count per 100 Metres; Pattern Changeover Time.		
Technology Developers & Solution Providers: Global: Karl Mayer, the dominant global supplier of warp knitting machinery.	Key References: International Textile Manufacturers Federation, Annual Report.	
Cross Media Effects: No water or chemical use; high machine speed carries a correspondingly higher per-unit electricity demand than slower knitting technologies.		
India Context & Strategic Considerations: India was reported as the leading visitor nation at ITMA Asia 2025 for Karl Mayer's warp knitting technology, reflecting strong domestic interest in expanding technical textile capability under the National Technical Textiles Mission.		

F3-12	Nonwoven Production Systems	
Transformation Direction Manufacturing Capability at Scale	TRL 9	Technology Type Manufacturing Equipment
Technology Focus Area Technical Textiles	Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Nonwoven manufacturing systems produce fabric-like structures by directly converting polymer or staple fibres into bonded webs without spinning yarn or fabric formation through weaving or knitting. Spunbond processes extrude continuous filaments that are deposited onto a moving conveyor before thermal or chemical bonding, while meltblown systems generate ultrafine fibres using high-velocity hot air. Integrated web formation, bonding, winding, and process control systems enable continuous production of engineered nonwoven materials with controlled structural and functional properties.		
Primary Applications: Medical nonwovens including masks and gowns; agricultural crop cover; filtration media; hygiene products; geotextiles.		
Environmental & Resource Benefits: Direct polymer-to-fabric conversion eliminates the spinning and weaving stages, reducing labour and water requirements compared with woven fabric production for equivalent applications; thermal bonding in high-end lines eliminates the need for chemical binders.		
Indicative CAPEX (India context): Rs 500 to 2,000 lakh per production line, depending on width, speed, and polymer type, representing a very high capital requirement. [Indicative estimate only; not independently verified against a published market source.]	OPEX Savings / Payback Period: Payback period: 8 to 12 years, requiring high production volume to justify investment.	
Key Performance Indicators (KPIs): Grammage Consistency (grams per square metre); Web Uniformity; Tensile Strength; Production Rate (metres per minute).	Reference Industries: Ahmedabad; Pune; Surat technical textile clusters; Panipat recycled nonwovens.	
Key Adoption Challenges: Grammage Consistency (grams per square metre); Web Uniformity; Tensile Strength; Production Rate (metres per minute).		
Technology Developers & Solution Providers: Global: Reifenhauser, Karl Mayer, Trutzschler. India: Ginni Filaments, Arise India.	Key References: Ministry of Textiles, National Technical Textiles Mission documentation.	
Cross Media Effects: Thermal bonding in high-end lines avoids chemical binders, but upstream polymer chip production carries a petrochemical feedstock footprint.		
India Context & Strategic Considerations: India's National Technical Textiles Mission offers funding support of up to Rs 200 crore for qualifying nonwoven production projects, and PM MITRA textile parks are incorporating nonwoven infrastructure into their planning.		

F3-13	Smart Functional Textile Systems	
Transformation Direction Innovation & Technology Origination	TRL 6	Technology Type Material Innovation
Technology Focus Area Technical Textiles	Roadmap Horizon Accelerate (2035–2047)	India Adoption (2026) Accelerate (2035–2047)
Technology Overview & Working Principle: Smart functional textile manufacturing systems integrate conductive materials, sensors, actuators, electronic components, or functional coatings into textile structures during fibre, yarn, fabric, or finishing processes. Integration techniques include conductive yarn insertion, embroidery, weaving, knitting, printing, lamination, and coating technologies, supported by digital manufacturing and electronic assembly processes. The resulting textile structures combine conventional mechanical performance with embedded sensing, communication, heating, monitoring, or other advanced functional capabilities.		
Primary Applications: Wearable health-monitoring garments; heated apparel; interactive sportswear; defence smart uniform applications.		
Environmental & Resource Benefits: No specific quantified environmental benefit identified in available literature; potential to reduce electronic waste if textile-integrated sensors displace separate wearable electronic devices.		
Indicative CAPEX (India context): Rs 100 to 500 lakh for a pilot production line; research and development stage in India. [Indicative estimate only; not independently verified against a published market source.]	OPEX Savings / Payback Period: Not commercially costed; research and development stage.	
Key Performance Indicators (KPIs): Conductivity Retention After Wash Cycles; Sensor Signal Accuracy; Durability Through Repeated Washing.	Reference Industries: Defence smart-uniform research and development; sportswear research institutions; medical wearable device development.	
Key Adoption Challenges: Conductivity Retention After Wash Cycles; Sensor Signal Accuracy; Durability Through Repeated Washing.		
Technology Developers & Solution Providers: Global: Loomia, Ohmatex. No India commercial supplier identified.	Key References: Ministry of Textiles, National Technical Textiles Mission documentation.	
Cross Media Effects: No specific cross-media data available in available literature for this category.		
India Context & Strategic Considerations: Smart and functional textiles remain a research and development horizon category for India's technical textiles ecosystem, aligned with National Technical Textiles Mission priorities but not yet reflected in domestic commercial production.		

F3-14	Low-Liquor Ratio Dyeing	
Transformation Direction Resource-Intelligent Manufacturing	TRL 9	Technology Type Manufacturing Equipment
Technology Focus Area Resource Efficiency	Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Low-liquor ratio dyeing systems reduce the volume of process liquor required for textile dyeing by optimizing machine geometry, liquor circulation, and fabric transport. Soft-flow, overflow, jet, and airflow dyeing machines maintain uniform dye distribution while operating with substantially lower liquor volumes than conventional equipment. Automated control of liquor ratio, temperature, circulation, and process sequencing ensures consistent dye penetration and reproducible dyeing conditions throughout the batch.		
Primary Applications: Cotton and polyester-blend knitted fabric dyeing in batch jet dyeing machines.		
Environmental & Resource Benefits: Reduces water consumption by 60 to 75 percent compared with conventional liquor ratios, with proportional reductions in energy for water heating, salt and chemical consumption per bath, and effluent volume. Leading machine manufacturers have demonstrated levels below 30 litres per kilogram for jet dyeing including pretreatment.		
Indicative CAPEX (India context): LLR jet or softflow machine (Thies, Fong's): Rs 20 to 60 lakh per machine. ULR airflow machine: Rs 40 to 100 lakh. ACME AM-ICD low-liquor-ratio conveyor dyeing system (launched ITMA Asia Singapore 2025): Rs 150 to 300 lakh depending on width. [Validated by Yamuna Machine Works Ltd via TMMA, May 2026]		OPEX Savings / Payback Period: Payback 3 to 5 years from water, chemical, and energy savings; 4 to 6 years for the newer ACME conveyor system.
Key Performance Indicators (KPIs): Liquor Ratio Achieved; Water Consumption per kg Fabric; Dye Fixation Rate (%); Cycle Time; Effluent Chemical Oxygen Demand.		Reference Industries: Tirupur knitwear dyeing; Ahmedabad cotton woven processing; Erode yarn dyeing.
Key Adoption Challenges: Liquor Ratio Achieved; Water Consumption per kg Fabric; Dye Fixation Rate (%); Cycle Time; Effluent Chemical Oxygen Demand.		
Technology Developers & Solution Providers: Global: Thies (iMaster H2O), Fong's, Hisaka, Dilmenler. India: Texfab Engineers, Surat; ACME Engineering, Surat.		Key References: Central Pollution Control Board, Zero Liquid Discharge guidelines; Gujarat Pollution Control Board, industry effluent standards. Validated by Yamuna Machine Works Ltd, TMMA industry consultation, May 2026.
Cross Media Effects: No offsetting trade-off identified; lower liquor ratio reduces water, chemical, and energy demand simultaneously.		
India Context & Strategic Considerations: Gujarat Pollution Control Board guidance recommends liquor ratios at or below 1:8 as baseline practice, while global best-in-class performance has reached below 1:4, indicating substantial room for improvement across India's dyeing sector.		

F3-15	Automated Dye & Chemical Dispensing Systems	
Transformation Direction Resource-Intelligent Manufacturing	TRL 9	Technology Type Manufacturing Equipment
Technology Focus Area Resource Efficiency	Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Automated dye and chemical dispensing systems accurately weigh, dissolve, prepare, and deliver dyes and auxiliary chemicals through centralized computer-controlled dosing equipment. The system integrates storage vessels, dispensing units, transfer pipelines, and process control software to supply dyeing machines with precisely formulated chemical solutions. Digital recipe management and automated material handling ensure consistent preparation and controlled delivery throughout dyeing operations.		
Primary Applications: All exhaust dyeing processes for cotton, polyester, and blended fabrics.		
Environmental & Resource Benefits: Reduces chemical waste from weighing errors and spillage; sealed dispensing systems reduce worker exposure to volatile organic compounds and dust from chemical handling.		
Indicative CAPEX (India context): Automated chemical dispensing system: Rs 30 to 80 lakh for a 10 to 20 vessel dyehouse. [Validated by Yamuna Machine Works Ltd via TMMA, May 2026]	OPEX Savings / Payback Period: Payback period: 2 to 4 years through reduced chemical waste and improved batch consistency.	
Key Performance Indicators (KPIs): Chemical Dispensing Accuracy (%); Spillage Incidents; Recipe Tracking Completeness; Batch Shade Consistency.	Reference Industries: Tirupur; Ahmedabad; Surat organized dyehouses.	
Key Adoption Challenges: Chemical Dispensing Accuracy (%); Spillage Incidents; Recipe Tracking Completeness; Batch Shade Consistency.		
Technology Developers & Solution Providers: Global: Lawer, Colorservice, both Italian manufacturers with established presence in leading textile-producing economies.	Key References: International Textile Manufacturers Federation, Annual Report. Validated by Yamuna Machine Works Ltd, TMMA industry consultation, May 2026.	
Cross Media Effects: No material trade-off; dispensing infrastructure itself has negligible resource footprint.		
India Context & Strategic Considerations: Automated dispensing systems are standard in leading textile-producing economies but remain limited in India, where manual dosing continues to contribute to dyeing inconsistency and elevated re-dyeing rates.		

F3-16		Right-First-Time Dyeing	
Transformation Direction Resource-Intelligent Manufacturing		TRL 8	Technology Type Process Technology
Technology Focus Area Resource Efficiency		Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Right-first-time dyeing systems integrate computerized colour management, spectrophotometric colour measurement, laboratory recipe prediction, automated dispensing, and process control to achieve target shades during the initial dyeing cycle. Digital colour matching algorithms correlate laboratory formulations with production conditions, while process monitoring maintains critical dyeing parameters throughout the operation. The system establishes standardized colour management across laboratory and production environments.			
Primary Applications: All exhaust dyeing processes across cotton, polyester, and blended fabric production.			
Environmental & Resource Benefits: Every avoided re-dye eliminates the full water, chemical, and energy consumption of that batch cycle, representing a high-multiplier resource saving relative to the cost of the enabling technology.			
Indicative CAPEX (India context): Spectrophotometer (Datacolor 600 or X-Rite): Rs 8 to 15 lakh. [Validated by Yamuna Machine Works Ltd via TMMA, May 2026]		OPEX Savings / Payback Period: Payback 2 to 4 years. Validator confirms growing adoption of computerised colour matching in Tirupur, though automated dosing remains limited to large mills.	
Key Performance Indicators (KPIs): Right-First-Time Rate (%); Re-Dyeing Rate (%); Shade Approval Time; Colour Difference Tolerance (Delta E).		Reference Industries: Tirupur; Ahmedabad; Surat dyeing clusters.	
Key Adoption Challenges: Right-First-Time Rate (%); Re-Dyeing Rate (%); Shade Approval Time; Colour Difference Tolerance (Delta E).			
Technology Developers & Solution Providers: Global: Lawer, Colorservice, X-Rite, Datacolor.		Key References: International Textile Manufacturers Federation, Annual Report. Validated by Yamuna Machine Works Ltd, TMMA industry consultation, May 2026.	
Cross Media Effects: No offsetting trade-off; the spectrophotometry and dispensing equipment required has negligible resource footprint relative to the re-dyeing waste it prevents.			
India Context & Strategic Considerations: India's re-dyeing rate is understood to be considerably higher than in leading competing textile economies, making right-first-time dyeing systems one of the highest-return process improvements available to the sector.			

F4-17		Continuous Bleaching	
Transformation Direction Resource-Intelligent Manufacturing		TRL 9	Technology Type Manufacturing Equipment
Technology Focus Area Resource Efficiency		Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Continuous bleaching systems combine peroxide bleaching with enzymatic catalase treatment in an integrated continuous processing line. Following peroxide bleaching, catalase enzymes decompose residual hydrogen peroxide into water and oxygen before subsequent wet processing stages. Automated control of chemical dosing, temperature, residence time, and fabric transport ensures stable bleaching performance and controlled peroxide neutralization throughout continuous operation.			
Primary Applications: Cotton and cotton-blend woven fabric continuous bleaching ranges.			
Environmental & Resource Benefits: Enzyme-assisted bleaching achieves 10 to 20 percent reduction in hydrogen peroxide consumption with lower overall environmental load, while eliminating the hot kill-wash step saves both water and steam energy.			
Indicative CAPEX (India context): Integrated continuous desizing-scouring-bleaching (DSB) range: Rs 50 to 100 lakh (validator-corrected range, narrower than the originally estimated Rs 50 lakh to 2 crore). Retrofit to an existing J-box: Rs 15 to 40 lakh. Separately, ozone-based bleaching as an alternative to conventional chlorine or peroxide bleaching: ozone generator and reaction system Rs 8 to 20 lakh for a standalone bleaching range. [Validated by Yamuna Machine Works Ltd via TMMA, May 2026]		OPEX Savings / Payback Period: Integrated DSB route: payback 3 to 5 years, with savings in water and steam, continuous production, and higher and more consistent quality of finished fabrics. Ozone bleaching route: payback 4 to 6 years.	
Key Performance Indicators (KPIs): Whiteness Index; Residual Hydrogen Peroxide in Fabric; Water Consumption per kg Fabric; Throughput Speed.		Reference Industries: Ahmedabad; Coimbatore; Bhilwara integrated woven processing mills.	
Key Adoption Challenges: Whiteness Index; Residual Hydrogen Peroxide in Fabric; Water Consumption per kg Fabric; Throughput Speed.			
Technology Developers & Solution Providers: Global: Kusters, Benninger, Monforts, Goller. India: Texpab Engineers, Surat.		Key References: International Textile Manufacturers Federation, Annual Report. Validated by Yamuna Machine Works Ltd, TMMA industry consultation, May 2026.	
Cross Media Effects: Catalase enzyme effluent is biodegradable; no offsetting chemical or energy trade-off identified relative to conventional alkaline bleaching.			
India Context & Strategic Considerations: Enzyme-assisted bleaching is recognized as a best available technique direction for India's wet processing sector, offering measurable chemical reduction with relatively straightforward retrofit requirements.			

F3-18		Wastewater Heat Recovery	
Transformation Direction Resource-Intelligent Manufacturing		TRL 9	Technology Type Energy Technology
Technology Focus Area Resource Efficiency		Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Wastewater heat recovery systems recover thermal energy from hot textile process effluent through plate, shell-and-tube, or other industrial heat exchangers. Heat transferred from outgoing wastewater preheats incoming process water before reuse in dyeing, washing, or preparation processes. Flow control systems, temperature monitoring, and heat exchanger management maintain continuous heat recovery while keeping wastewater and fresh water streams physically separated.			
Primary Applications: All hot wet-processing dyehouses with elevated-temperature effluent discharge.			
Environmental & Resource Benefits: Recovers thermal energy that would otherwise be discharged with effluent, reducing fossil fuel consumption for water heating and lowering associated carbon dioxide emissions.			
Indicative CAPEX (India context): Rs 10 to 30 lakh per heat exchanger unit. [Indicative estimate only; not independently verified against a published market source.]		OPEX Savings / Payback Period: Payback period: 2 to 4 years through boiler fuel savings, with documented savings of 15 to 25 percent of boiler fuel demonstrated in comparable South Asian textile facility case studies.	
Key Performance Indicators (KPIs): Effluent Inlet and Outlet Temperature; Heat Recovered per Tonne of Fabric; Boiler Fuel Saving (%).		Reference Industries: Tirupur; Surat; Ahmedabad hot dyeing operations.	
Key Adoption Challenges: Effluent Inlet and Outlet Temperature; Heat Recovered per Tonne of Fabric; Boiler Fuel Saving (%).			
Technology Developers & Solution Providers: Global: Alfa Laval, GEA. India: Thermax, Forbes Marshall.		Key References: International Textile Manufacturers Federation, Annual Report; Partnership for Cleaner Textile, case study documentation.	
Cross Media Effects: No offsetting trade-off; heat exchanger fouling from high total dissolved solids effluent requires periodic cleaning maintenance.			
India Context & Strategic Considerations: Wastewater heat recovery is established practice internationally and is increasingly recommended for India’s dyeing clusters, where hot effluent discharge represents an underutilized energy recovery opportunity.			

F3-19	Stenter Heat Recovery	
Transformation Direction Resource-Intelligent Manufacturing	TRL 9	Technology Type Energy Technology
Technology Focus Area Resource Efficiency	Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Stenter heat recovery systems capture waste heat from the exhaust gases of textile stenter machines using air-to-air or air-to-water heat exchangers. Recovered thermal energy is transferred to incoming combustion air, process air, or water used elsewhere within the manufacturing facility. Integrated dampers, temperature sensors, and automated control systems regulate heat recovery according to production conditions and exhaust gas characteristics.		
Primary Applications: Stenter and tenter frame operations across cotton, synthetic, and blended fabric finishing.		
Environmental & Resource Benefits: Reduces natural gas or furnace oil consumption for stenter operation; requires prior treatment of exhaust air for volatile organic compounds and formaldehyde before heat exchange to avoid fouling and to meet air quality requirements.		
Indicative CAPEX (India context): Stenter flue gas heat recovery unit: Rs 7 to 20 lakh per stenter. [Validated by TMMA General cross-cutting consultation, May 2026]	OPEX Savings / Payback Period: Payback 0.2 to 1 year — 2 to 12 months, one of the shortest paybacks identified across the entire compendium, according to the validator.	
Key Performance Indicators (KPIs): Gas Consumption per Metre of Fabric; Inlet Air Temperature Preheat Gain; Heat Recovery Efficiency (%).	Reference Industries: Surat; Ahmedabad; Tirupur wet processing clusters with gas-fired stenter equipment.	
Key Adoption Challenges: Gas Consumption per Metre of Fabric; Inlet Air Temperature Preheat Gain; Heat Recovery Efficiency (%).		
Technology Developers & Solution Providers: Global: Monforts (Eco Therm range), Bruckner. India: Yamuna Textile Machines, Surat.	Key References: International Textile Manufacturers Federation, Annual Report; Gujarat Pollution Control Board, air quality guidance. Validated by TMMA cross-cutting general technology consultation, May 2026.	
Cross Media Effects: Stenter exhaust requires volatile organic compound treatment, typically regenerative thermal oxidation, before heat exchange to avoid fouling and to meet air quality requirements.		
India Context & Strategic Considerations: Gujarat Pollution Control Board has identified stenter exhaust as a significant air quality concern in processing clusters, making combined regenerative thermal oxidation and heat recovery systems an increasingly recommended best practice.		

F3-20	Digital Waterless Dyeing Systems	
Transformation Direction Resource-Intelligent Manufacturing	TRL 7	Technology Type Process Technology
Technology Focus Area Resource Efficiency	Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Digital waterless dyeing systems apply dyes directly onto textile substrates through digitally controlled application technologies integrated with continuous drying and fixation processes. Precision-controlled deposition systems deliver colour only where required, eliminating conventional immersion dyeing for suitable applications. Digital process control coordinates colour application, drying, fixation, and fabric transport within a continuous manufacturing sequence.		
Primary Applications: Fabric piece dyeing for cotton and blended fabrics in a waterless, single-pass process.		
Environmental & Resource Benefits: Leading commercial systems have demonstrated water consumption reductions of up to 95 percent and energy reductions of up to 85 percent compared with conventional dyeing, with chemical use reductions of up to 35 percent.		
Indicative CAPEX (India context): Not publicly disclosed at commercial scale; systems remain at demonstration stage with limited installations globally. [Indicative estimate only; not independently verified against a published market source.]	OPEX Savings / Payback Period: Reported cost reductions of up to 50 percent compared with traditional dyeing processes at demonstrated production volumes, though broader commercial-scale validation remains limited.	
Key Performance Indicators (KPIs): Water Saving (%) Relative to Conventional Exhaust Dyeing; Energy Saving (%); Chemical Reduction (%); Wastewater Generation.	Reference Industries: No confirmed India installation identified; global demonstration installations exist in Europe.	
Key Adoption Challenges: Water Saving (%) Relative to Conventional Exhaust Dyeing; Energy Saving (%); Chemical Reduction (%); Wastewater Generation.		
Technology Developers & Solution Providers: Global: Alchemie Technology (Endeavour system).	Key References: Alchemie Technology, Endeavour low carbon digital textile dyeing production documentation; IEEE Spectrum, coverage of digital dyeing technology.	
Cross Media Effects: No offsetting trade-off identified in available literature; the developer reports the process as wastewater-free with substantial energy reduction.		
India Context & Strategic Considerations: This technology has been identified in industry literature with specific quantified performance data, making it a notable technology to monitor for future India deployment as the commercial installation base expands beyond current demonstration sites.		

F3-21		Foam Dyeing	
Transformation Direction Resource-Intelligent Manufacturing		TRL 8	Technology Type Process Technology
Technology Focus Area Resource Efficiency		Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Foam dyeing systems apply dyes and auxiliary chemicals as a stabilized foam rather than a conventional aqueous liquor. Foam is generated through controlled mixing of air, water, surfactants, and dye formulations before being uniformly applied to the textile substrate. Automated foam generation, application, penetration, and drying systems regulate foam characteristics and chemical distribution throughout the continuous dyeing process.			
Primary Applications: Pretreatment, finishing, and dyeing applications on knitted and nonwoven substrates.			
Environmental & Resource Benefits: Substantially reduces water and chemical consumption relative to padding, with corresponding reduction in drying energy demand.			
Indicative CAPEX (India context): Rs 60 to 150 lakh per foam applicator system. [Indicative estimate only; not independently verified against a published market source.]		OPEX Savings / Payback Period: Not precisely quantified in available data; technology remains at early adoption stage.	
Key Performance Indicators (KPIs): Wet Pickup (%); Water Consumption per kg; Drying Energy Consumption; Foam Bubble Stability.		Reference Industries: Limited pilot-scale application identified; technology demonstration stage in India.	
Key Adoption Challenges: Wet Pickup (%); Water Consumption per kg; Drying Energy Consumption; Foam Bubble Stability.			
Technology Developers & Solution Providers: Global: Gaston Systems, Alliance Machine Systems, Monforts (foam application option).		Key References: International Textile Manufacturers Federation, Annual Report.	
Cross Media Effects: No offsetting trade-off identified relative to conventional padding.			
India Context & Strategic Considerations: Foam dyeing remains at limited pilot and demonstration stage in India, positioning it as an early adoption technology with meaningful resource-saving potential once commercially proven at scale.			

F3-22		Supercritical CO ₂ Dyeing	
Transformation Direction Resource-Intelligent Manufacturing		TRL 8	Technology Type Process Technology
Technology Focus Area Resource Efficiency		Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Supercritical carbon dioxide dyeing systems utilize carbon dioxide above its critical temperature and pressure as the dye transport medium instead of water. Under supercritical conditions, carbon dioxide dissolves suitable disperse dyes and transports them into synthetic fibres within a sealed high-pressure vessel. Following dyeing, pressure reduction separates the dye from the carbon dioxide, allowing the gas to be recovered and recirculated within a closed-loop process.			
Primary Applications: Polyester and nylon dyeing exclusively, as a waterless process.			
Environmental & Resource Benefits: Eliminates water use entirely from the dyeing process, along with the drying stage required in conventional aqueous dyeing, since fabric emerges dry from the process; salt and alkali are not required.			
Indicative CAPEX (India context): Very high, approximately ten times conventional dyeing machine cost; limited commercial installations globally. [Indicative estimate only; not independently verified against a published market source.]		OPEX Savings / Payback Period: Energy saving from eliminated drying stage; payback exceeds 10 years at current installation scale and cost.	
Key Performance Indicators (KPIs): Water Consumption (target: zero); Carbon Dioxide Recovery Rate (%); Dye Exhaustion Rate; Colour Fastness.		Reference Industries: India's first commercial supercritical carbon dioxide dyeing installation has been reported through a collaboration involving Arvind Limited, H&M Group, and Deven Supercriticals.	
Key Adoption Challenges: Water Consumption (target: zero); Carbon Dioxide Recovery Rate (%); Dye Exhaustion Rate; Colour Fastness.			
Technology Developers & Solution Providers: Global: DyeCoo (Netherlands). India: Deven Supercriticals Pvt Ltd, manufacturer of the SupraUno waterless dyeing system.		Key References: Deven Supercriticals Pvt Ltd, SupraUno Waterless Dyeing Technology documentation; Arvind Limited, H&M Group and Deven Supercriticals, joint announcement of India's first commercial supercritical carbon dioxide dyeing installation.	
Cross Media Effects: Requires substantial upfront energy for carbon dioxide compression to supercritical pressure, though this is offset by eliminating the drying stage required in aqueous dyeing.			
India Context & Strategic Considerations: India has established its first commercial supercritical carbon dioxide dyeing installation through Deven Supercriticals in partnership with Arvind Limited and H&M Group, positioning India among the earliest adopters of this technology globally rather than solely a future prospect.			

F3-23		Nano-Bubble Dyeing	
Transformation Direction Innovation & Technology Origination		TRL 6	Technology Type Process Technology
Technology Focus Area Resource Efficiency		Roadmap Horizon Accelerate (2035–2047)	India Adoption (2026) Accelerate (2035–2047)
Technology Overview & Working Principle: Nano-bubble dyeing systems employ microscopic gas bubbles dispersed within the dye bath to enhance mass transfer between dye solution and textile fibres. Controlled bubble generation modifies liquid behaviour and improves interaction between dye molecules and fibre surfaces under low-liquor processing conditions. Integrated process controls regulate bubble generation, liquor circulation, temperature, and dyeing parameters throughout the operation.			
Primary Applications: Cotton and denim fabric dyeing at ultra-low liquor ratio.			
Environmental & Resource Benefits: Dramatically lower water and chemical consumption at liquor ratios approaching 1:1 compared with conventional dyeing, with proportionally lower wastewater generation and associated energy saving.			
Indicative CAPEX (India context): Nano-bubble generator retrofit for denim processing: Rs 8 to 20 lakh per washing machine. [Validated by Yamuna Machine Works Ltd via TMMA, May 2026]		OPEX Savings / Payback Period: Payback 3 to 5 years. Validator confirms current India application is concentrated in Ahmedabad and Surat denim processing, used for washing, bleaching, and enzyme finishing stages specifically.	
Key Performance Indicators (KPIs): Liquor Ratio Achieved; Wash and Rub Fastness Grades; Depth of Shade; Air Permeability.		Reference Industries: No confirmed India commercial installation identified; relevant to future Tirupur and Surat dyeing modernization.	
Key Adoption Challenges: Liquor Ratio Achieved; Wash and Rub Fastness Grades; Depth of Shade; Air Permeability.			
Technology Developers & Solution Providers: Global: Jeanologia (H2Zero system, related water-saving denim technology). No dedicated India commercial supplier identified for nano-bubble dyeing specifically.		Key References: Cellulose, Springer Nature, published research on nanobubbles in textile wet processing applications and resource reduction potential. Validated by Yamuna Machine Works Ltd, TMMA industry consultation, May 2026.	
Cross Media Effects: No offsetting trade-off identified in available literature at the ultra-low liquor ratios reported.			
India Context & Strategic Considerations: Nano-bubble dyeing is identified in peer-reviewed research as a promising water reduction technology; India's water-stressed dyeing clusters, including Tirupur and Surat, represent a strong future application context once the technology matures beyond research and demonstration stage.			

F3-24		Ultrasound-Assisted Dyeing	
Transformation Direction Innovation & Technology Origination		TRL 6	Technology Type Process Technology
Technology Focus Area Resource Efficiency		Roadmap Horizon Accelerate (2035–2047)	India Adoption (2026) Accelerate (2035–2047)
Technology Overview & Working Principle: Ultrasound-assisted dyeing systems use high-frequency acoustic waves to generate cavitation within the dye liquor during textile processing. The formation and collapse of microscopic bubbles produce localized turbulence that enhances mass transfer between the dye solution and textile fibres. Integrated ultrasonic transducers operate alongside conventional dyeing equipment, while automated process controls regulate ultrasonic frequency, power, temperature, and dyeing conditions throughout the treatment cycle.			
Primary Applications: Cotton, wool, and synthetic batch dyeing at potentially reduced temperature.			
Environmental & Resource Benefits: Potential energy saving from reduced dyeing temperature and shorter cycle time, without additional chemical load.			
Indicative CAPEX (India context): Rs 20 to 60 lakh per ultrasound bath attachment. [Indicative estimate only; not independently verified against a published market source.]		OPEX Savings / Payback Period: Not quantified in available data; technology remains at research and demonstration stage.	
Key Performance Indicators (KPIs): Temperature Reduction Relative to Conventional Dyeing; Cycle Time Reduction (%); Dye Exhaustion Improvement.		Reference Industries: Research institutions and premium batch dyeing mills; no widespread India commercial deployment identified.	
Key Adoption Challenges: Temperature Reduction Relative to Conventional Dyeing; Cycle Time Reduction (%); Dye Exhaustion Improvement.			
Technology Developers & Solution Providers: Global: Hielscher Ultrasonics. No India commercial supplier identified for textile-scale application.		Key References: Peer-reviewed textile processing literature on ultrasound-assisted dyeing mechanisms.	
Cross Media Effects: Ultrasonic generator equipment adds electricity demand, offset by potential reductions in dyeing temperature and cycle time.			
India Context & Strategic Considerations: Domestic research institutions including the Ahmedabad Textile Industry's Research Association have piloted ultrasound-assisted processing, indicating existing India research capacity in this area ahead of commercial-scale application.			

F3-25		Microwave-Assisted Textile Processing	
Transformation Direction Innovation & Technology Origination		TRL 6	Technology Type Process Technology
Technology Focus Area Resource Efficiency		Roadmap Horizon Accelerate (2035–2047)	India Adoption (2026) Accelerate (2035–2047)
Technology Overview & Working Principle: Microwave-assisted textile processing utilizes electromagnetic radiation to generate volumetric heating by directly exciting polar molecules within textile substrates and process liquids. Unlike conventional surface heating, microwave energy is distributed throughout the material, enabling rapid and uniform temperature development. Process control systems regulate microwave power, exposure time, and treatment conditions to maintain consistent heating during dyeing, drying, and other wet-processing operations.			
Primary Applications: Cotton and wool dyeing; potential application in accelerating enzymatic processing steps.			
Environmental & Resource Benefits: Potential energy saving through reduced dyeing time and lower processing temperature, without additional chemical requirement.			
Indicative CAPEX (India context): Rs 20 to 80 lakh per microwave processing unit. [Indicative estimate only; not independently verified against a published market source.]		OPEX Savings / Payback Period: Not quantified in available data; research and development stage globally.	
Key Performance Indicators (KPIs): Dyeing Time Reduction (%); Temperature Reduction; Dye Exhaustion Rate; Energy Consumption per kg Fabric.		Reference Industries: Research institutions including academic textile engineering departments; no established India commercial application.	
Key Adoption Challenges: Dyeing Time Reduction (%); Temperature Reduction; Dye Exhaustion Rate; Energy Consumption per kg Fabric.			
Technology Developers & Solution Providers: No commercial textile-specific microwave processing supplier identified in available literature.		Key References: Peer-reviewed textile engineering literature on microwave-assisted dyeing techniques.	
Cross Media Effects: Microwave generation requires electricity input; net energy trade-off relative to conventional heating has not been quantified in available literature.			
India Context & Strategic Considerations: India's technical institutions, including the Indian Institutes of Technology and the Ahmedabad Textile Industry's Research Association, possess relevant research capability to pilot microwave-assisted processing, positioning this as a longer-term research priority.			

F3-26		Enzymatic Pre-treatment & Bio-Scouring	
Transformation Direction Resource-Intelligent Manufacturing		TRL 9	Technology Type Process Technology
Technology Focus Area Advanced Sustainable Chemistry		Roadmap Horizon Align (2026–2030)	India Adoption (2026)Align (2026–2030)
Technology Overview & Working Principle: Enzymatic pre-treatment and bio-scouring systems employ naturally derived enzymes to remove non-cellulosic impurities, starches, pectins, proteins, and other surface materials from textile fibres before dyeing or finishing. Enzyme formulations are applied under controlled temperature, pH, and reaction conditions to selectively catalyse the removal of targeted impurities without significantly affecting the fibre structure. Automated dosing and process control ensure consistent treatment performance.			
Primary Applications: Cotton and cotton-blend woven fabric pretreatment, covering desizing and scouring stages.			
Environmental & Resource Benefits: Lower processing temperature substantially reduces thermal energy demand; biodegradable enzyme effluent has markedly lower chemical oxygen demand than conventional alkaline scouring effluent.			
Indicative CAPEX (India context): Marginal capital investment — enzyme cost replaces conventional chemical cost with no new equipment required for existing continuous ranges. Enzyme dosing system: Rs 2 to 5 lakh. [Validated by Yamuna Machine Works Ltd via TMMA, May 2026]		OPEX Savings / Payback Period: Water and steam savings. Payback 1 to 2 years from chemical and energy savings (validator corrected from originally estimated 1 to 3 years to a tighter 1 to 2 year range).	
Key Performance Indicators (KPIs): Temperature Reduction Relative to Alkaline Baseline; Effluent Chemical Oxygen Demand Reduction (%); Water Consumption per kg; Enzyme Cost per kg Fabric.		Reference Industries: Tirupur knitwear dyeing; Ahmedabad cotton woven processing; Surat synthetic blend pretreatment.	
Key Adoption Challenges: Temperature Reduction Relative to Alkaline Baseline; Effluent Chemical Oxygen Demand Reduction (%); Water Consumption per kg; Enzyme Cost per kg Fabric.			
Technology Developers & Solution Providers: Global: Novozymes, BASF (BioAct range), AB Enzymes. India: ITC Specialty Chemicals.		Key References: European Commission, Joint Research Centre, Best Available Techniques Reference Document for the Textiles Industry. Validated by Yamuna Machine Works Ltd, TMMA industry consultation, May 2026.	
Cross Media Effects: No offsetting trade-off; enzyme cost is the primary consideration rather than an environmental one.			
India Context & Strategic Considerations: India's generally warm climate favours enzyme reaction efficiency, and enzymatic pretreatment is recognized as a best available technique direction under both European Union and Gujarat best available techniques reference frameworks.			

F3-27		Cellulase Bio-Polishing	
Transformation Direction Resource-Intelligent Manufacturing		TRL 9	Technology Type Process Technology
Technology Focus Area Advanced Sustainable Chemistry		Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Cellulase bio-polishing systems apply cellulase enzymes to selectively remove protruding surface fibres from cellulosic textiles through controlled enzymatic hydrolysis. The treatment modifies the outer fibre surface while preserving the bulk structure of the fabric under carefully regulated processing conditions. Computer-controlled dosing, temperature, pH, and treatment time maintain consistent enzyme activity and fabric surface characteristics throughout the process.			
Primary Applications: Cotton knitwear surface finishing; viscose fabric finishing; denim bio-stonewashing.			
Environmental & Resource Benefits: Operates at moderate temperature of 50 to 60 degrees Celsius using biodegradable enzyme, reducing pilling tendency in the finished fabric; bio-stonewashing avoids the environmental impact of pumice stone mining and disposal associated with conventional stonewashing.			
Indicative CAPEX (India context): Enzyme cost replaces pumice or chemical cost — no new equipment required for existing exhaust dyeing machines. Enzyme dosing optimisation: Rs 50,000 to 2 lakh. [Validated by Yamuna Machine Works Ltd via TMMA, May 2026]		OPEX Savings / Payback Period: Payback 1 to 2 years from pumice disposal cost savings and premium fabric value.	
Key Performance Indicators (KPIs): Fabric Weight Loss (typically 0.5 to 2%); Pilling Grade per International Standard Scale; Surface Smoothness; Enzyme Dose per Gram of Fabric.		Reference Industries: Tirupur knitwear; Ahmedabad cotton processing; denim finishing mills.	
Key Adoption Challenges: Fabric Weight Loss (typically 0.5 to 2%); Pilling Grade per International Standard Scale; Surface Smoothness; Enzyme Dose per Gram of Fabric.			
Technology Developers & Solution Providers: Global: Novozymes (DeniMax range), AB Enzymes. India: Zytex Biotech, Surat.		Key References: European Commission, Joint Research Centre, Best Available Techniques Reference Document for the Textiles Industry. Validated by Yamuna Machine Works Ltd, TMMA industry consultation, May 2026.	
Cross Media Effects: No offsetting trade-off; enzyme dosing accuracy is an operational rather than environmental consideration.			
India Context & Strategic Considerations: India's warm climate reduces the additional heating energy required for enzyme processing relative to cooler manufacturing regions.			

F3-28		Nitrogen-Assisted Indigo Dyeing	
Transformation Direction Resource-Intelligent Manufacturing		TRL 8	Technology Type Process Technology
Technology Focus Area Advanced Sustainable Chemistry		Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Nitrogen-assisted indigo dyeing systems perform indigo reduction and dyeing within a controlled low-oxygen environment maintained by nitrogen gas. The inert atmosphere stabilizes the chemical reduction process by minimizing uncontrolled oxidation during dye preparation and application. Automated systems regulate nitrogen supply, dye chemistry, oxidation-reduction conditions, and process parameters throughout continuous denim dyeing operations.			
Primary Applications: Denim yarn indigo dyeing on rope or slasher dyeing ranges.			
Environmental & Resource Benefits: Reduces sodium hydrosulphite consumption by limiting atmospheric re-oxidation losses during the dyeing cycle, lowering the associated sulphate and sulphite load in dyehouse effluent.			
Indicative CAPEX (India context): New installation: approximately 1.25 times higher capital cost than a conventional indigo dyeing range. Modification of existing lines: Rs 200 to 300 lakh. [Validated by Prashant Westpoint Pvt Ltd via TMMA, May 2026 — commercial name: Prashant Green Dyeing Technology, Multidip Nitrogen Reactor for Indigo Dyeing]		OPEX Savings / Payback Period: Payback 2 to 3 years.	
Key Performance Indicators (KPIs): Sodium Hydrosulphite Consumption per kg Yarn; Dye Penetration Consistency; Nitrogen Consumption.		Reference Industries: Prashant Westpoint Pvt Ltd (part of the Prashant Group, Ahmedabad — the same group confirmed elsewhere in this compendium as India's leading indigenous manufacturer of warping and sizing machinery)	
Key Adoption Challenges: Sodium Hydrosulphite Consumption per kg Yarn; Dye Penetration Consistency; Nitrogen Consumption.			
Technology Developers & Solution Providers: No specific commercial supplier identified in available literature for nitrogen-assisted indigo dyeing systems specifically.		Key References: Validated by Prashant Westpoint Pvt Ltd, TMMA industry consultation, May 2026 (commercial technology: Prashant Green Dyeing Technology, Multidip Nitrogen Reactor). Prior literature gap flag resolved.	
Cross Media Effects: Nitrogen supply requires energy for generation or compression; net trade-off against sodium hydrosulphite reduction has not been quantified in available literature.			
India Context & Strategic Considerations: This technology is included to reflect its identification as a distinct process variant from electrochemical indigo reduction. Available literature does not provide India-specific performance or installation data, representing a genuine information gap requiring further verification.			

F3-29		Salt-Free Reactive Dyeing	
Transformation Direction Resource-Intelligent Manufacturing		TRL 8	Technology Type Process Technology
Technology Focus Area Advanced Sustainable Chemistry		Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Salt-free reactive dyeing systems utilize modified reactive dye chemistries, optimized process conditions, or alternative application techniques to promote dye fixation without the conventional use of large quantities of inorganic electrolyte. Computer-controlled dosing, liquor preparation, temperature regulation, and fixation conditions maintain consistent dye-fibre reaction kinetics while ensuring uniform colour development throughout the dyeing cycle.			
Primary Applications: Cotton and viscose reactive dyeing for woven fabric.			
Environmental & Resource Benefits: Salt elimination reduces total dissolved solids in dyehouse effluent by 30 to 50 percent, a critical benefit for zero liquid discharge system performance; cold processing eliminates the steam requirement for bath heating.			
Indicative CAPEX (India context): Cold pad-batch (CPB) route: padding mangle and batching system Rs 30 to 80 lakh, significantly less than equivalent exhaust batch dyeing capacity — validator marked this range as confirmed correct. Cationised-cotton route: cationisation unit added to existing processing line, Rs 100 to 300 lakh, with no new dyeing machine required. [Validated by Yamuna Machine Works Ltd via TMMA, May 2026]		OPEX Savings / Payback Period: CPB route: payback 2 to 3 years, savings in dyes, water, and reduction in rejection of dyed fabrics — validator confirmed this payback as correct. Cationised-cotton route: payback 3 to 5 years from ZLD operating cost reduction and salt cost saving.	
Key Performance Indicators (KPIs): Salt Consumption per kg Fabric (target: near zero); Water Consumption; Effluent Chemical Oxygen Demand; Dye Fixation Rate.		Reference Industries: Ahmedabad; Tirupur; Erode cotton dyeing clusters.	
Key Adoption Challenges: Salt Consumption per kg Fabric (target: near zero); Water Consumption; Effluent Chemical Oxygen Demand; Dye Fixation Rate.			
Technology Developers & Solution Providers: Global: Bezema (Bezaktiv S salt-free dye range), Huntsman Textile Effects, DyStar.		Key References: European Commission, Joint Research Centre, Best Available Techniques Reference Document for the Textiles Industry. Validated by Yamuna Machine Works Ltd, TMMA industry consultation, May 2026.	
Cross Media Effects: No offsetting trade-off; cold processing avoids rather than adds energy demand relative to conventional heated dyeing.			
India Context & Strategic Considerations: Salt in reactive dyeing effluent is a primary driver of high total dissolved solids in India's textile wastewater, making salt-free dyeing a recognized best available technique for clusters pursuing zero liquid discharge compliance.			

F3-30		PFAS-Free Durable Water Repellent Finishes	
Transformation Direction Resource-Intelligent Manufacturing		TRL 8	Technology Type Process Technology
Technology Focus Area Advanced Sustainable Chemistry		Roadmap Horizon Amplify (2030–2035)	India Adoption (2026)Amplify (2030–2035)
Technology Overview & Working Principle: PFAS-free durable water repellent finishing systems apply fluorine-free chemical formulations to textile surfaces to impart liquid-repellent properties without the use of per- and polyfluoroalkyl substances (PFAS). Functional finishes are deposited through controlled padding, spraying, coating, or similar application processes followed by drying and curing. Automated process control regulates chemical application, curing temperature, and fabric handling to achieve uniform surface treatment.			
Primary Applications: Sportswear; outdoor apparel; workwear requiring water repellent functional finishing.			
Environmental & Resource Benefits: Eliminates persistent, bioaccumulative per- and polyfluoroalkyl substances from textile effluent and finished product, addressing a class of chemicals of significant environmental and health concern.			
Indicative CAPEX (India context): Chemical cost only — C0 (fluorine-free) DWR is typically 15 to 30 percent more expensive than C6 PFC on a per-application basis, though the gap is narrowing. No new equipment required for existing finishing lines. [Validated by Yamuna Machine Works Ltd via TMMA, May 2026]		OPEX Savings / Payback Period: Payback framed as regulatory compliance value that cannot be delayed, and market access value for EU export, rather than a conventional financial payback.	
Key Performance Indicators (KPIs): Per- and Polyfluoroalkyl Substance Content (target: non-detect); Water Repellent Performance Retention After Wash Cycles; Manufacturing Restricted Substances List Conformance.		Reference Industries: Export-oriented mills in Tirupur, Surat, and Bengaluru serving global sportswear and outdoor apparel brands.	
Key Adoption Challenges: Per- and Polyfluoroalkyl Substance Content (target: non-detect); Water Repellent Performance Retention After Wash Cycles; Manufacturing Restricted Substances List Conformance.			
Technology Developers & Solution Providers: Global: Rudolf GmbH (Bionic-Finish Eco range), Daikin Industries (C6 durable water repellent range), Archroma, BASF.		Key References: Zero Discharge of Hazardous Chemicals Foundation, Manufacturing Restricted Substances List; European Union, restriction proposals under the Registration, Evaluation, Authorisation and Restriction of Chemicals regulation. Validated by Yamuna Machine Works Ltd, TMMA industry consultation, May 2026.	
Cross Media Effects: Fluorine-free alternatives generally require more frequent reapplication over the garment lifetime than fluorocarbon-based finishes, given their lower wash durability.			
India Context & Strategic Considerations: European Union restrictions on per- and polyfluoroalkyl substances in textiles are progressing, making PFAS-free reformulation an increasingly urgent requirement for India's export-oriented functional textile manufacturers.			

F3-31		Precision Spray Finishing Systems	
Transformation Direction Resource-Intelligent Manufacturing		TRL 8	Technology Type Process Technology
Technology Focus Area Advanced Sustainable Chemistry		Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Precision spray finishing systems apply textile finishing chemicals through electronically controlled spray nozzles that deliver measured quantities of functional formulations directly onto the fabric surface. Computer-controlled spray patterns, flow rates, nozzle positioning, and fabric transport ensure uniform chemical application while minimizing excess wet pickup. The system integrates chemical preparation, spray application, drying, and process monitoring within a continuous finishing line.			
Primary Applications: Functional finishing including water repellence, antimicrobial treatment, and softening applied at the stenter infeed stage.			
Environmental & Resource Benefits: Eliminates padding bath chemical disposal entirely and reduces overapplication compared with conventional pad application, since chemical is applied only in the quantity required rather than through full immersion.			
Indicative CAPEX (India context): TexCoat G4 (Baldwin): Rs 40 to 80 lakh depending on fabric width. [Validated by Yamuna Machine Works Ltd via TMMA, May 2026]		OPEX Savings / Payback Period: Payback 3 to 5 years from chemical and water savings.	
Key Performance Indicators (KPIs): Chemical Consumption per Square Metre Applied Relative to Padding; Bath Waste Eliminated; Application Uniformity.		Reference Industries: Organized mills in Tirupur, Ahmedabad, and Surat finishing operations.	
Key Adoption Challenges: Chemical Consumption per Square Metre Applied Relative to Padding; Bath Waste Eliminated; Application Uniformity.			
Technology Developers & Solution Providers: Global: Baldwin Technology (TexCoat G4 system), Weitmann and Konrad.		Key References: Apparel Impact Institute, Precision Spray Finishing Technology Assessment, TexCoat G4 documentation. Validated by Yamuna Machine Works Ltd, TMMA industry consultation, May 2026.	
Cross Media Effects: No offsetting trade-off; spray application itself uses no water and requires no bath disposal.			
India Context & Strategic Considerations: Precision spray finishing addresses a specific gap identified by the European Union Best Available Techniques Reference Document as an alternative finishing application method, with India entry expected to follow as brand requirements for precise, low-waste finishing increase.			

F3-32		Electrochemical Indigo Reduction	
Transformation Direction Innovation & Technology Origination		TRL 6	Technology Type Process Technology
Technology Focus Area Advanced Sustainable Chemistry		Roadmap Horizon Accelerate (2035–2047)	India Adoption (2026) Accelerate (2035–2047)
Technology Overview & Working Principle: Electrochemical indigo reduction systems convert insoluble indigo into its soluble leuco form through electrochemical reactions within a controlled electrolytic cell rather than relying solely on conventional chemical reducing agents. Electrical current drives reduction reactions under monitored operating conditions, while automated control systems regulate voltage, current density, electrolyte composition, and dye circulation to maintain stable reduction throughout the dyeing process.			
Primary Applications: Vat dye and indigo denim yarn dyeing.			
Environmental & Resource Benefits: Eliminates or substantially reduces sodium hydrosulphite consumption, removing the associated sulphate and sulphite discharge load from denim dyehouse effluent; published research demonstrates industry-level colour fastness properties achievable with this method.			
Indicative CAPEX (India context): Rs 30 to 100 lakh per electrochemical dyeing unit. [Indicative estimate only; not independently verified against a published market source.]		OPEX Savings / Payback Period: Sodium hydrosulphite chemical cost elimination; payback not fully quantified at pilot scale.	
Key Performance Indicators (KPIs): Colour Fastness Grade; Indigo Reduction Potential; Current Efficiency (%); Iron Mediator Removal from Fabric.		Reference Industries: Denim yarn dyeing mills, primarily concentrated in Ahmedabad.	
Key Adoption Challenges: Colour Fastness Grade; Indigo Reduction Potential; Current Efficiency (%); Iron Mediator Removal from Fabric.			
Technology Developers & Solution Providers: No commercial textile electrochemical dyeing system supplier identified; research-scale apparatus described in peer-reviewed literature.		Key References: Advanced Technology in Textiles, Springer Nature, published research on electrochemical dye reduction mechanisms.	
Cross Media Effects: Iron mediator removal from dyed fabric requires an additional processing step and associated chemical input not present in conventional reduction.			
India Context & Strategic Considerations: Ahmedabad's denim cluster is the primary application context for electrochemical indigo reduction in India, representing a longer-term research and development priority given the technology's current pilot-stage status.			

F3-33	Sol-Gel PFAS-Free Finishing	
Transformation Direction Innovation & Technology Origination	TRL 6	Technology Type Process Technology
Technology Focus Area Advanced Sustainable Chemistry	Roadmap Horizon Accelerate (2035–2047)	India Adoption (2026) Accelerate (2035–2047)
Technology Overview & Working Principle : Sol-gel functional finishing systems produce thin inorganic or hybrid organic-inorganic coatings on textile substrates through controlled hydrolysis and condensation of precursor solutions. The resulting nanostructured coating is deposited onto the fabric surface and subsequently cured to create durable functional layers. Process parameters including precursor composition, solution preparation, application method, drying, and curing are carefully controlled to ensure consistent coating formation and performance.		
Primary Applications: Technical textiles; sportswear water repellent finishing; outdoor apparel; workwear.		
Environmental & Resource Benefits: Eliminates per- and polyfluoroalkyl substances from the finishing process, addressing persistent organic pollutant concerns associated with conventional fluorocarbon durable water repellent chemistry.		
Indicative CAPEX (India context): Rs 20 to 60 lakh for sol-gel finishing preparation and application setup. [Indicative estimate only; not independently verified against a published market source.]	OPEX Savings / Payback Period: Payback period: 4 to 8 years, weighed against regulatory compliance risk avoidance and reformulation cost of PFAS-based alternatives.	
Key Performance Indicators (KPIs): Water Repellence Contact Angle (target above 140 degrees); Durability After Wash Cycles; Per- and Polyfluoroalkyl Substance Content (target non-detect); Nanoparticle Leaching in Wash Water.	Reference Industries: Technical textile exporters and sportswear manufacturers supplying European Union brands.	
Key Adoption Challenges: Water Repellence Contact Angle (target above 140 degrees); Durability After Wash Cycles; Per- and Polyfluoroalkyl Substance Content (target non-detect); Nanoparticle Leaching in Wash Water.		
Technology Developers & Solution Providers: Global: Rudolf GmbH (Bionic-Finish Eco), CHT Group, Sanitized AG.	Key References: European Union, restriction proposals under the Registration, Evaluation, Authorisation and Restriction of Chemicals regulation.	
Cross Media Effects: Nanoparticle release into wash water during use is an emerging area requiring further study relative to the PFAS discharge it replaces.		
India Context & Strategic Considerations: European Union restriction developments on per- and polyfluoroalkyl substances make sol-gel finishing an increasingly relevant PFAS-free alternative for India’s technical textile export sector.		

F3-34		Plasma Surface Treatment	
Transformation Direction Innovation & Technology Origination		TRL 7	Technology Type Process Technology
Technology Focus Area Advanced Sustainable Chemistry		Roadmap Horizon Accelerate (2035–2047)	India Adoption (2026) Accelerate (2035–2047)
Technology Overview & Working Principle: Plasma surface treatment systems modify textile surfaces using ionized gas generated under atmospheric or low-pressure conditions. Reactive plasma species interact with the outer fibre surface to alter surface energy, wettability, adhesion, or chemical functionality without affecting the bulk properties of the material. The process is performed within controlled treatment chambers or continuous atmospheric plasma systems, with automated regulation of gas composition, power input, treatment duration, and material handling.			
Primary Applications: Synthetic fibre surface treatment for improved dye uptake and bonding; technical textile surface preparation.			
Environmental & Resource Benefits: Entirely dry process requiring no water or chemical input, reducing chemical pretreatment load for applicable substrates.			
Indicative CAPEX (India context): Rs 100 to 300 lakh per plasma treatment unit. [Indicative estimate only; not independently verified against a published market source.]		OPEX Savings / Payback Period: Payback depends heavily on the specific water and chemical savings achieved relative to the conventional process being replaced; not precisely quantified in available data.	
Key Performance Indicators (KPIs): Surface Energy (contact angle below 10 degrees target); Dye Uptake Improvement (%); Water Saved Relative to Conventional Scouring.		Reference Industries: Technical textile and high-specification finishing mills.	
Key Adoption Challenges: Surface Energy (contact angle below 10 degrees target); Dye Uptake Improvement (%); Water Saved Relative to Conventional Scouring.			
Technology Developers & Solution Providers: Global: Enercon, Europlasma, Plasmatreat (openair-plasma technology).		Key References: European Commission, Joint Research Centre, Best Available Techniques Reference Document for the Textiles Industry.	
Cross Media Effects: Ozone and ultraviolet-based plasma configurations require off-gas management for worker safety.			
India Context & Strategic Considerations: Plasma surface treatment remains a technology to monitor rather than deploy in India's current wet processing sector, pending a clearer commercial case for conventional textile substrates as equipment costs decline internationally.			

F3-35		Plasma Wool Shrink-Resist Treatment	
Transformation Direction Innovation & Technology Origination		TRL 6	Technology Type Process Technology
Technology Focus Area Advanced Sustainable Chemistry		Roadmap Horizon Accelerate (2035–2047)	India Adoption (2026) Accelerate (2035–2047)
Technology Overview & Working Principle: Plasma wool shrink-resist treatment systems utilize controlled plasma discharge to modify the outer cuticle scales of wool fibres, reducing the fibre surface characteristics responsible for felting shrinkage. Surface activation is achieved through physical and chemical interactions between plasma species and the fibre surface under carefully controlled processing conditions. The treatment is integrated with continuous wool finishing operations using automated control of plasma intensity, treatment atmosphere, and processing speed.			
Primary Applications: Wool fabric shrink-proofing for machine-washable knitwear and sportswear.			
Environmental & Resource Benefits: Eliminates chlorination-derived adsorbable organic halide discharge, one of the more persistent and toxic effluent streams associated with conventional wool processing; entirely dry process with no water use.			
Indicative CAPEX (India context): Rs 80 to 200 lakh per plasma treatment unit. [Indicative estimate only; not independently verified against a published market source.]		OPEX Savings / Payback Period: Payback period: 5 to 10 years, driven primarily by regulatory compliance considerations rather than direct cost savings.	
Key Performance Indicators (KPIs): Shrink Resistance (area change below 3% after standard wash test); Felting Tendency; Plasma Treatment Speed; Adsorbable Organic Halide Reduction in Effluent.		Reference Industries: Ludhiana woollen sector; Bhilwara suiting; Kullu Valley wool processing.	
Key Adoption Challenges: Shrink Resistance (area change below 3% after standard wash test); Felting Tendency; Plasma Treatment Speed; Adsorbable Organic Halide Reduction in Effluent.			
Technology Developers & Solution Providers: Global: Enercon, Plasmatreat.		Key References: European Commission, Joint Research Centre, Best Available Techniques Reference Document for the Textiles Industry, section on emerging techniques for wool processing.	
Cross Media Effects: Ozone and ultraviolet off-gas management is required for worker safety in plasma treatment, though the process itself uses no water.			
India Context & Strategic Considerations: Ludhiana is India's principal wool processing cluster, and plasma-based shrink-resist treatment is identified as an emerging best available technique target for wool processing in the European Union reference framework, positioning it as a future compliance consideration for India's wool exporters.			

F3-36		Zero Liquid Discharge (ZLD) Systems	
Transformation Direction Resource-Intelligent Manufacturing		TRL 9	Technology Type Resource Recovery Technology
Technology Focus Area Circular Resource Recovery		Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Zero Liquid Discharge (ZLD) systems integrate multiple physical, chemical, and thermal treatment technologies to recover water and eliminate liquid effluent discharge from industrial facilities. The treatment sequence typically combines primary treatment, biological treatment, membrane separation, concentration, and crystallization processes to progressively recover reusable water while converting dissolved solids into manageable solid residues. Automated monitoring and process control coordinate the operation of individual treatment units within the integrated system.			
Primary Applications: All wet processing clusters operating under zero liquid discharge regulatory mandate, including Tirupur, Surat, and Pali-Balotra.			
Environmental & Resource Benefits: Achieves water recovery rates of 75 to 90 percent and eliminates liquid effluent discharge entirely, addressing acute water stress in India's dyeing clusters.			
Indicative CAPEX (India context): Rs 150 to 200 lakh per 100 kilolitre per day for base CAPEX (verified against 2025-26 Indian market benchmarks), rising to Rs 600 to 1,200 lakh per 500 kilolitre per day and Rs 1,200 to 2,500 lakh or more per 1 million litre per day for large installations with crystalliser and high-TDS handling; final cost is highly sensitive to effluent salinity and technology stack selected.		OPEX Savings / Payback Period: Water recovery value and regulatory compliance protection against shutdown risk; payback period: 8 to 15 years.	
Key Performance Indicators (KPIs): Water Recovery Rate (%); Final Effluent Total Dissolved Solids; Salt Recovery Rate (where crystallizer used); Energy Consumption per Cubic Metre Treated.		Reference Industries: Tirupur, recognized as India's first zero liquid discharge textile cluster; Surat; Pali-Balotra, Rajasthan; Ahmedabad.	
Key Adoption Challenges: Water Recovery Rate (%); Final Effluent Total Dissolved Solids; Salt Recovery Rate (where crystallizer used); Energy Consumption per Cubic Metre Treated.			
Technology Developers & Solution Providers: Global: Aquatech, Veolia, SUEZ. India: Thermax, Ion Exchange India, Praj Industries.		Key References: Spans Envirotech, ETP Plant Cost India 2025 and ZLD Plant Cost India 2025, Effluent Treatment Plant Price Guides; Central Pollution Control Board, Zero Liquid Discharge guidelines.	
Cross Media Effects: Multiple effect evaporation is highly energy intensive; salt and sludge by-products require disposal or a reuse pathway to avoid becoming a new hazardous waste burden.			
India Context & Strategic Considerations: Tirupur's zero liquid discharge transition, achieved through combined effluent treatment plants and reverse osmosis recovery systems, stands as a globally recognized case study now being extended to Surat, Pali-Balotra, and Sanganer.			

F3-37		Reverse Osmosis (RO)	
Transformation Direction Resource-Intelligent Manufacturing		TRL 9	Technology Type Resource Recovery Technology
Technology Focus Area Circular Resource Recovery		Roadmap Horizon Align (2026–2030)	India Adoption (2026)Align (2026–2030)
Technology Overview & Working Principle : Reverse osmosis water recovery systems utilize semi-permeable membranes to separate dissolved salts, colour, organic compounds, and other contaminants from treated industrial wastewater under high pressure. The process produces purified permeate suitable for reuse while concentrating dissolved contaminants into a reject stream for further treatment. Automated pressure control, membrane monitoring, flow regulation, and cleaning systems maintain stable separation performance and water recovery efficiency.			
Primary Applications: Zero liquid discharge system feed concentration; effluent reuse applications outside full zero liquid discharge configurations.			
Environmental & Resource Benefits: Enables direct process water reuse from permeate, providing a substantial freshwater replacement, while concentrating the reject stream for further processing in multiple effect evaporation.			
Indicative CAPEX (India context): Rs 30 to 80 lakh per 100 kilolitre per day reverse osmosis unit. [Indicative estimate only; not independently verified against a published market source.]		OPEX Savings / Payback Period: Water recovery rates of 75 to 85 percent are typical for textile reverse osmosis applications; payback depends on water reuse value and regulatory compliance requirements.	
Key Performance Indicators (KPIs): Water Recovery Rate (%); Permeate Total Dissolved Solids (target below 500 milligrams per litre for reuse); Membrane Flux; Membrane Life.		Reference Industries: Tirupur, Surat, Pali-Balotra, and Ahmedabad effluent treatment plants.	
Key Adoption Challenges: Water Recovery Rate (%); Permeate Total Dissolved Solids (target below 500 milligrams per litre for reuse); Membrane Flux; Membrane Life.			
Technology Developers & Solution Providers: Global: DuPont Water Solutions, Toray, Hydranautics, Koch Separation Solutions. India: Ion Exchange India, Thermax.		Key References: Central Pollution Control Board, Zero Liquid Discharge guidelines.	
Cross Media Effects: Energy consumption of 5 to 10 kilowatt-hours per cubic metre for high total dissolved solids textile effluent is the principal trade-off, alongside membrane replacement waste.			
India Context & Strategic Considerations: Reverse osmosis is the central technology enabling Tirupur's zero liquid discharge transition, and Ion Exchange India and Thermax are established domestic suppliers of textile-scale reverse osmosis systems.			

F3-38		Caustic Soda Recovery	
Transformation Direction Resource-Intelligent Manufacturing		TRL 9	Technology Type Resource Recovery Technology
Technology Focus Area Circular Resource Recovery		Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle : Caustic soda recovery systems regenerate spent sodium hydroxide solutions generated during textile mercerization through evaporation and concentration processes. Multi-effect evaporators or similar thermal concentration systems remove water from dilute caustic solutions to restore the concentration required for reuse within the mercerizing process. Automated process control regulates temperature, pressure, concentration, and flow conditions to maintain consistent chemical recovery.			
Primary Applications: Cotton woven mercerising, including denim mercerising and knit tubular mercerising operations.			
Environmental & Resource Benefits: Recovered caustic reduces sodium hydroxide purchase requirement and substantially reduces total dissolved solids load in effluent, an important contribution to zero liquid discharge system performance.			
Indicative CAPEX (India context): Low-temperature evaporator unit: Rs 40 to 80 lakh per unit. [Validated by Yamuna Machine Works Ltd via TMMA, May 2026]		OPEX Savings / Payback Period: Payback 2 to 4 years from caustic savings.	
Key Performance Indicators (KPIs): Caustic Recovery Rate (%); Sodium Hydroxide Concentration in Recovered Stream; Steam Consumption for Evaporation; Effluent Total Dissolved Solids Reduction.		Reference Industries: Gujarat mills with large mercerising units (validated reference region)	
Key Adoption Challenges: Caustic Recovery Rate (%); Sodium Hydroxide Concentration in Recovered Stream; Steam Consumption for Evaporation; Effluent Total Dissolved Solids Reduction.			
Technology Developers & Solution Providers: Global: Kusters, Goller (mercerising machines); Alfa Laval, GEA (evaporation systems). India: Thermax.		Key References: European Commission, Joint Research Centre, Best Available Techniques Reference Document for the Textiles Industry. Validated by Yamuna Machine Works Ltd, TMMA industry consultation, May 2026.	
Cross Media Effects: Steam energy for evaporation is required and represents an ongoing operating cost and fuel demand.			
India Context & Strategic Considerations: Caustic recovery is documented in Gujarat processing mills as delivering demonstrated payback, and is recognized as best available technique for mercerising operations under both European and Gujarat reference frameworks.			

F3-39		Primary Effluent Treatment Plants (ETP)	
Transformation Direction Resource-Intelligent Manufacturing		TRL 9	Technology Type Resource Recovery Technology
Technology Focus Area Circular Resource Recovery		Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Primary effluent treatment plants remove suspended solids, colour, oils, and other readily separable contaminants from textile wastewater through a combination of physical and chemical treatment processes. Treatment typically includes screening, equalization, pH adjustment, coagulation, flocculation, sedimentation, and sludge separation prior to biological treatment. Integrated instrumentation and automated chemical dosing systems regulate treatment performance under varying wastewater characteristics.			
Primary Applications: All textile effluent treatment plants and common effluent treatment plants, representing a universal baseline requirement.			
Environmental & Resource Benefits: Achieves colour removal of 60 to 80 percent and suspended solids removal exceeding 90 percent, enabling effective downstream biological treatment.			
Indicative CAPEX (India context): Rs 20 to 50 lakh for a 50 kilolitre per day basic biological and coagulation system, rising to Rs 150 to 400 lakh for a 500 kilolitre per day installation and Rs 800 lakh or more for a fully automated 1 million litre per day plant (verified against 2025 Indian market benchmarks).		OPEX Savings / Payback Period: Primarily a regulatory compliance investment; ongoing chemical and sludge disposal cost of approximately Rs 2 to 5 lakh per year.	
Key Performance Indicators (KPIs): Colour Removal (%); Suspended Solids in Settled Effluent; Chemical Oxygen Demand Reduction (%); Sludge Volume Generated.		Reference Industries: All textile effluent treatment plants and common effluent treatment plants across India.	
Key Adoption Challenges: Colour Removal (%); Suspended Solids in Settled Effluent; Chemical Oxygen Demand Reduction (%); Sludge Volume Generated.			
Technology Developers & Solution Providers: Global: SUEZ, BASF (polyelectrolytes). India: Thermax, Ion Exchange India.		Key References: Spans Envirotech, ETP Plant Cost India 2025, Effluent Treatment Plant Price Guide; Central Pollution Control Board, effluent treatment plant design guidelines.	
Cross Media Effects: Sludge generated is classified as hazardous waste requiring compliant transport and disposal, and coagulant chemical input is an ongoing consumable.			
India Context & Strategic Considerations: Coagulation-flocculation is a universal baseline requirement across India's textile effluent treatment infrastructure and forms the foundation upon which all further treatment, including zero liquid discharge, is built.			

F3-40	Membrane Bioreactor (MBR)	
Transformation Direction Resource-Intelligent Manufacturing	TRL 9	Technology Type Resource Recovery Technology
Technology Focus Area Circular Resource Recovery	Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Membrane bioreactor systems combine biological wastewater treatment with membrane filtration within an integrated treatment process. Biological microorganisms degrade dissolved organic matter while submerged or external membrane modules separate treated water from biomass and suspended solids. Automated control systems continuously regulate aeration, membrane filtration, sludge management, and cleaning cycles to maintain stable biological treatment and filtration performance.		
Primary Applications: Textile effluent treatment plant secondary treatment; common effluent treatment plant upgrades supporting zero liquid discharge readiness.		
Environmental & Resource Benefits: Achieves 70 to 80 percent chemical oxygen demand removal and suspended solids below 5 milligrams per litre, providing high-quality feed water for downstream reverse osmosis and reducing membrane fouling in subsequent treatment stages.		
Indicative CAPEX (India context): Rs 40 to 120 lakh per 100 kilolitre per day membrane bioreactor unit. [Indicative estimate only; not independently verified against a published market source.]	OPEX Savings / Payback Period: Improved effluent quality reduces reverse osmosis fouling and associated operating cost in downstream zero liquid discharge processing. Payback period: 6 to 10 years.	
Key Performance Indicators (KPIs): Chemical Oxygen Demand Removal (%); Suspended Solids in Permeate; Membrane Flux; Membrane Life.	Reference Industries: Tirupur common effluent treatment plants; large Ahmedabad mills; Pali effluent treatment infrastructure.	
Key Adoption Challenges: Chemical Oxygen Demand Removal (%); Suspended Solids in Permeate; Membrane Flux; Membrane Life.		
Technology Developers & Solution Providers: Global: Xylem, Pall Corporation, Koch Membrane Systems. India: Ion Exchange India.	Key References: European Commission, Joint Research Centre, Best Available Techniques Reference Document for the Textiles Industry.	
Cross Media Effects: Concentrated sludge from the membrane process requires hazardous waste disposal; membrane replacement generates periodic waste.		
India Context & Strategic Considerations: Membrane bioreactor technology is increasingly specified for India textile effluent treatment plant upgrades, since consistent feed water quality is essential for reliable zero liquid discharge system performance.		

F3-41	Advanced Oxidation Processes (AOP)	
Transformation Direction Resource-Intelligent Manufacturing	TRL 8	Technology Type Resource Recovery Technology
Technology Focus Area Circular Resource Recovery	Roadmap Horizon Amplify (2030–2035)	India Adoption (2026)Amplify (2030–2035)
Technology Overview & Working Principle: Advanced oxidation process systems generate highly reactive oxidizing species capable of degrading persistent organic compounds, colour, and refractory contaminants that are resistant to conventional biological treatment. Oxidation may be achieved through combinations of ozone, ultraviolet radiation, hydrogen peroxide, catalysts, or electrochemical processes under controlled operating conditions. Automated systems regulate oxidant generation, reaction conditions, and treatment performance to achieve targeted contaminant degradation.		
Primary Applications: Post-biological treatment colour removal; common effluent treatment plant polishing; brine concentrate treatment in zero liquid discharge systems.		
Environmental & Resource Benefits: Achieves colour removal exceeding 90 percent from reactive dye effluent and degrades organic compounds resistant to biological treatment, enabling water reuse.		
Indicative CAPEX (India context): Rs 25 to 80 lakh per 100 kilolitre per day advanced oxidation unit. [Indicative estimate only; not independently verified against a published market source.]	OPEX Savings / Payback Period: Payback period: 5 to 10 years, driven by colour compliance requirements and enabling downstream water reuse.	
Key Performance Indicators (KPIs): Colour Removal (%); Chemical Oxygen Demand Reduction (%); Hydrogen Peroxide or Ozone Dose; Energy Consumption per Cubic Metre Treated.	Reference Industries: Tirupur and Surat common effluent treatment plant polishing stages; Pali-Balotra brine concentrate treatment.	
Key Adoption Challenges: Colour Removal (%); Chemical Oxygen Demand Reduction (%); Hydrogen Peroxide or Ozone Dose; Energy Consumption per Cubic Metre Treated.		
Technology Developers & Solution Providers: Global: Trojan Technologies, Xylem (Ozonía). India: Aquatech, Ion Exchange India.	Key References: European Commission, Joint Research Centre, Best Available Techniques Reference Document for the Textiles Industry; Gujarat Pollution Control Board, colour discharge limit guidance.	
Cross Media Effects: High energy consumption for ultraviolet or ozone generation is the principal trade-off, together with hydrogen peroxide chemical input where used.		
India Context & Strategic Considerations: Gujarat Pollution Control Board has established colour discharge limits for Surat's textile effluent, making advanced oxidation processes a primary compliance pathway for this constraint.		

F3-42	UASB Biogas Recovery	
Transformation Direction Resource-Intelligent Manufacturing	TRL 9	Technology Type Resource Recovery Technology
Technology Focus Area Circular Resource Recovery	Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Upflow Anaerobic Sludge Blanket (UASB) systems biologically treat high-strength industrial wastewater under anaerobic conditions while simultaneously producing biogas. Wastewater flows upward through a dense blanket of anaerobic microorganisms that convert biodegradable organic matter into methane-rich biogas and stabilized biomass. Gas-solid-liquid separation systems, sludge management, and process monitoring maintain stable reactor operation and continuous biogas collection.		
Primary Applications: Large wet processing mills generating high chemical oxygen demand effluent from cotton reactive dyeing and printing operations.		
Environmental & Resource Benefits: Achieves 60 to 70 percent chemical oxygen demand removal before aerobic treatment, generating biogas that can offset fossil fuel consumption elsewhere in the facility, while reducing the aeration energy required for downstream aerobic treatment.		
Indicative CAPEX (India context): Rs 30 to 80 lakh per 100 kilolitre per day upflow anaerobic sludge blanket unit. [Indicative estimate only; not independently verified against a published market source.]	OPEX Savings / Payback Period: Biogas energy recovery value and reduced aeration cost. Payback period: 5 to 10 years.	
Key Performance Indicators (KPIs): Chemical Oxygen Demand Removal in Upflow Anaerobic Sludge Blanket Stage (%); Biogas Yield per kg Chemical Oxygen Demand Removed; Methane Content of Biogas; Downstream Aerobic Energy Reduction.	Reference Industries: Large integrated mills in Tirupur and Surat with consistently high chemical oxygen demand effluent streams.	
Key Adoption Challenges: Chemical Oxygen Demand Removal in Upflow Anaerobic Sludge Blanket Stage (%); Biogas Yield per kg Chemical Oxygen Demand Removed; Methane Content of Biogas; Downstream Aerobic Energy Reduction.		
Technology Developers & Solution Providers: Global: Paques, Veolia. India: Praj Industries, Ion Exchange India.	Key References: European Commission, Joint Research Centre, Best Available Techniques Reference Document for the Textiles Industry.	
Cross Media Effects: Uncaptured methane slip from the anaerobic process is a greenhouse gas risk requiring flaring or utilization rather than venting.		
India Context & Strategic Considerations: Anaerobic pre-treatment can reduce total effluent treatment plant energy consumption by a meaningful margin in large integrated mills, and Praj Industries is an established Indian supplier of this technology.		

F3-43		Sludge Drying Technologies	
Transformation Direction Resource-Intelligent Manufacturing		TRL 9	Technology Type Resource Recovery Technology
Technology Focus Area Circular Resource Recovery		Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Sludge drying and resource recovery systems reduce the moisture content of wastewater treatment sludge using thermal, solar, mechanical, or hybrid drying technologies prior to transport, disposal, or beneficial utilization. Integrated sludge handling equipment, drying systems, material conveying, and storage infrastructure ensure controlled processing of dewatered sludge. Automated monitoring of temperature, moisture content, and material flow supports stable drying performance and downstream resource recovery or disposal operations.			
Primary Applications: Effluent treatment plant and common effluent treatment plant sludge dewatering across all textile processing clusters.			
Environmental & Resource Benefits: Reduces sludge volume by approximately 80 percent, lowering transport-related emissions and disposal cost, and enabling co-processing options that recover material value from otherwise landfilled sludge.			
Indicative CAPEX (India context): Rs 20 to 60 lakh per paddle dryer; Rs 5 to 15 lakh per 100 square metres of covered solar drying bed. [Indicative estimate only; not independently verified against a published market source.]		OPEX Savings / Payback Period: Reduced sludge disposal transport cost through volume reduction. Payback period: 4 to 8 years for mechanical dryers; comparatively lower cost for solar drying where land is available.	
Key Performance Indicators (KPIs): Moisture Content Reduction (%); Sludge Volume Reduction; Energy Consumption per Tonne of Water Evaporated (mechanical dryers only).		Reference Industries: All cluster effluent treatment plants, including Tirupur, Surat, and Pali-Balotra.	
Key Adoption Challenges: Moisture Content Reduction (%); Sludge Volume Reduction; Energy Consumption per Tonne of Water Evaporated (mechanical dryers only).			
Technology Developers & Solution Providers: Global: Nara Machinery (paddle dryers). India: local fabricators for solar drying bed construction.		Key References: Central Pollution Control Board, Hazardous Waste Management Rules.	
Cross Media Effects: Mechanical paddle drying requires steam energy; solar drying requires significant land area, both trade-offs against the sludge volume and transport emissions reduction achieved.			
India Context & Strategic Considerations: Gujarat's high solar irradiance makes solar sludge drying particularly well suited to the state's textile processing clusters, while mechanical paddle dryers remain necessary where land is constrained.			

F3-44		Closed-Loop Process Water Recycling Systems	
Transformation Direction Resource-Intelligent Manufacturing		TRL 8	Technology Type Resource Recovery Technology
Technology Focus Area Circular Resource Recovery		Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Closed-loop process water recycling systems recover, purify, and recirculate treated process water within textile manufacturing facilities through an integrated treatment and reuse infrastructure. The system combines wastewater treatment, membrane filtration, disinfection, storage, and distribution to continuously supply recycled water for suitable process applications. Automated monitoring of water quality, flow, and treatment performance ensures reliable operation while maintaining compliance with process water quality requirements.			
Primary Applications: Denim garment washing and wet processing water recycling at the facility level.			
Environmental & Resource Benefits: Targets 90 to 100 percent water recycling for the specific process stream addressed, eliminating per-unit effluent disposal requirements for that processing step.			
Indicative CAPEX (India context): Rs 200 to 500 lakh per closed-loop recycling system. [Indicative estimate only; not independently verified against a published market source.]		OPEX Savings / Payback Period: Water and effluent disposal cost savings; payback dependent on facility scale and local water tariff structure.	
Key Performance Indicators (KPIs): Water Recycling Rate (%); Effluent to Drain (target near zero); Recycled Water Quality (total dissolved solids, colour); Energy for Reverse Osmosis and Ultraviolet Treatment.		Reference Industries: Ahmedabad denim garment factories; Bengaluru denim wash units.	
Key Adoption Challenges: Water Recycling Rate (%); Effluent to Drain (target near zero); Recycled Water Quality (total dissolved solids, colour); Energy for Reverse Osmosis and Ultraviolet Treatment.			
Technology Developers & Solution Providers: Global: Jeanologia (H2Zero system).		Key References: Jeanologia, H2Zero Water-Saving Dyeing Technology for Denim Processing documentation.	
Cross Media Effects: Reverse osmosis concentrate from the closed loop requires disposal, and energy is required for ultraviolet treatment and membrane pumping.			
India Context & Strategic Considerations: Ahmedabad's substantial denim garment washing sector represents the primary India application context for closed-loop process water recycling technology.			

F3-45	Closed-Loop Water & Chemical Systems	
Transformation Direction Resource-Intelligent Manufacturing	TRL 6	Technology Type Process Technology
Technology Focus Area Circular Resource Recovery	Roadmap Horizon Accelerate (2035–2047)	India Adoption (2026) Accelerate (2035–2047)

Technology Overview & Working Principle: Closed-loop water and chemical recovery systems integrate water recycling with the recovery, purification, and reuse of selected process chemicals from textile manufacturing operations. Separation technologies such as membrane filtration, evaporation, distillation, ion exchange, or chemical concentration are combined with water treatment to recover reusable process streams. Centralized process control continuously monitors water quality, chemical concentration, and recovery efficiency to maintain stable operation across interconnected recycling systems.

Primary Applications: Advanced wet processing facilities pursuing comprehensive circular resource management.	
Environmental & Resource Benefits: Would extend water recycling benefits to include chemical recovery and reuse, further reducing both fresh water intake and chemical purchase requirements if fully realized at commercial scale.	
Indicative CAPEX (India context): Not commercially costed; research and demonstration stage.	OPEX Savings / Payback Period: Not applicable at current pre-commercial stage.
Key Performance Indicators (KPIs): Combined Water and Chemical Recovery Rate (%); Fresh Water Intake Reduction; Chemical Purchase Reduction.	Reference Industries: No confirmed India commercial installation identified.
Key Adoption Challenges: Combined Water and Chemical Recovery Rate (%); Fresh Water Intake Reduction; Chemical Purchase Reduction.	
Technology Developers & Solution Providers: No specific commercial supplier identified for fully integrated water and chemical closed-loop systems at this technology readiness level.	Key References: European Commission, Joint Research Centre, Best Available Techniques Reference Document for the Textiles Industry, emerging techniques section.
Cross Media Effects: Integrating chemical recovery alongside water recycling would introduce additional process energy and reagent requirements not yet characterized at commercial scale.	
India Context & Strategic Considerations: This represents a longer-term research and development horizon building upon the closed-loop water recycling systems already being deployed in Ahmedabad's denim sector, extending the circularity principle to chemical inputs as well.	

F3-46	Laser & Ozone Denim Finishing	
Transformation Direction Resource-Intelligent Manufacturing	TRL 9	Technology Type Process Technology
Technology Focus Area Specialty Processing	Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)

Technology Overview & Working Principle: Laser and ozone denim finishing systems create faded, worn, and decorative surface effects using digitally controlled laser engraving and ozone oxidation technologies. Laser systems selectively modify the indigo-dyed fabric surface through programmed energy delivery, while ozone treatment oxidizes indigo colour under controlled atmospheric conditions within enclosed processing chambers. Computer-controlled process parameters ensure consistent finishing patterns and repeatable treatment quality across production batches.

Primary Applications: Denim jeans finishing, including whiskering, fading, and distressing effects.	
Environmental & Resource Benefits: Eliminates potassium permanganate discharge entirely, along with the silicosis risk associated with sandblasting, replacing both with a digitally controlled, largely dry finishing process for laser treatment, and a substantially reduced water and chemical footprint for ozone treatment compared with conventional stone or chemical washing.	
Indicative CAPEX (India context): Laser fading unit (Jeanologia EVO): Rs 15 to 40 lakh. Ozone cabinet (Jeanologia G2 or Tonello): Rs 5 to 15 lakh. Standalone ozone generator and reaction chamber for denim bleaching (substituting sodium hypochlorite): Rs 15 to 40 lakh per installation. Related air-based system, Jeanologia Atmos (atmospheric washing, no water): Rs 80 to 150 lakh, with the complementary eFlow system at Rs 25 to 50 lakh. [Validated by GA Morgan Dynamics Pvt Ltd and Yamuna Machine Works Ltd via TMMA, May 2026]	OPEX Savings / Payback Period: Payback 3 to 5 years from chemical, water, and liability cost savings for laser and ozone systems; 4 to 6 years for the Atmos air-based system. Jeanologia penetration is confirmed as growing in Ahmedabad and Bengaluru denim units.
Key Performance Indicators (KPIs): Garments per Hour; Water Consumption (near zero for laser stage); Potassium Permanganate Discharge (target zero); Silicosis Incident Rate (target zero).	Reference Industries: Ahmedabad denim garment washing; Bengaluru denim finishing.
Key Adoption Challenges: Garments per Hour; Water Consumption (near zero for laser stage); Potassium Permanganate Discharge (target zero); Silicosis Incident Rate (target zero).	
Technology Developers & Solution Providers: Global: Jeanologia (Atmos laser system, G2 ozone system), Tonello.	Key References: Gujarat Pollution Control Board, industry guidance on hazardous chemical restrictions in denim processing. Validated by GA Morgan Dynamics Pvt Ltd and Yamuna Machine Works Ltd, TMMA industry consultation, May 2026.
Cross Media Effects: Laser dust requires extraction ventilation; ozone treatment requires off-gas management for worker safety.	
India Context & Strategic Considerations: Ahmedabad is India's principal denim manufacturing centre, and Gujarat Pollution Control Board restrictions on potassium permanganate use are a significant regulatory driver accelerating the adoption of laser and ozone finishing as replacement technologies.	

F3-47		Digital Inkjet Textile Printing	
Transformation Direction Resource-Intelligent Manufacturing		TRL 9	Technology Type Manufacturing Equipment
Technology Focus Area Specialty Processing		Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Digital inkjet textile printing systems deposit textile inks directly onto fabric using computer-controlled print heads that precisely eject microscopic droplets according to digital design data. The process integrates digital image processing, colour management, fabric transport, ink delivery, drying, and fixation within a continuous production workflow. Automated print control ensures accurate pattern reproduction, colour consistency, and repeatable printing performance across varying production runs.			
Primary Applications: Short-run fashion fabric printing; customized and personalized prints; athleisure fabric; home furnishing fabric; sari and dress material printing.			
Environmental & Resource Benefits: Eliminates screen washing water entirely and removes residual print paste waste; industry data indicates approximately 70 percent water saving compared with rotary screen printing when accounting for the full printing process including screen preparation and cleaning.			
Indicative CAPEX (India context): Multi-pass printer: Rs 15 to 50 lakh, with Chinese brands cost-competitive. Single-pass industrial line: Rs 100 to 500 lakh. [Validated by Yamuna Machine Works Ltd via TMMA, May 2026]		OPEX Savings / Payback Period: Payback 3 to 5 years for multi-pass short-run flexibility; 5 to 8 years for single-pass at volume.	
Key Performance Indicators (KPIs): Print Resolution (dots per inch); Ink Consumption per Square Metre; Production Speed; Colour Gamut Range.		Reference Industries: Surat digital textile printing sector, showing rapid growth; Tirupur; Jaipur sari and dress material printing.	
Key Adoption Challenges: Print Resolution (dots per inch); Ink Consumption per Square Metre; Production Speed; Colour Gamut Range.			
Technology Developers & Solution Providers: Global: EFI Reggiani, MS Printing Solutions, Kornit Digital, Mimaki, Epson. India: Colorjet India, Ahmedabad.		Key References: European Commission, Joint Research Centre, Best Available Techniques Reference Document for the Textiles Industry. Validated by Yamuna Machine Works Ltd, TMMA industry consultation, May 2026.	
Cross Media Effects: Ink fixation requires steam or thermosol energy input for curing, though this is common to both digital and conventional printing routes.			
India Context & Strategic Considerations: Colorjet India, based in Ahmedabad, is a confirmed domestic manufacturer of digital textile printing machines, and Surat's digital printing sector is expanding rapidly as an alternative to conventional rotary screen printing for shorter production runs.			

F3-48		Nanotechnology Functional Coatings (Nano-Silver, Nano-TiO2, Nano-Silica)	
Transformation Direction Resource-Intelligent Manufacturing		TRL 8	Technology Type Material Innovation
Technology Focus Area Advanced Sustainable Chemistry		Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Functional nanotechnology coating systems apply engineered nanoscale materials to textile surfaces to impart specialized physical, chemical, or biological properties. Nanomaterials are deposited through coating, padding, spraying, sol-gel processing, or similar application techniques, followed by controlled drying and curing. Process parameters governing particle dispersion, coating uniformity, deposition rate, and curing conditions are carefully controlled to achieve consistent functional surface characteristics.			
Primary Applications: Medical textiles requiring antimicrobial properties; sportswear requiring odour control; outdoor fabrics requiring ultraviolet protection; protective workwear; broader technical textile applications.			
Environmental & Resource Benefits: Achieves functional performance, such as antimicrobial activity, at very low particle loading compared with conventional chemical finishes, potentially reducing total chemical mass applied per unit of fabric for equivalent functional performance.			
Indicative CAPEX (India context): Nanoparticle synthesis or purchase and application system: Rs 500 to 1,500 lakh for a specialty finishing unit. [Validated by Yamuna Machine Works Ltd via TMMA, May 2026]		OPEX Savings / Payback Period: Payback 5 to 8 years, justified through premium product value rather than cost avoidance.	
Key Performance Indicators (KPIs): Antimicrobial efficacy retention after wash cycles; ultraviolet protection factor; wash durability of functional coating; nanoparticle release rate into wash water.		Reference Industries: Limited to research and development institutions and specialty finishing units. [TMMA-validated]	
Key Adoption Challenges: Antimicrobial efficacy retention after wash cycles; ultraviolet protection factor; wash durability of functional coating; nanoparticle release rate into wash water.			
Technology Developers & Solution Providers: No specific commercial supplier named by validator; application is described as specialty and R&D-institution concentrated in India at present.		Key References: Validated by Yamuna Machine Works Ltd, TMMA industry consultation, May 2026.	
Cross Media Effects: Nanoparticle release into wash water during garment laundering is an emerging environmental and ecotoxicological concern, particularly for nano-silver, requiring further study before broad adoption can be considered environmentally favourable relative to conventional finishes.			
India Context & Strategic Considerations: This technology is broader in application scope than the sol-gel PFAS-free finishing already covered in F4-20 — that card addresses water repellence specifically via silica or titanium dioxide nanolayers, while this card covers antimicrobial, UV-protective, and odour-control applications using a wider range of nanoparticle types including nano-silver, which carries a distinct and more significant ecotoxicological profile.			

F3-49		Radio-Frequency Drying for Yarn and Technical Textiles	
Transformation Direction Resource-Intelligent Manufacturing		TRL 8	Technology Type Process Technology
Technology Focus Area Specialty Processing		Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Radio frequency drying systems remove moisture from textile materials by generating electromagnetic fields that produce volumetric heating within the material. Moisture molecules absorb radio frequency energy, enabling uniform internal heating and controlled moisture removal throughout the product. Integrated control systems regulate power output, treatment time, material transport, and drying conditions to ensure consistent moisture reduction across different textile substrates.			
Primary Applications: Yarn package drying after dyeing, and drying of technical textiles where uniform moisture removal through a thick or dense material is required.			
Environmental & Resource Benefits: Reduces drying energy and time relative to conventional convective drying for substrates where uniform through-drying is otherwise difficult to achieve, avoiding the over-drying of surface layers needed to fully dry the core.			
Indicative CAPEX (India context): Rs 5,000 to 20,000 lakh depending on system power rating and working width. [Validated by TMMA General cross-cutting consultation, May 2026]		OPEX Savings / Payback Period: Payback 4 to 7 years.	
Key Performance Indicators (KPIs): Drying time relative to conventional convective drying; moisture uniformity through substrate thickness; energy consumption per kilogram of water removed.		Reference Industries: Very low — limited India installations; Strayfield is confirmed as entering the India market. [TMMA-validated]	
Key Adoption Challenges: Drying time relative to conventional convective drying; moisture uniformity through substrate thickness; energy consumption per kilogram of water removed.			
Technology Developers & Solution Providers: Strayfield (radio-frequency drying systems, entering India market per validator; exhibited at ITMA Asia Singapore 2025).		Key References: Validated by TMMA cross-cutting general technology consultation, May 2026.	
Cross Media Effects: Lower energy consumption than conventional drying for suitable substrates; no water or chemical impact; electromagnetic field management is a workplace safety rather than environmental consideration.			
India Context & Strategic Considerations: Strayfield's entry into the India market, confirmed by validators and consistent with its exhibition at ITMA Asia Singapore 2025, positions this as an emerging rather than established India technology, with the narrowest cost-effective application being yarn packages and technical textiles specifically rather than general-purpose fabric drying.			



F4-01		CAD/CAM Pattern Making	
Transformation Direction Digital Infrastructure & Traceability		TRL 9	Technology Type Design & Digital Technology
Technology Focus Area Digital Product Development		Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: CAD/CAM pattern making systems digitize garment pattern development, grading, marker planning, and production preparation within an integrated computer-aided design and manufacturing environment. Designers develop and modify digital pattern pieces that are automatically graded into multiple sizes and arranged into optimized cutting markers. The system integrates design software, pattern databases, marker optimization algorithms, and downstream cutting equipment to enable standardized pattern development and seamless transfer of production data.			
Primary Applications: Digital pattern grading and marker planning for woven and knit garment cutting across all garment categories.			
Environmental & Resource Benefits: Manual marker making typically generates 10 to 15 percent cutting waste; software-optimized marker planning reduces this waste, directly lowering fabric consumption, embedded water, and dye chemical waste per garment produced.			
Indicative CAPEX (India context): 2D CAD licence: Rs 5 to 15 lakh per workstation (Gerber or Lectra). 3D virtual prototyping: Rs 8 to 25 lakh per seat. Related automated cutting hardware (Gerber Z7, Lectra Vector, or Morgan-brand cutters): single-ply cutting range Rs 150 to 200 lakh; multi-ply automated cutting Rs 120 to 170 lakh depending on target garment productivity. Automatic fabric spreading machine: Rs 15 to 40 lakh. [Validated by GA Morgan Dynamics Pvt Ltd via TMMa, May 2026]		OPEX Savings / Payback Period: Payback 2 to 3 years from fabric savings alone for CAD/CAM software; validator corrected the automated cutting hardware payback to 2.5 years, shorter than originally estimated 3 to 5 years.	
Key Performance Indicators (KPIs): Marker Efficiency or Fabric Utilization (%); Pattern Grading Accuracy; Marker Planning Time per Style.		Reference Industries: Reference plants confirmed by validator: Arvind, Kitex, Rupa, Lux, Meenu, Blueback, Best Corp, Savi Global	
Key Adoption Challenges: Marker Efficiency or Fabric Utilization (%); Pattern Grading Accuracy; Marker Planning Time per Style.			
Technology Developers & Solution Providers: Global: Gerber Technology, Lectra. India: Tukatech partnership presence.		Key References: Baseline Assessment Report, textile manufacturing waste data; Partnership for Cleaner Textile, apparel efficiency case studies. Validated by GA Morgan Dynamics Pvt Ltd, TMMa industry consultation, May 2026.	
Cross Media Effects: No offsetting trade-off; software licensing and workstation electricity demand is negligible relative to the fabric waste avoided.			
India Context & Strategic Considerations: Manual marker making continues to generate approximately 10 to 15 percent cutting waste across much of India's garment sector, and computer-aided design adoption is already standard in organized export-oriented facilities globally, with India's gap concentrated in reaching micro, small, and medium enterprises.			

F4-02		3D Virtual Prototyping	
Transformation Direction Digital Infrastructure & Traceability		TRL 8	Technology Type Design & Digital Technology
Technology Focus Area Digital Product Development		Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: 3D virtual prototyping systems create digital garment prototypes by combining garment patterns, fabric properties, and virtual body models within a computer simulation environment. The software simulates garment fit, drape, appearance, and construction using physics-based modelling and digital visualization tools. Integrated design platforms enable virtual pattern modification, material substitution, and fit evaluation while maintaining digital continuity between product development and manufacturing processes.			
Primary Applications: Fashion export sampling and design approval; mass customization; brand prototype review processes.			
Environmental & Resource Benefits: Each physical sampling round eliminated saves the fabric, dyeing or printing, sewing, and international shipping associated with that sample, representing a meaningful cumulative reduction in resource use and transport emissions across a garment's development cycle.			
Indicative CAPEX (India context): Rs 15 to 50 lakh for three-dimensional design software and a body scanning unit. [Indicative estimate only; not independently verified against a published market source.]		OPEX Savings / Payback Period: Physical sampling typically involves design iteration, cutting, stitching, photography, international shipment, buyer review, and revision, with each round adding three to four weeks to development timelines; eliminating two to three physical sample cycles can remove six to ten weeks from product development lead time. Payback period: under 2 years through sample cost and lead time reduction.	
Key Performance Indicators (KPIs): Physical Samples Eliminated per Style; Development Lead Time Reduction; Fit Approval Time.		Reference Industries: Organized apparel exporters across Bengaluru, Delhi National Capital Region, Mumbai, and Chennai.	
Key Adoption Challenges: Physical Samples Eliminated per Style; Development Lead Time Reduction; Fit Approval Time.			
Technology Developers & Solution Providers: Global: CLO3D, Browzwear. India: Tukatech partnership presence; TC2 body scanning technology.		Key References: Textile World, coverage of three-dimensional digital sampling benefits, March 2024; FashionatingWorld, Turkey sourcing competitiveness report, 2024.	
Cross Media Effects: No offsetting trade-off; the primary resource cost is computing infrastructure for rendering, which is small relative to the physical sampling avoided.			
India Context & Strategic Considerations: Physical sampling lead time is a significant driver of India's competitive disadvantage relative to sourcing destinations such as Turkey, which increasingly differentiate on sampling responsiveness rather than sewing speed alone.			

F4-03	Direct-to-Garment (DTG) Digital Printing	
Transformation Direction Manufacturing Capability at Scale	TRL 8	Technology Type Manufacturing Equipment
Technology Focus Area Digital Product Development	Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Direct-to-garment (DTG) digital printing systems apply textile inks directly onto finished garments using high-resolution inkjet print heads controlled by digital image data. Garments are positioned on precision platens while computerized print systems accurately deposit inks according to digital artwork before subsequent fixation through thermal curing or other appropriate methods. Integrated colour management, print control, and garment positioning systems ensure consistent image reproduction throughout production.		
Primary Applications: T-shirt and knitwear digital print decoration; on-demand fashion; e-commerce personalization.		
Environmental & Resource Benefits: Eliminates screen washing water and paste waste entirely; on-demand production model eliminates overstock inventory associated with conventional bulk screen-printed production runs.		
Indicative CAPEX (India context): Rs 80 to 200 lakh per direct-to-garment printing machine. [Indicative estimate only; not independently verified against a published market source.]		OPEX Savings / Payback Period: Payback period: 3 to 5 years, driven by short-run production economics rather than bulk order volume.
Key Performance Indicators (KPIs): Ink Consumption per Garment; Print Speed (garments per hour); Colour Fastness; Substrate Range.		Reference Industries: Tirupur T-shirt manufacturing; Delhi National Capital Region on-demand fashion; e-commerce aggregator supply chains.
Key Adoption Challenges: Ink Consumption per Garment; Print Speed (garments per hour); Colour Fastness; Substrate Range.		
Technology Developers & Solution Providers: Global: Kornit Digital (Atlas MAX system), Epson (SureColor range), Brother (GTX range).		Key References: Baseline Assessment Report, digital printing adoption trends.
Cross Media Effects: Ink cost per garment exceeds bulk screen printing on a per-unit basis, though this reflects economics rather than a distinct environmental trade-off.		
India Context & Strategic Considerations: India's growing direct-to-consumer fashion e-commerce sector is the primary market driver for direct-to-garment printing adoption, with Kornit Digital maintaining an established India distribution network.		

F4-04	Automated CNC Sewing Systems	
Transformation Direction Manufacturing Capability at Scale	TRL 8	Technology Type Manufacturing Equipment
Technology Focus Area Manufacturing Automation	Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Automated CNC sewing systems execute programmable sewing operations using computer numerical control to coordinate material positioning, stitching paths, thread management, and machine movement. Servo-controlled mechanisms guide fabric handling and stitch formation according to predefined digital sewing programs, enabling repeatable execution of standardized sewing operations. Integrated sensors monitor machine performance, thread integrity, and sewing accuracy throughout the production cycle.		
Primary Applications: Trousers, shirts, and denim manufacturing operations involving high-volume repetitive sewing tasks.		
Environmental & Resource Benefits: Improved consistency reduces defect-related rework, lowering the thread, fabric, and pressing energy associated with reworked garments.		
Indicative CAPEX (India context): Rs 5 to 20 lakh per automated sewing unit. [Indicative estimate only; not independently verified against a published market source.]	OPEX Savings / Payback Period: Achieves productivity three to five times manual operation for the specific repetitive operations addressed. Payback period: 2 to 5 years.	
Key Performance Indicators (KPIs): Units per Hour Relative to Manual Baseline; Defect Rate (%); Operator-to-Output Ratio.	Reference Industries: Bengaluru, Delhi National Capital Region, and Chennai garment export units.	
Key Adoption Challenges: Units per Hour Relative to Manual Baseline; Defect Rate (%); Operator-to-Output Ratio.		
Technology Developers & Solution Providers: Global: Juki, Pegasus, Durkopp Adler, Eastman Machine.	Key References: Advanced Technology in Apparel Manufacturing, Springer Nature, published research on automated sewing systems.	
Cross Media Effects: No material trade-off; electricity demand per machine is comparable to manual sewing machine operation.		
India Context & Strategic Considerations: India's garment manufacturing sector remains predominantly manual, and automated sewing units for even a modest share of repetitive operations represent a meaningful productivity opportunity given the scale of India's export garment production.		

F4-05		Automatic Fabric Spreading	
Transformation Direction Manufacturing Capability at Scale		TRL 9	Technology Type Manufacturing Equipment
Technology Focus Area Manufacturing Automation		Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Automatic fabric spreading systems prepare multiple fabric layers for cutting by accurately unwinding, aligning, tensioning, and stacking fabric plies onto cutting tables. Servo-controlled spreading carriages maintain uniform fabric tension, edge alignment, and layer positioning across varying fabric types. Integrated sensors monitor fabric defects, roll diameter, and spreading accuracy, while computerized control systems coordinate spreading speed, layer count, and material handling throughout the operation.			
Primary Applications: Woven garment cutting room operations across shirts, trousers, denim, and ladies wear production.			
Environmental & Resource Benefits: Reduces spreading-induced tension variation, which is a source of garment dimension defects during cutting, lowering the associated re-cutting waste.			
Indicative CAPEX (India context): Rs 15 to 40 lakh per automatic fabric spreading machine. [Indicative estimate only; not independently verified against a published market source.]		OPEX Savings / Payback Period: Payback period: 2 to 4 years through productivity gains and defect reduction.	
Key Performance Indicators (KPIs): Spreading Speed (metres per minute); Ply Count Accuracy; Tension Variation Across the Fabric Lay; Splice Detection Accuracy.		Reference Industries: Large garment factories in Bengaluru, Delhi National Capital Region, and Chennai.	
Key Adoption Challenges: Spreading Speed (metres per minute); Ply Count Accuracy; Tension Variation Across the Fabric Lay; Splice Detection Accuracy.			
Technology Developers & Solution Providers: Global: Gerber Technology, Lectra, Eastman Machine.		Key References: Advanced Technology in Apparel Manufacturing, Springer Nature.	
Cross Media Effects: No water or chemical trade-off; electricity demand is comparable to the manual spreading process displaced.			
India Context & Strategic Considerations: India's garment cutting rooms remain predominantly reliant on manual spreading, representing a significant automation opportunity relative to the standard practice in leading competing garment manufacturing economies.			

F4-06		Direct-Drive Servo Sewing Systems	
Transformation Direction Resource-Intelligent Manufacturing		TRL 9	Technology Type Manufacturing Equipment
Technology Focus Area Manufacturing Automation		Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Direct-drive servo sewing systems utilize electronically controlled servo motors directly coupled to the sewing machine drive mechanism to provide precise control of machine speed and torque. Digital motor controllers regulate acceleration, deceleration, needle positioning, and rotational speed according to programmed operating parameters. Integrated electronic controls coordinate motor operation with sewing functions to ensure consistent machine performance throughout garment assembly processes.			
Primary Applications: All industrial lockstitch and overlock sewing operations across garment manufacturing.			
Environmental & Resource Benefits: A documented case study at Hamza Clothing Ltd, conducted under the Partnership for Cleaner Textile programme, found direct-drive servo motors deliver approximately 45 percent lower energy consumption compared with clutch motors, in a context where sewing machines were found to account for approximately 70 percent of energy use in the studied apparel manufacturing facility.			
Indicative CAPEX (India context): Servo motor machine: Rs 15,000 to 40,000 per machine, compared with Rs 8,000 to 20,000 for a clutch-motor equivalent. [Validated by GA Morgan Dynamics Pvt Ltd via TMMA, May 2026 — independently corroborating the range used in this card]		OPEX Savings / Payback Period: Payback 1.5 to 3 years from energy savings, corroborating the PaCT/Hamza Clothing Ltd case study finding of approximately 45 percent lower energy consumption for servo versus clutch motors.	
Key Performance Indicators (KPIs): Energy Consumption per Machine per Shift Relative to Clutch Motor Baseline; Idle-Time Energy Loss; Stitch Count Accuracy.		Reference Industries: Garment export factories across Bengaluru, Delhi National Capital Region, Tirupur, and Chennai.	
Key Adoption Challenges: Energy Consumption per Machine per Shift Relative to Clutch Motor Baseline; Idle-Time Energy Loss; Stitch Count Accuracy.			
Technology Developers & Solution Providers: Global: Juki, Brother, Jack Sewing Machine, Yamata.		Key References: Partnership for Cleaner Textile, Installation of Energy Efficient Servo Motor-based Sewing Machines, Hamza Clothing Ltd case study, 2023. Validated by GA Morgan Dynamics Pvt Ltd, TMMA industry consultation, May 2026, independently corroborating the Partnership for Cleaner Textile Hamza Clothing Ltd case study.	
Cross Media Effects: No offsetting trade-off; servo motors consume less electricity than the clutch motors they replace under all operating conditions.			
India Context & Strategic Considerations: This is among the most precisely documented energy interventions available for India's garment sector, with the Hamza Clothing Ltd case study providing a directly verifiable 45 percent energy reduction figure from clutch-to-servo motor conversion.			

F4-07		Robotic Sewing	
Transformation Direction Innovation & Technology Origination		TRL 6	Technology Type Manufacturing Equipment
Technology Focus Area Manufacturing Automation		Roadmap Horizon Accelerate (2035–2047)	India Adoption (2026) Accelerate (2035–2047)
Technology Overview & Working Principle: Robotic sewing systems combine industrial robots, machine vision, programmable manipulators, and automated sewing equipment to perform selected garment assembly operations with minimal manual intervention. Vision systems continuously detect fabric position and geometry, while robotic motion control coordinates material handling and sewing operations in real time. The system integrates sensing, positioning, and programmable automation to accommodate flexible textile materials during sewing processes.			
Primary Applications: High-volume basic garment assembly, primarily demonstrated for T-shirts and similarly simple garment constructions.			
Environmental & Resource Benefits: No direct environmental benefit identified in available literature at the current technology readiness level.			
Indicative CAPEX (India context): Not commercially costed at scale; technology remains at research and demonstration stage globally.		OPEX Savings / Payback Period: Not commercially viable at current technology readiness level; India's labour cost advantage further reduces near-term return on investment relative to higher labour-cost manufacturing economies.	
Key Performance Indicators (KPIs): Garments per Hour; Fabric Handling Accuracy; Defect Rate Relative to Manual Sewing.		Reference Industries: No India deployment identified; robotic sewing remains virtually absent in domestic production globally outside demonstration facilities.	
Key Adoption Challenges: Garments per Hour; Fabric Handling Accuracy; Defect Rate Relative to Manual Sewing.			
Technology Developers & Solution Providers: Global: SoftWear Automation (SEWBOT platform).		Key References: SoftWear Automation, SEWBOT Automated Apparel Manufacturing Platform documentation; Advanced Technology in Apparel Manufacturing, Springer Nature.	
Cross Media Effects: No cross-media data available at current technology readiness level; the water-soluble polymer pretreatment used to stiffen fabric for robotic handling requires subsequent removal.			
India Context & Strategic Considerations: Robotic sewing is virtually absent in India due to high cost and its global demonstration-stage status, and India's labour cost advantage over developed markets means this remains a long-term technology-watch category rather than a near-term deployment priority.			

F4-08		Ultrasonic Welding & Sew-Free Bonding	
Transformation Direction Manufacturing Capability at Scale		TRL 8	Technology Type Process Technology
Technology Focus AreaAdvanced Garment Construction		Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Ultrasonic welding and sew-free bonding systems join textile materials through localized application of high-frequency mechanical vibration and pressure without conventional stitching. Ultrasonic energy generates localized heat at the interface of compatible materials, creating a bonded joint under controlled process conditions. Digital control systems regulate vibration frequency, welding pressure, treatment duration, and material positioning to ensure consistent bond formation across production operations.			
Primary Applications: Waterproof garment seam construction; sportswear seam sealing; medical textile assembly; seamless lingerie construction.			
Environmental & Resource Benefits: Eliminates thread, needle, and sewing machine lubricating oil entirely from the seam construction process, representing a clean manufacturing alternative for compatible fabric types.			
Indicative CAPEX (India context): Rs 20 to 60 lakh per ultrasonic welding unit. [Indicative estimate only; not independently verified against a published market source.]		OPEX Savings / Payback Period: Payback period: 3 to 6 years for technical textile applications commanding an appropriate price premium.	
Key Performance Indicators (KPIs): Seam Strength (peel and shear, Newtons per centimetre); Water Column Resistance; Weld Speed.		Reference IndustriesT: echnical textile manufacturers; premium sportswear producers.	
Key Adoption Challenges: Seam Strength (peel and shear, Newtons per centimetre); Water Column Resistance; Weld Speed.			
Technology Developers & Solution Providers: Global: Branson Ultrasonics (Emerson group), Herrmann Ultrasonics.		Key References: Journal of Industrial Textiles, SAGE Publications, published research on ultrasonic welding technology for waterproof and technical textile seam applications, 2021.	
Cross Media Effects: Entirely dry process; no offsetting trade-off identified for compatible thermoplastic substrates.			
India Context & Strategic Considerations: Growing demand for ultrasonic welding technology is emerging within India's technical textiles sector, supported by National Technical Textiles Mission priorities.			

F4-09		Autonomous Garment Manufacturing	
Transformation Direction Innovation & Technology Origination		TRL 5	Technology Type Manufacturing Equipment
Technology Focus Area Advanced Garment Construction		Roadmap Horizon Accelerate (2035–2047)	India Adoption (2026) Accelerate (2035–2047)
Technology Overview & Working Principle: Autonomous garment manufacturing systems integrate automated material handling, robotic assembly, machine vision, intelligent process control, and digitally connected production equipment within a coordinated manufacturing environment. Production data is exchanged between interconnected machines to enable automated workflow management, process sequencing, quality monitoring, and material movement with minimal manual intervention. Centralized control systems coordinate individual manufacturing processes across the production line.			
Primary Applications: High-volume basic garment production, primarily T-shirts and basic knitwear, envisioned for future full-cell automation.			
Environmental & Resource Benefits: No direct environmental benefit identified in available literature at the current technology readiness level.			
Indicative CAPEX (India context): Very high; no commercial-scale cost data available given the pre-commercial status of fully integrated autonomous manufacturing cells. [Indicative estimate only; not independently verified against a published market source.]		OPEX Savings / Payback Period: Not commercially viable at current technology readiness level and India's labour cost baseline; payback exceeds 15 years at current estimated cost.	
Key Performance Indicators (KPIs): Garments per Hour per Cell for Complete Assembly; Fabric Handling Accuracy Across Multiple Stations; End-to-End Quality Pass Rate.		Reference Industries: No India deployment expected before the mid-2030s.	
Key Adoption Challenges: Garments per Hour per Cell for Complete Assembly; Fabric Handling Accuracy Across Multiple Stations; End-to-End Quality Pass Rate.			
Technology Developers & Solution: SoftWear Automation (SEWBOT platform), Sewts.		Key References: Advanced Technology in Apparel Manufacturing, Springer Nature.	
Cross Media Effects: No cross-media data available at current technology readiness level.			
India Context & Strategic Considerations: Autonomous garment manufacturing sits at the far end of India's technology horizon, positioned for the 2035 to 2047 period once global fabric-handling flexibility constraints are resolved, and is a category to watch rather than plan around in the near term.			

F4-10		RFID Tagging, Warehouse Management and EDI Buyer Integration	
Transformation Direction Digital Infrastructure & Traceability		TRL 8	Technology Type Digital Technology
Technology Focus Area Supply Chain Traceability		Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: RFID-enabled warehouse management and electronic data interchange (EDI) systems integrate automatic product identification, inventory management, warehouse operations, and digital information exchange across the apparel supply chain. RFID tags enable real-time tracking of garments and logistics units, while warehouse management software coordinates storage, movement, and dispatch operations. EDI platforms exchange standardized production, inventory, shipping, and order information between manufacturers, logistics providers, and buyers through secure digital communication.			
Primary Applications: Garment factories with significant warehouse operations, export packing floors, and large organised manufacturers with buyer-mandated inventory visibility requirements.			
Environmental & Resource Benefits: Improves inventory accuracy, reducing overproduction and stock discrepancies that would otherwise result in wasted finished garment production.			
Indicative CAPEX (India context): RFID tags: Rs 2 to 8 per tag, a cost that is declining over time. RFID readers and portals: Rs 3 to 8 lakh per gate. Warehouse management system software: Rs 15 to 50 lakh implementation. [Validated by GA Morgan Dynamics Pvt Ltd via TMMA, May 2026]		OPEX Savings / Payback Period: Payback 3 to 5 years from inventory accuracy and buyer compliance value.	
Key Performance Indicators (KPIs): Inventory accuracy (%); RFID read rate at portals; electronic data interchange transaction success rate; shipment confirmation turnaround time.		Reference Industries: Growing in large export units; rare in the MSME supply chain. [TMMA-validated]	
Key Adoption Challenges: Inventory accuracy (%); RFID read rate at portals; electronic data interchange transaction success rate; shipment confirmation turnaround time.			
Technology Developers & Solution Providers: No specific commercial supplier named by validator; technology is described generically as an established RFID, warehouse management system, and EDI integration stack.		Key References: Validated by GA Morgan Dynamics Pvt Ltd, TMMA industry consultation, May 2026.	
Cross Media Effects: No material environmental trade-off; RFID tag manufacturing and disposal represents a minor additional electronic waste stream relative to the garment itself.			
India Context & Strategic Considerations: This technology was validated as a distinct gap by a garment machinery TMMA member but has no equivalent card elsewhere in this compendium; it is functionally adjacent to but distinct from Manufacturing Execution Systems (F0-03), addressing warehouse and buyer-facing logistics rather than shop-floor production tracking.			

F4-11		Automated Pattern Matching for Plaid and Check Fabric Cutting	
Transformation Direction Manufacturing Capability at Scale		TRL 9	Technology Type Manufacturing Equipment
Technology Focus Area Manufacturing Automation		Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Automated pattern matching systems align plaid, striped, checked, and other repeat-pattern fabrics during spreading, marker planning, and cutting to ensure continuity of the fabric design across garment panels. The system combines high-resolution imaging, machine vision, digital pattern recognition, and CAD/CAM software to identify fabric repeat intervals and automatically adjust marker placement before cutting. Integrated CNC cutting equipment, servo-controlled material positioning, and automated registration systems maintain accurate pattern alignment throughout the cutting process, ensuring consistent matching across assembled garment components.			
Primary Applications: Cutting of plaid, check, and other repeating-pattern woven fabrics for shirting and similar garment categories where pattern-matching at seams is a quality requirement.			
Environmental & Resource Benefits: Directly reduces fabric waste through improved marker-to-pattern alignment accuracy, lowering the over-allowance fabric typically added to accommodate manual pattern-matching error.			
Indicative CAPEX (India context): Not separately quantified by validator; described as an add-on capability to existing computerised cutting systems rather than a standalone machine investment.		OPEX Savings / Payback Period: Payback approximately 0.5 years, the shortest payback figure among all TMMA-validated technologies in this compendium. [Validated by GA Morgan Dynamics Pvt Ltd via TMMA, May 2026]	
Key Performance Indicators (KPIs): Fabric saving on check fabrics (validator-confirmed range: 4 to 6 percent); pattern-match accuracy at seams; cutting cycle time relative to manual pattern matching.		Reference Industries: High (35–65%). [TMMA-validated]	
Key Adoption Challenges: Fabric saving on check fabrics (validator-confirmed range: 4 to 6 percent); pattern-match accuracy at seams; cutting cycle time relative to manual pattern matching.			
Technology Developers & Solution Providers: Reference installations confirmed by validator: Aquarelle, Arvind, Zodiac, Ranger, Radik, Blazo, Texport.		Key References: Validated by GA Morgan Dynamics Pvt Ltd, TMMA industry consultation, May 2026.	
Cross Media Effects: Reduces fabric waste directly through improved cutting accuracy; no water, chemical, or energy trade-off beyond the automated cutting system it operates within.			
India Context & Strategic Considerations: With a validator-confirmed payback of roughly six months, this is the fastest-payback technology identified anywhere in this compendium, though its applicability is narrower than most cards, being specific to plaid and check fabric categories rather than general garment cutting.			



F5-01	Digital Product Passport (DPP) Platform	
Transformation Direction Digital Infrastructure & Traceability	TRL 8	Technology Type Digital Technology
Technology Focus Area Product Compliance	Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Digital Product Passport (DPP) platforms establish a standardized digital record that captures verified information on a textile product throughout its lifecycle. The platform aggregates data from multiple sources, including material composition, manufacturing processes, certifications, environmental attributes, repair information, and end-of-life guidance. Unique digital identifiers link physical products to cloud-based data repositories, while standardized data exchange protocols enable authorized stakeholders to securely access, update, and verify product information across the value chain.		
Primary Applications: All textile and apparel exports destined for European Union markets.		
Environmental & Resource Benefits: Enables continued European Union market access beyond the compliance deadline and reduces greenwashing risk by requiring verifiable supporting data for sustainability claims made on products.		
Indicative CAPEX (India context): Rs 10 to 50 lakh for information technology integration per exporter, depending on the complexity of existing data systems. [Indicative estimate only; not independently verified against a published market source.	OPEX Savings / Payback Period: Primarily a market access protection investment rather than a direct cost-saving measure.	
Key Performance Indicators (KPIs): Digital Product Passport Data Field Completeness (%); Batch-Level Traceability Coverage; Carbon Footprint Data Availability per Product.	Reference Industries: All European Union-exporting clusters, including Tirupur, Surat, Bengaluru, and Ludhiana.	
Key Adoption Challenges: Digital Product Passport Data Field Completeness (%); Batch-Level Traceability Coverage; Carbon Footprint Data Availability per Product.		
Technology Developers & Solution Providers: Global: TrusTrace, TextileGenesis, Circularise.	Key References: European Union, Ecodesign for Sustainable Products Regulation. Cross-validated by GA Morgan Dynamics Pvt Ltd, TMMA industry consultation, May 2026.	
Cross Media Effects: No material trade-off; the platform itself is a data and reporting function.		
India Context & Strategic Considerations: The Ecodesign for Sustainable Products Regulation is expected to introduce specific requirements for textile products around 2025, with implementation by 2027, making Digital Product Passport readiness an urgent near-term priority for India's European Union-facing export sector.		

F5-02	ZDHC-Compliant Chemical Management Systems	
Transformation Direction Resource-Intelligent Manufacturing	TRL 9	Technology Type Digital Technology
Technology Focus Area Product Compliance	Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: ZDHC-compliant chemical management systems digitally manage chemical inventories, procurement, usage, compliance verification, and wastewater monitoring in accordance with the Zero Discharge of Hazardous Chemicals (ZDHC) framework. The system integrates chemical databases, supplier declarations, material safety information, laboratory test results, and restricted substance requirements into a centralized platform. Automated compliance checks, approval workflows, and reporting tools support chemical selection, inventory control, and documentation throughout manufacturing operations.		
Primary Applications: All wet processing operations, including dyeing, printing, and finishing, within global brand supply chains.		
Environmental & Resource Benefits: Directly reduces the discharge of hazardous chemicals to textile effluent, addressing a defined and continuously updated list of substances of concern.		
Indicative CAPEX (India context): Chemical substitution: cost-neutral to 5 to 15 percent premium per auxiliary chemical. Chemical management system: Rs 5 to 15 lakh per unit. Third-party ZDHC verification: Rs 1 to 3 lakh per facility per year. RSL testing: Rs 50,000 to 1.5 lakh per test package per season. [Validated by Yamuna Machine Works Ltd via TMMA, May 2026]	OPEX Savings / Payback Period: Payback is realized through continued supply chain qualification for major brand customers rather than direct cost savings.	
Key Performance Indicators (KPIs): Manufacturing Restricted Substances List Conformance (%); Zero Discharge of Hazardous Chemicals Gateway Score; Chemical Audit Pass Rate.	Reference Industries: Tirupur, Surat, and Ahmedabad export-oriented wet processing units.	
Key Adoption Challenges: Manufacturing Restricted Substances List Conformance (%); Zero Discharge of Hazardous Chemicals Gateway Score; Chemical Audit Pass Rate.		
Technology Developers & Solution Providers: Global: Zero Discharge of Hazardous Chemicals Foundation (framework administrator); Bureau Veritas, Intertek, SGS (verification and testing).	Key References: H&M Group, Chemicals and Zero Discharge of Hazardous Chemicals Wastewater Management in the Supply Chain, sustainability disclosure documentation; Inditex, Innovation, Collaboration and Continuous Improvement for Chemical Safety documentation. Validated by Yamuna Machine Works Ltd, TMMA industry consultation, May 2026.	
Cross Media Effects: No offsetting trade-off; the compliance system itself is a data and testing function rather than a physical process.		
India Context & Strategic Considerations: Zero Discharge of Hazardous Chemicals Gateway compliance is increasingly moving from a voluntary practice to a prerequisite requirement for supplying major global brands, making this compliance infrastructure a market access necessity rather than a discretionary investment.		

F5-03		Spectrophotometric Quality Control & Accredited Laboratory Testing	
Transformation Direction Manufacturing Capability at Scale		TRL 9	Technology Type Testing & Quality Technology
Technology Focus Area Product Compliance		Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Spectrophotometric quality control and accredited laboratory testing systems measure, evaluate, and verify textile product characteristics using standardized analytical instruments and internationally recognized testing methodologies. Spectrophotometers quantify colour characteristics by measuring light reflectance across the visible spectrum, while accredited laboratories perform physical, chemical, and performance testing in accordance with established national and international standards. Digital laboratory information management systems capture, analyse, and maintain testing records to support quality assurance and compliance verification.			
Primary Applications: Colour shade approval and quality control; restricted substance testing for chemical compliance documentation.			
Environmental & Resource Benefits: No direct environmental benefit; indirectly supports quality improvements that reduce re-dyeing rates, which carry their own resource-saving benefits.			
Indicative CAPEX (India context): Basic in-house lab covering colour measurement and key physical tests: Rs 15 to 50 lakh. REACH/RSL chemical testing via accredited third-party lab: Rs 5 to 20 lakh per year service cost. [Validated by GA Morgan Dynamics Pvt Ltd via TMMA, May 2026]		OPEX Savings / Payback Period: Payback 2 to 4 years from defect reduction and buyer claim avoidance.	
Key Performance Indicators (KPIs): Shade Approval Accuracy (Delta E tolerance); National Accreditation Board for Testing and Calibration Laboratories Accreditation Status; Restricted Substances List Test Pass Rate.		Reference Industries: Established in Tirupur via Intertek, SGS, and Textile Committee laboratories; less developed in other clusters	
Key Adoption Challenges: Shade Approval Accuracy (Delta E tolerance); National Accreditation Board for Testing and Calibration Laboratories Accreditation Status; Restricted Substances List Test Pass Rate.			
Technology Developers & Solution Providers: Global: X-Rite, Datacolor; SGS, Bureau Veritas, Intertek (third-party testing services).		Key References: National Accreditation Board for Testing and Calibration Laboratories, accreditation standards, Government of India. Validated by GA Morgan Dynamics Pvt Ltd, TMMA industry consultation, May 2026.	
Cross Media Effects: No material trade-off; laboratory equipment and reagent use for testing is minor relative to the facility's overall chemical footprint.			
India Context & Strategic Considerations: Test data from National Accreditation Board for Testing and Calibration Laboratories accredited facilities carries specific legal admissibility at European Union customs, making accredited laboratory infrastructure a distinct compliance function beyond routine internal quality control.			

F5-04		Life Cycle Assessment (LCA) Platforms	
Transformation Direction Digital Infrastructure & Traceability		TRL 8	Technology Type Digital Technology
Technology Focus Area Product Compliance		Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Life Cycle Assessment (LCA) platforms quantify the environmental impacts of textile products and manufacturing processes across their entire lifecycle using internationally recognized assessment methodologies. The platform integrates inventory data on raw materials, energy consumption, water use, transportation, manufacturing processes, product use, and end-of-life scenarios to generate environmental impact assessments. Embedded databases, calculation engines, and reporting tools support standardized modelling, scenario analysis, and environmental performance evaluation.			
Primary Applications: Product-level environmental impact disclosure supporting brand Environmental, Social and Governance reporting and European Union sustainability compliance requirements.			
Environmental & Resource Benefits: Reveals the full environmental footprint across the supply chain rather than carbon emissions alone, enabling targeted efficiency interventions at the highest-impact production stage.			
Indicative CAPEX (India context): Third-party GHG audit to ISO 14064: Rs 3 to 8 lakh. [Validated by GA Morgan Dynamics Pvt Ltd via TMMA, May 2026]		OPEX Savings / Payback Period: A compliance and market access investment rather than a direct cost-saving measure.	
Key Performance Indicators (KPIs): Life Cycle Assessment Impact Categories Covered; Data Completeness Across Product Lifecycle Stages; Third-Party Verification Status.		Reference Industries: Large export mills preparing for European Union Ecodesign for Sustainable Products Regulation and India's Business Responsibility and Sustainability Reporting Core disclosure requirements.	
Key Adoption Challenges: Life Cycle Assessment Impact Categories Covered; Data Completeness Across Product Lifecycle Stages; Third-Party Verification Status.			
Technology Developers & Solution Providers: Global: Worldly (Higg Index platforms), Carbonfact, PRe Sustainability (SimaPro).		Key References: International Organization for Standardization 14040 and 14044, Life Cycle Assessment standards. Validated by GA Morgan Dynamics Pvt Ltd, TMMA industry consultation, May 2026.	
Cross Media Effects: No offsetting trade-off; the assessment function itself is a data and reporting activity.			
India Context & Strategic Considerations: Life Cycle Assessment platforms represent a more comprehensive and methodologically advanced capability than basic carbon footprint reporting, positioning them as a data infrastructure investment for exporters moving beyond initial compliance toward deeper sustainability performance disclosure.			

F5-05	Science-Based Target (SBT) Management Platforms	
Transformation Direction Resource-Intelligent Manufacturing	TRL 8	Technology Type Digital Technology
Technology Focus Area Product Compliance	Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Science-Based Target (SBT) management platforms support the planning, monitoring, and reporting of organizational greenhouse gas reduction targets aligned with recognized climate methodologies. The platform integrates operational data, emissions inventories, energy consumption records, production information, and emission factors to monitor progress against approved decarbonization pathways. Automated calculation engines, dashboards, and reporting modules enable continuous performance tracking and standardized disclosure of climate targets and implementation progress.		
Primary Applications: Export-oriented mills reporting into brand Environmental, Social and Governance and Science Based Targets initiative programmes.		
Environmental & Resource Benefits: Drives measurable facility-level energy, water, and chemical efficiency improvement as Science Based Targets initiative trajectories require demonstrated Scope 1 and Scope 2 emissions reduction over time.		
Indicative CAPEX (India context): Higg FEM subscription and verification: Rs 2 to 5 lakh per facility per year. SBTi target-setting support: Rs 5 to 15 lakh, one-time, consultant-assisted. [Validated by GA Morgan Dynamics Pvt Ltd via TMMA, May 2026]	OPEX Savings / Payback Period: A compliance and market access investment protecting brand relationship continuity rather than a direct cost saving.	
Key Performance Indicators (KPIs): Science Based Targets initiative Validation Status; Higg Facility Environmental Module Completion Score; Scope 1 and Scope 2 Emissions Tracked Against Target Trajectory.	Reference Industries: Large export mills reporting to brands including H&M, Inditex, and PVH under their respective sustainability programmes.	
Key Adoption Challenges: Science Based Targets initiative Validation Status; Higg Facility Environmental Module Completion Score; Scope 1 and Scope 2 Emissions Tracked Against Target Trajectory.		
Technology Developers & Solution Providers: Global: Worldly (Higg Index platforms), Carbonfact. India: Bureau Veritas India, verification support.	Key References: Science Based Targets initiative, Sectoral Decarbonization Approach documentation. Validated by GA Morgan Dynamics Pvt Ltd, TMMA industry consultation, May 2026.	
Cross Media Effects: No material trade-off; the platform itself is a data and reporting function rather than a physical process.		
India Context & Strategic Considerations: Science Based Target validation is a more advanced, longer-horizon capability than basic carbon footprint reporting, reflecting the growing practice of global brands cascading formal decarbonization commitments down through their India supplier base.		

F5-06	Future Digital Compliance Ecosystems	
Transformation Direction nDigital Infrastructure & Traceability	TRL 6	Technology Type Digital Technology
Technology Focus Area Product Compliance	Roadmap Horizon Accelerate (2035–2047)	India Adoption (2026) Accelerate (2035–2047)
Technology Overview & Working Principle: Future digital compliance ecosystems integrate multiple regulatory, sustainability, product, and supply chain information systems into an interoperable digital framework supporting evolving compliance requirements. The ecosystem combines enterprise platforms, traceability systems, environmental reporting tools, certification databases, and regulatory information exchange through standardized digital interfaces. Secure data sharing, automated validation, and interoperable information architecture enable coordinated compliance management across multiple jurisdictions and value chain participants.		
Primary Applications: Integrated compliance reporting across Digital Product Passport, carbon footprint, chemical management, and traceability requirements.		
Environmental & Resource Benefits: Would reduce the administrative burden of maintaining multiple separate compliance systems, potentially improving data accuracy and consistency across environmental reporting frameworks.		
Indicative CAPEX (India context): Not commercially costed; research and development horizon technology.		OPEX Savings / Payback Period: Not applicable at current pre-commercial stage.
Key Performance Indicators (KPIs): Cross-Framework Data Integration Completeness; Reporting Duplication Reduction; Compliance Data Consistency.		Reference Industries: No current India implementation identified; concept remains at an early conceptual stage globally.
Key Adoption Challenges: Cross-Framework Data Integration Completeness; Reporting Duplication Reduction; Compliance Data Consistency.		
Technology Developers & Solution Providers: No specific commercial supplier identified for integrated cross-framework compliance platforms at this technology readiness level.		Key References: European Union, Ecodesign for Sustainable Products Regulation; Science Based Targets initiative documentation.
Cross Media Effects: No cross-media data identified in available literature for this pre-commercial category.		
India Context & Strategic Considerations : This represents a long-term research and development horizon category, anticipating the eventual convergence of the multiple separate digital compliance systems that exporters currently must maintain individually.		

F5-07	Blockchain-Based Supply Chain Traceability	
Transformation Direction Digital Infrastructure & Traceability	TRL 8	Technology Type Digital Technology
Technology Focus Area Supply Chain Traceability	Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Blockchain-based supply chain traceability platforms establish a decentralized and tamper-evident record of material movement and processing throughout the textile value chain. Each transaction, including raw material sourcing, manufacturing, certification, logistics, and ownership transfer, is recorded as a cryptographically validated entry within a distributed ledger. Standardized digital records, consensus mechanisms, and secure data exchange enable authorized stakeholders to verify chain-of-custody information while maintaining data integrity across interconnected supply chain systems.		
Primary Applications: Premium export garment supply chains; sustainable fashion traceability; regulatory due diligence documentation.		
Environmental & Resource Benefits: No direct environmental benefit; indirectly supports sustainability claims verification and prevents greenwashing across the supply chain.		
Indicative CAPEX (India context): Platform access: Rs 5 to 20 lakh per year for a SaaS blockchain platform. Integration with existing ERP or PLM systems: Rs 10 to 30 lakh. [Validated by GA Morgan Dynamics Pvt Ltd via TMMA, May 2026]	OPEX Savings / Payback Period: Payback framed as strategic and compliance value — market access for EU DPP-regulated markets — rather than conventional financial payback.	
Key Performance Indicators (KPIs): Supply Chain Node Coverage (%); Data Completeness per Product; Third-Party Verification Pass Rate.	Reference Industries: Export-oriented clusters including Tirupur, Bengaluru, Delhi National Capital Region, and Surat.	
Key Adoption Challenges: Supply Chain Node Coverage (%); Data Completeness per Product; Third-Party Verification Pass Rate.		
Technology Developers & Solution Providers Global: TextileGenesis, TrusTrace, FibreTrace, Circularise.	Key References TextileGenesis, Fibre-to-Retail Blockchain Traceability Platform for Fashion Supply Chains documentation. Validated by GA Morgan Dynamics Pvt Ltd, TMMA industry consultation, May 2026.	
Cross Media Effects No material trade-off; the distributed ledger infrastructure itself has a modest computing energy footprint.		
India Context & Strategic Considerations: Blockchain traceability is increasingly required by global brands sourcing from India, and forms part of the data infrastructure required for European Union due diligence and Digital Product Passport compliance from 2027.		

F5-08	Product Carbon Footprint (PCF) Platforms	
Transformation Direction Digital Infrastructure & Traceability	TRL 8	Technology Type Digital Technology
Technology Focus Area Supply Chain Traceability	Roadmap Horizon Align (2026–2030)	India Adoption (2026) Align (2026–2030)
Technology Overview & Working Principle: Product Carbon Footprint (PCF) platforms calculate and manage greenhouse gas emissions associated with textile products using standardized life cycle accounting methodologies. The platform integrates data on material inputs, manufacturing operations, energy consumption, transportation, packaging, and end-of-life assumptions with verified emission factor databases to generate product-level carbon inventories. Automated calculation engines, data validation tools, and reporting modules support standardized carbon footprint assessment, documentation, and information exchange.		
Primary Applications: Shipment-level carbon footprint reporting for Carbon Border Adjustment Mechanism compliance and brand disclosure requirements.		
Environmental & Resource Benefits: Provides the data foundation for identifying the highest-impact stages of production for targeted decarbonization investment.		
Indicative CAPEX (India context): Rs 10 to 30 lakh per facility for platform licensing and data integration. [Indicative estimate only; not independently verified against a published market source.]	OPEX Savings / Payback Period: A compliance and market access investment protecting continued export eligibility rather than a direct cost saving.	
Key Performance Indicators (KPIs): Tonnes of Carbon Dioxide Equivalent per kg of Textile Produced; Scope 1, 2, and 3 Emissions Breakdown; Carbon Border Adjustment Mechanism Exposure.	Reference Industries: Export mills shipping to the European Union under Carbon Border Adjustment Mechanism scope.	
Key Adoption Challenges: Tonnes of Carbon Dioxide Equivalent per kg of Textile Produced; Scope 1, 2, and 3 Emissions Breakdown; Carbon Border Adjustment Mechanism Exposure.		
Technology Developers & Solution Providers: Global: Carbonfact, Worldly (Higg Index platforms).	Key References: Central Electricity Authority, Ministry of Power, Government of India, Carbon Dioxide Baseline Database for the Indian Power Sector, 2023.	
Cross Media Effects: No offsetting trade-off; the platform itself is a data and reporting function.		
India Context & Strategic Considerations: The Carbon Border Adjustment Mechanism is expected to extend to textiles in a future implementation phase, making product-level carbon footprint reporting an increasingly urgent requirement for India's European Union-facing export sector.		

F5-09	Fibre-Level Physical Traceability Technologies	
Transformation Direction Digital Infrastructure & Traceability	TRL 8	Technology Type Testing & Quality Technology
Technology Focus Area Supply Chain Traceability	Roadmap Horizon Amplify (2030–2035)	India Adoption (2026) Amplify (2030–2035)
Technology Overview & Working Principle: Fibre-level physical traceability technologies establish the identity and origin of textile fibres through the use of unique physical, chemical, biological, or isotopic identifiers that remain associated with the material throughout processing and manufacturing. The technology utilizes marker application, intrinsic material fingerprinting, forensic analysis, or isotopic characterization, supported by laboratory-based or portable detection systems to authenticate fibre provenance. Verification results are integrated with digital traceability platforms to enable independent confirmation of fibre identity and chain-of-custody records across the textile value chain.		
Primary Applications: Premium provenance verification for cotton, silk, and wool supply chains serving sustainability-conscious brand programmes.		
Environmental & Resource Benefits: No direct environmental benefit; enables verification of sustainable sourcing claims, supporting market mechanisms that reward genuinely lower-impact fibre production choices.		
Indicative CAPEX (India context): Rs 5 to 20 lakh per facility for tagging system integration. [Indicative estimate only; not independently verified against a published market source.]	OPEX Savings / Payback Period: Payback is realized through premium market access for verified-origin fibre rather than direct operational cost savings.	
Key Performance Indicators (KPIs): Proportion of Fibre Physically Traceable Through the Supply Chain (%); Reader Verification Accuracy at Each Node; Data Immutability.	Reference Industries: Organized cotton, silk, and wool export supply chains.	
Key Adoption Challenges: Proportion of Fibre Physically Traceable Through the Supply Chain (%); Reader Verification Accuracy at Each Node; Data Immutability.		
Technology Developers & Solution Providers: Global: Oritain (isotope testing), Haelixa (deoxyribonucleic acid marker tagging), FibreTrace (luminescent pigment and spectroscopic tracing).	Key References: Oritain, Scientific Isotope Testing for Fibre Origin Verification and Supply Chain Traceability documentation; Haelixa, Deoxyribonucleic Acid Marker-Based Textile and Fibre Traceability Solutions documentation; FibreTrace, Luminescent Pigment and Spectroscopic Fibre Traceability Technology documentation; Textile Exchange, Traceability Technologies and Physical Verification Systems in Textile Supply Chains, 2024.	
Cross Media Effects: Tracer application and reader infrastructure has a negligible resource footprint relative to the fibre volumes being verified.		
India Context & Strategic Considerations: Physical fibre-level traceability is expected to make premium provenance claims for Indian cotton, silk, and wool physically verifiable in alignment with Digital Product Passport requirements taking effect from 2027.		



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For further information:

PAGE Secretariat

UN Environment Resources and Market Branch
11 -13 Chemin des Anémones CH -1219
Chatelaine -Geneva Switzerland





Vienna International Centre, Wagramer Strabe 5, P.O.
Box 300, A-1400 Vienna, Austria



O.ITI@unido.org



www.unido.org



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