December 2024

Sector Insights

Sector: Textile Recycling

Industry Group: Waste & Recycling

AGRICULTURE & FOOD | ENERGY & POWER | MATERIALS & CHEMICALS | RESOURCES & ENVIRONMENTAL MANAGEMENT | TRANSPORTATION & LOGISTICS | WASTE & RECYCLING

ENABLING TECHNOLOGIES, BUSINESS MODELS, AND THEMES

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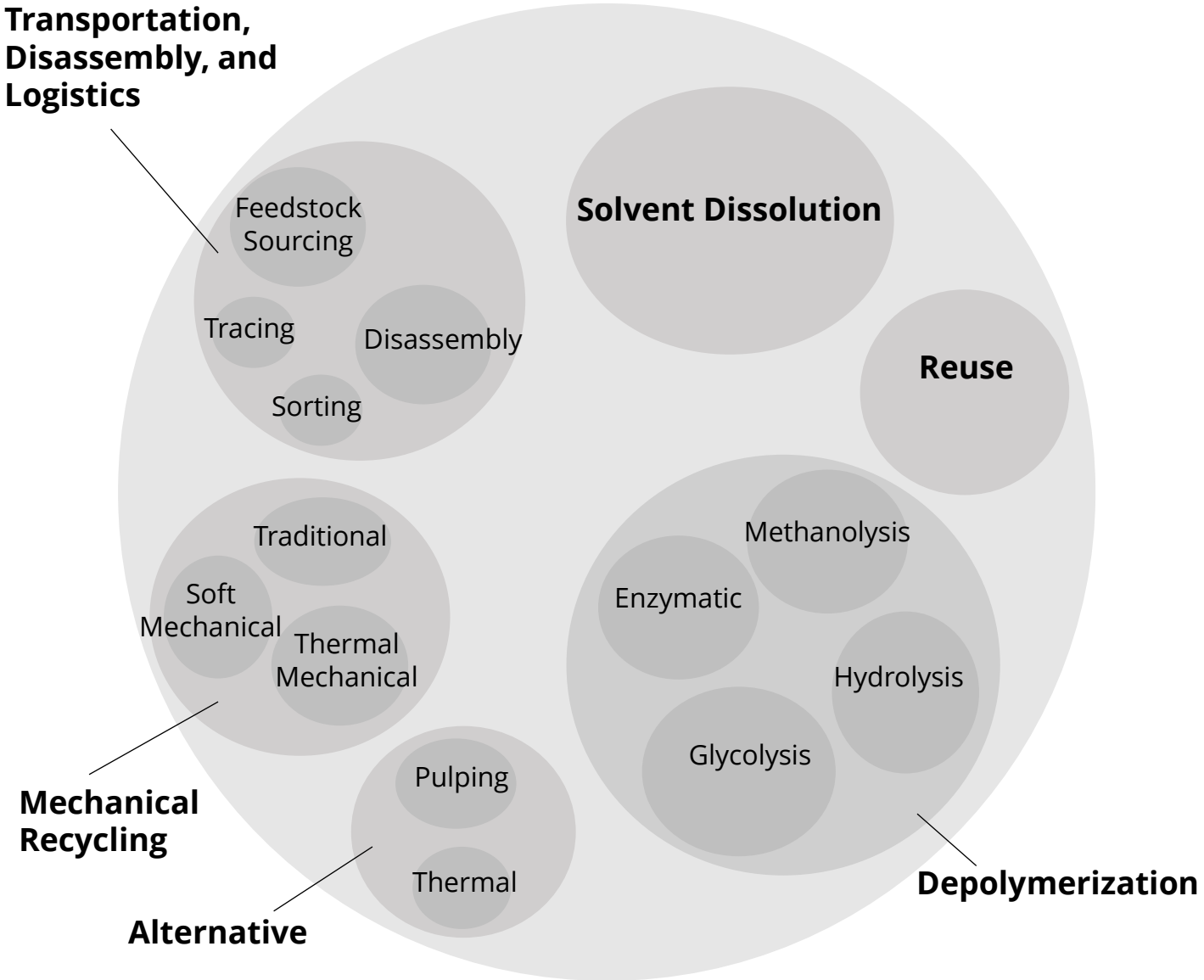
Textile Recycling Level-Setting



Key Segments & Sub Segments

Textile recycling falls within the waste management branch of Cleantech Group's taxonomy. Textile recycling produces recycled fiber, plastic, and metal. There are 66 relevant companies in i3, organized within the following taxonomy:

Pretreatment

- **Transportation, Disassembly, and Logistics**: Collects, hauls, and prepares textile waste for specific recycling processes. The disassembly and sortation components are adopting new software solutions at great benefit

Treatment

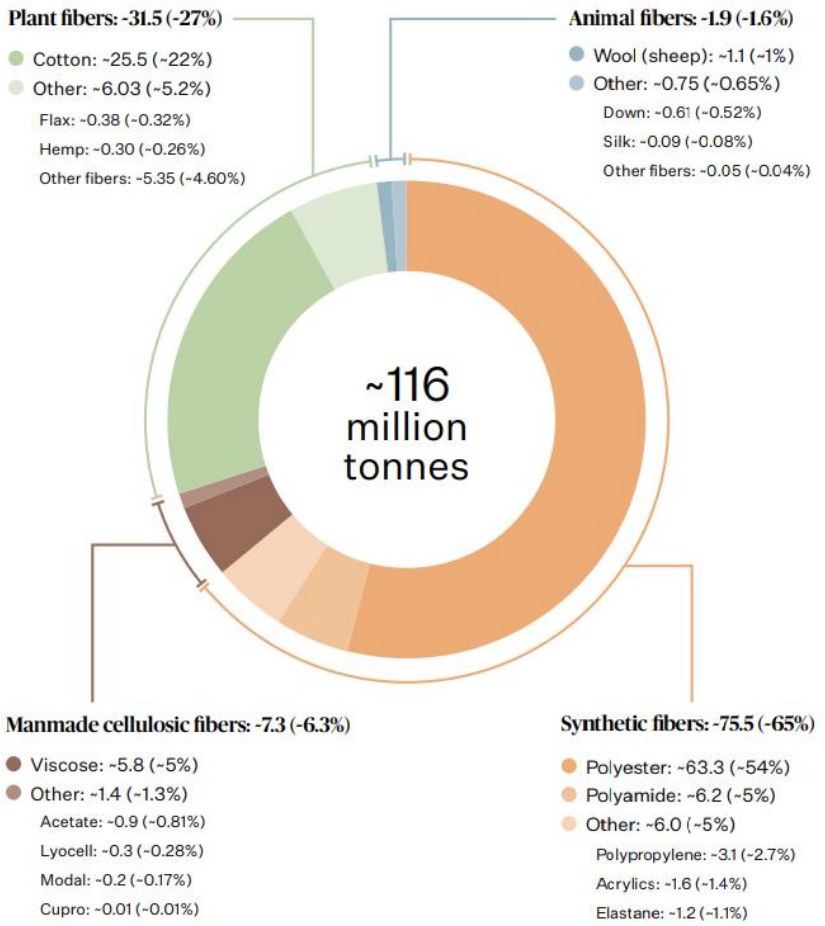
- **Recycling Processes**: Chemical and non-chemical recycling processes with a focus on depolymerization, mechanical recycling, and solvent dissolution. Each process is growing to fill a specific industry need but unable to process all waste efficiently. Alternative processes fall under a chemical process labeled hereafter as thermal or pulping, a specialty cotton or mixed waste recycling process

Executive Summary: Textile Recycling

Voluntary waste reduction has failed, mandating more aggressive technology and policy measures

- The textile industry has a 14% recycling rate but produces ~ 6% of landfill volume, 10% of global emissions, 20% of global water pollution
- By 2030, fiber-to-fiber recycling could recycle 28-40 million tons of textile waste while open-loop could recycle 11-17 million tons (APFLG)
- Textile recycling has five technologies that compete today:
  - **Mechanical Recycling:** TRL 9, Grinds fiber into low quality recyclate
  - **Solvent Dissolution**: TRL 5/6, Solvents dissolve and filter polymers from textile waste leaving recyclers with pure organic and inorganic fibers
  - **Thermal**: TRL 7, Gasification to break down fiber into syngas
  - **Depolymerization:** TRL 6/7, Chemical reactions to break down polymers in textiles into high quality constituent monomers
  - **Pulping:** TRL 7, Chemically degrades fibers into a pulp for respinning
- No single technology will dominate due to feedstock specialization
  - Mechanical recycling suited to consolidate animal fiber market
  - **Solvent dissolution will become the most prized technology next decade**, specializing in mixed cotton/polyester blends (Figure 1)
  - Thermal will be phased out, pure cotton will still be handled by pulping, and depolymerization will specialize in polyamide (nylon)
- **Aggressive policy mandates needed to create recycling ecosystem**
  - Voluntary corporate recycling goals remain off-track and low-impact
  - Textile recycling is not capable of reaching maturity without policy aid, e.g., EPR can improve the global textile recovery rate to well above 30%
- Solvent dissolution & infrared/ML sortation are technology areas of low saturation, high impact, high return investment opportunity

Figure 1: Global Fiber Production (in million tons and % of global fiber production)

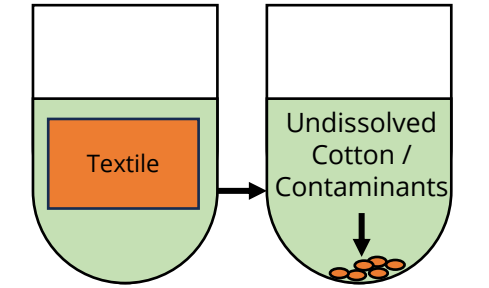


Source: Textile Exchange (2023), This chart includes recycled fibers. Other animal fibers included. Other plant fibers included.

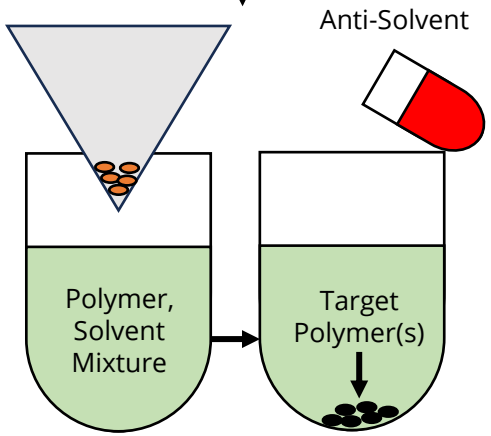
Figure 2: Novel Technologies Overview

Diagrams assume required sortation, pretreatment before specified recycling process

Solvent Dissolution



Dissolve Polymers in Solvent



Recover Cotton and Contaminants

Add Anti-Solvent, Precipitate Polymer

Recover Polymer, Solvent & Anti-Solvent

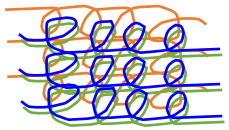
Depolymerization

Catalyzed Chemical Depolymerization (Hydrolysis)

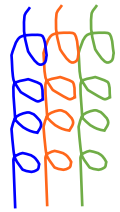
Separation, Purification, Distillation of Monomers

Repolymerization into Nylon

Mechanical



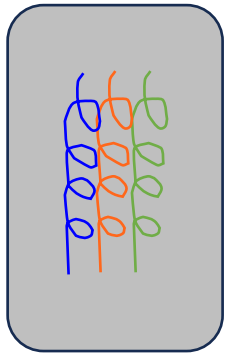
Mixed Textile Waste Shredded into Smaller Pieces



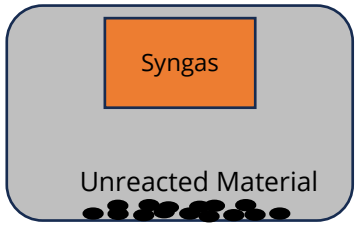
Carding Machine Shortens and Aligns Fibers

Fibers are Spun Together into Low Quality Yarn

Thermal Gasification



Shredded Textile Waste Fed into Gasifier, Heated to Produce Gaseous Hydrocarbons (Syngas)



Syngas is Cleaned and Removed from Unreacted Material in a Cyclonic Separator Before Use

Source: Cleantech Group

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Textile Recycling: Setting the Stage

Despite clear promise of textile recycling and high environmental impact, poor recycling economics limit growth

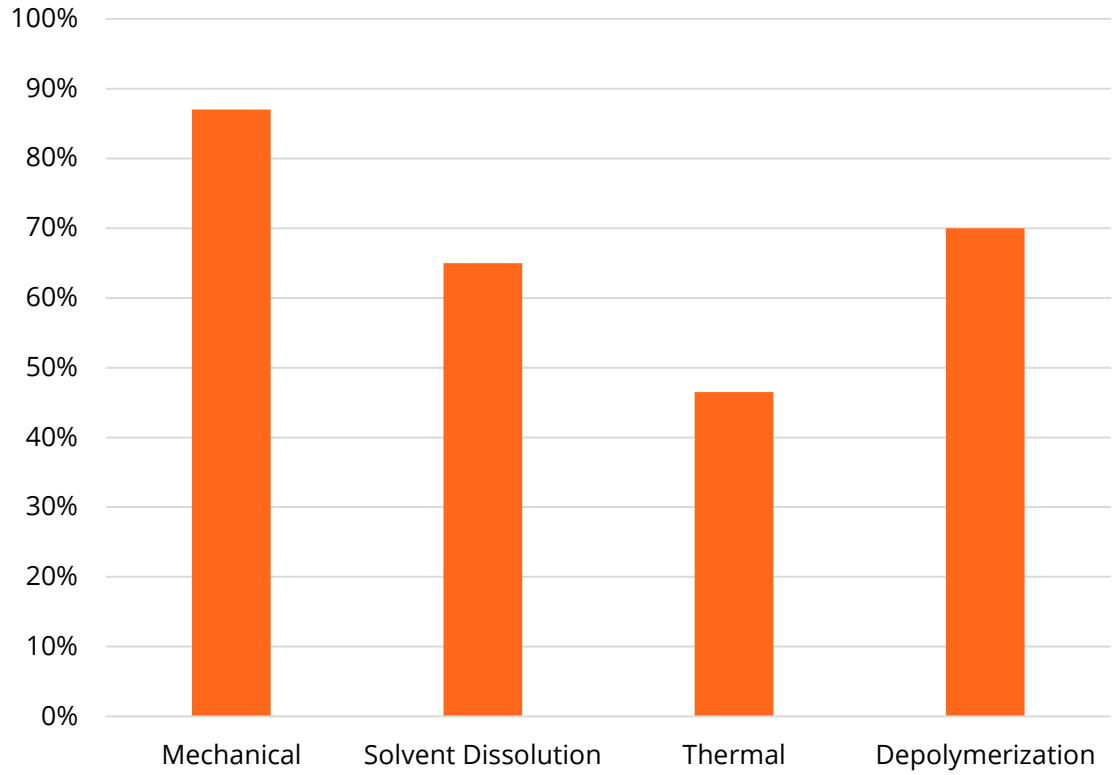
Chemical Recycling is needed to recycle synthetic fiber

- Textile recycling has a comparable LCA to reuse, especially in countries with high textile consumption through fast-fashion garments
- The incumbent technology, mechanical recycling, has limited applications
- Chemical recycling can recycle fiber back to virgin quality, but no process can handle all fibers, requiring extensive waste sortation to optimize recycling
- Supply chain shortcomings preventing scaling:
  - **Collection low & waste is increasing:** Only 14% of post-consumer textiles are collected for recycling and textile waste is set to increase by 50% by 2030 (GFA) necessitating rapid and impactful collection infrastructure improvements
  - **Fast fashion pushing demand:** Low-quality, trendy clothing is mass produced, quickly worn-out and inundates waste systems without recycling capacity
  - **Sorting inefficiency limits recycling:** Impactful automated sortation is not ready for commercial scale, often causes severe system malfunction due to errors

Impact of Textile Recycling is Environmental, Not Economic

- Annual textile waste will increase by 50% in the next five years, roughly doubling end-of-life textile emissions from landfilling and incineration
- Polyester production is responsible for 40% of textile industry's annual emissions and creates the majority of textile waste
- Recycled synthetic fibers (polyester, nylon, acrylic) reduce GHG footprint by 15–35 tons of carbon dioxide, e.g., compared to virgin production (Figure 3)
- Fiber-to-fiber recycling eliminates pollution from pesticide use, textile dyes
- Reduces reliance on ineffective and misleading reuse programs:
  - Reuse not applicable to most synthetic textiles due to low quality
  - 75% of "reused" textiles are exported to the global south, where waste management infrastructure is ill-equipped to handle high-volume textile waste

Figure 3: GHG Reduction Potential (as a percent of virgin garment emissions)



Data Source: Higg MSI; JESRT: 8(7), July 2019; JRC Technical Report, 2021; Mistra Future Fashion, 2019. Specific process emissions will vary for Solvent Dissolution and Depolymerization depending on specific chemicals used.

Source: Cleantech Group

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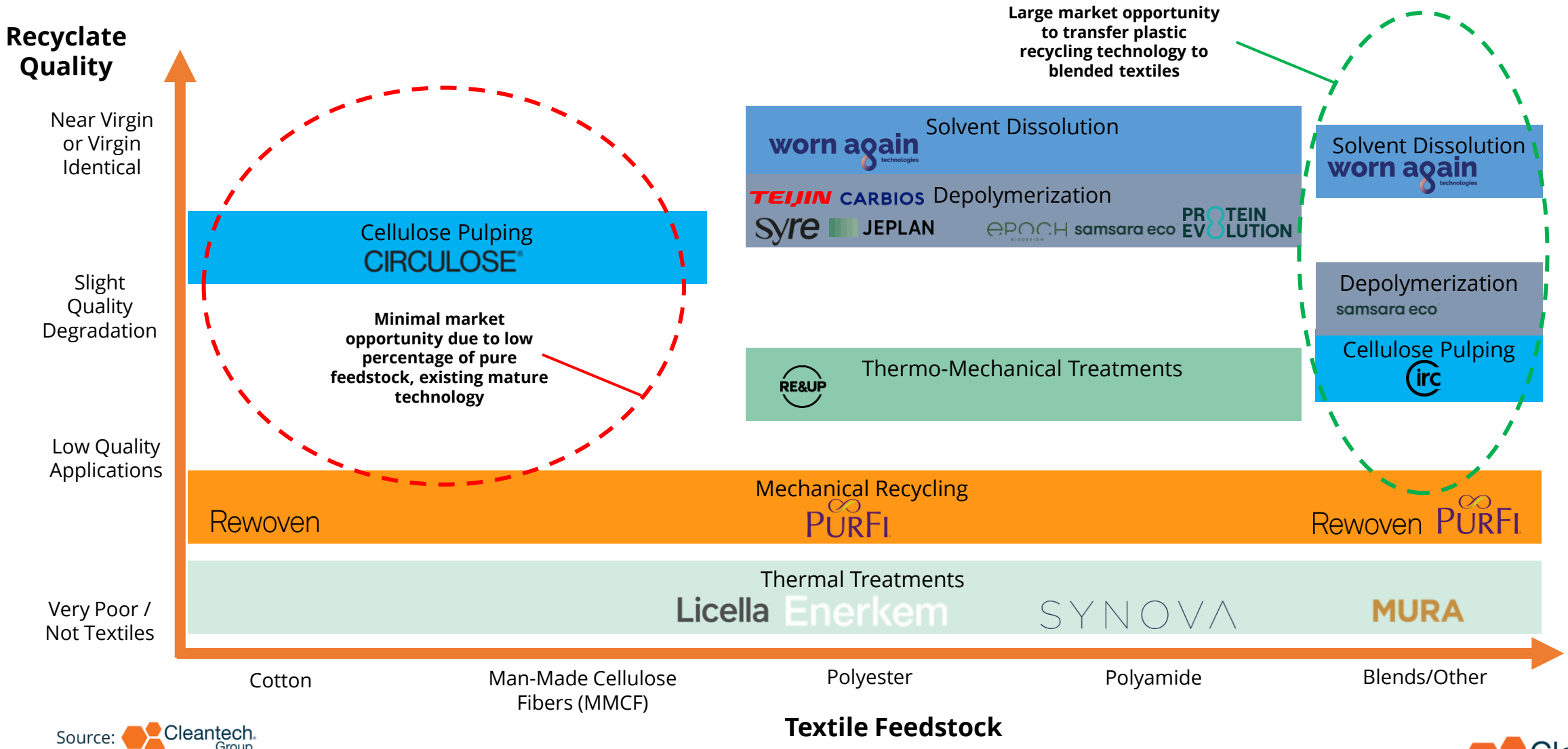
Figure 4: Recycling Process Efficiency, Material Application

Solvent dissolution and depolymerization are progressing well, winner will specialize in blended textiles



Source: Cleantech Group

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Challenges – Sorting Blended Textiles Prohibits Commercial Scaling

Feedstock diversity will force technology specialization over next decade

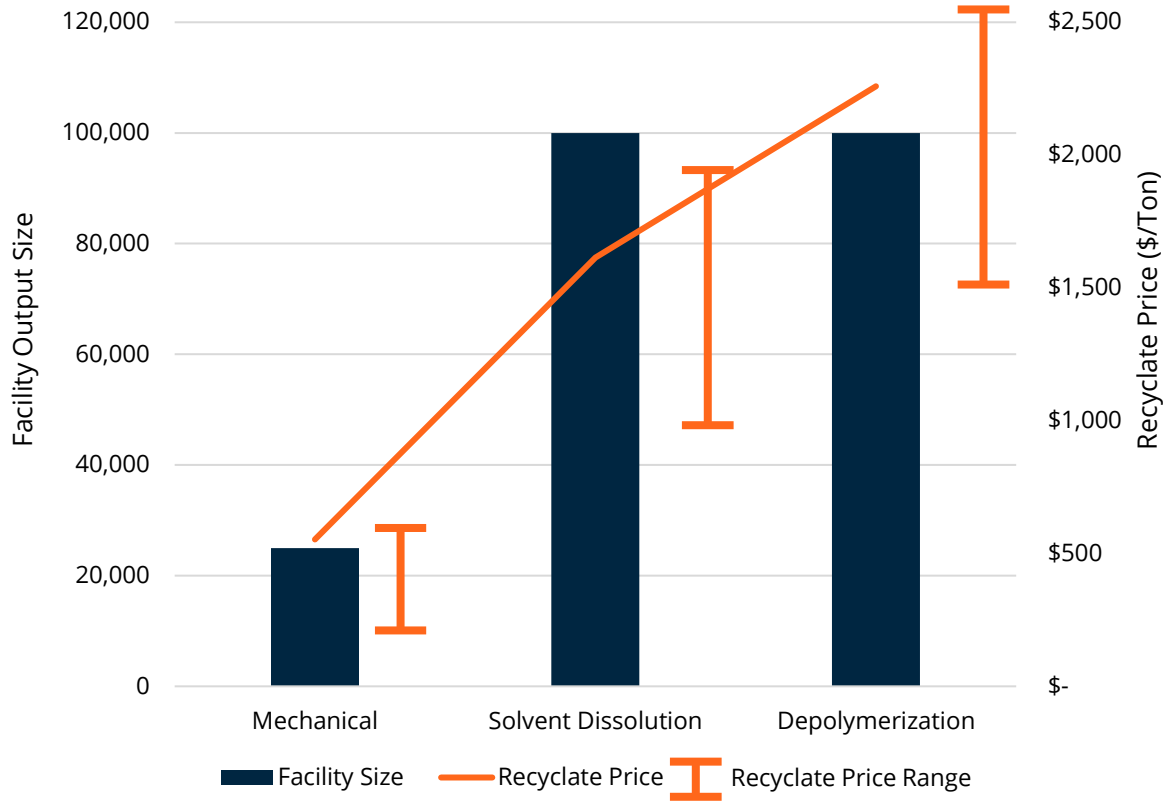
Technical Barriers

- Input issues
  - **Low collection rates**: Feedstock collection rates are extremely low, maxing out at 30% in Europe and 12% in the U.S.
  - **Sorting:** Recycling will require costly and often inaccurate hand-sorting until near-infrared scanning systems (NIRS) are commercialized at scale, 5-10 years away
  - **Contamination:** Blended textiles are incinerated today due to recycling difficulty; new technologies do little to solve this and are not close to commercial viability
- Offtake issues
  - **Quality Degradation**: Traditional mechanical recycling leads to fiber shortening, resulting in lower quality recycled fibers with limited applications
  - Manufacturers unwilling to pay **50-100% green premium** for recyclate (Figure 5)
  - Recycled fiber is not standardized and often unfit for textile manufacturing

Economic Barriers

- **Cost**
  - Higher quality chemical recycling processes incur significantly higher operating costs from sorting and pre-processing
  - Demand for high purity feedstock is outpacing supply, disrupting the economics
- **Scaling issues**
  - Fragmented value chain incurs significant costs, but vertical integration has yet to be successfully demonstrated
  - A lack of localized collection, sorting, and pre-processing infrastructure hampers the supply of high-quality feedstock to recycling facilities
- **Competition**
  - Low prices of virgin fibers make most recycled fibers non-competitive
  - Inconsistent recycle quality reduces trust in recycled market compared to virgin

Figure 5: Optimal Facility Size and Average Recyclate Price by Technology



Note: Thermal Gasification omitted as it does not produce direct textile recyclate. Figures are estimated to 2030 projections for economies of scale on recyclate market price. Optimum facility size based on industry interviews.

Source: Cleantech Group

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Drivers – Textile Recycling Still 50-100% More Expensive Than Virgin Production

Virgin fiber price parity is the guiding metric for textile recyclers and remains out of reach

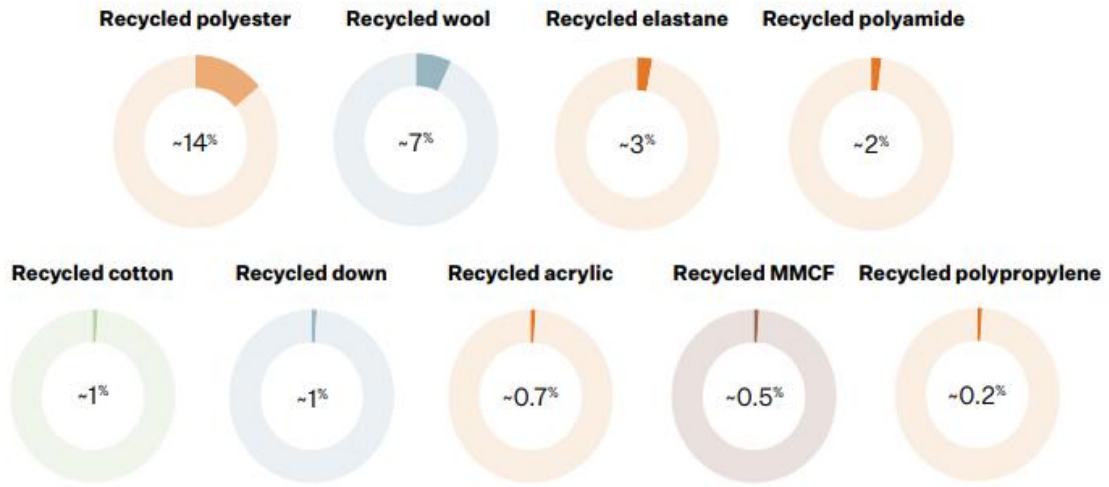
Economic Dynamics of Demand

- Macro outlook: **Recyclers seek 100,000 ton/year facilities, investors unconvinced**
  - Textile recycling is unprofitable below 25,000 tons/year regardless of technology
  - Recyclers want to mirror the economies of scale from incumbent manufacturers
  - Investors dissuaded by low recyclate offtake demand, feedstock difficulties including high sortation cost, reliance on manual labor for high purity, material inconsistencies
- Micro outlook: **Recycling economics hindered by high-cost, low availability of high-purity feedstock**
  - Novel methods require commercially unavailable, high purity feedstock to be profitable
  - High purity feedstocks are likely 5-10 years away due to low collection rates, high waste export rates, and sorting inefficiency
- **Polyester has shown the strongest growth** in demand, fueled by bottle-to-textile PET recycling (Figure 6); recycled polyamide and cotton demand is increasing through specialized partnerships but remains low due to high cost relative to virgin production

Market Conditions

- Supply chain shortcomings
  - Textile waste collection infrastructure does not capture **70-88% of feedstock**, leaving it to be landfilled or incinerated; collected textile waste is usually exported to Africa, LATAM
  - Textile recyclers have yet to determine optimal fiber ratios to achieve economies of scale
  - Extended Producer Responsibility (EPR) mandates assign manufacturers responsibility for proper waste disposal but are only active with minimal enforcement in EU, some U.S. states
- Policies that would help
  - Government-enforced EPR for corporations and education campaigns for citizens like the EU's Waste Framework Directive remedy gaps in textile waste mismanagement
  - State-led or funded modernization of textile sorting infrastructure (E.g., Los Angeles' LASAN)
  - Limiting textile waste exports, standardizing fabric blends to promote recyclability

Figure 6: Market Share of Recycled Fiber by Type



Source: Textile Exchange (2023)

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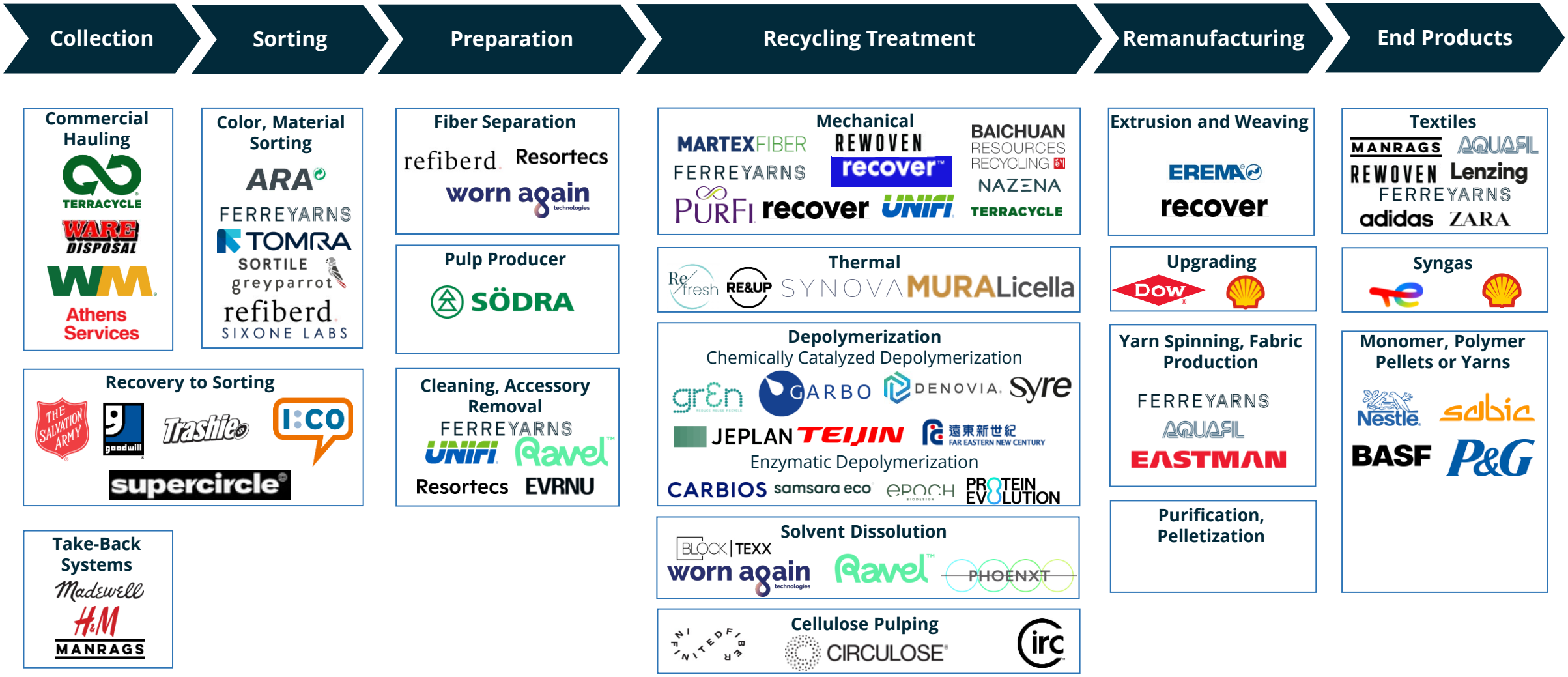
End-of-Life Textile Value Chain/Landscape



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State of Novel Technologies

Mechanical recycling not suitable to tackle textile waste issue but other processes have serious drawbacks

	TRL	Production Characteristics	Environmental Issues	Innovations
Mechanical	– 9, low quality recyclate – Accepts diverse feedstock – Commercial textile recycling standard	– Most cost-effective today, characterized by low energy requirement – ~$440 per ton of recyclate	– Optimal process for textile recycling but likely infeasible due to strict feedstock requirements to match chemical recycling output	– "Soft" mechanical recycling preserves fiber length better than conventional technologies but at an unscalable price
Solvent Dissolution	– 5-6, high quality recyclate – Accepts diverse feedstock – Challenges with scaling novel tech economically	– Best positioned to recycle mixed-synthetic fibers economically – ~$990-$1,675 per ton of recyclate	– High chemical use drives up GHG footprint – Requires extensive waste management	– Recent research indicates high yields in processing mixed polycotton blends – Application of AI solvent identification software
Thermal	– 7, syngas – Narrow feedstocks, primarily applicable to synthetic feedstocks	– High downstream refining costs – ~$700-1,100 per ton of recyclate	– Higher GHG footprint than any other process – Open-loop, syngas byproduct not used for textiles	– Full integration into existing syngas plants to produce novel fuels
Depolymerization	– 6-7, high quality recyclate – Handles several polymers well but requires 80%+ purity of target polymers	– 50-200 kT plants viewed as plateau for economy of scale – ~$1,200-$2,000 per ton of recyclate	– High water use and energy requirement but offers significant GHG savings	– Ongoing research on catalyst design and AI-informed genetic engineering for enzymatic – Speed up reaction time, lower water use

Textile Recycling: Regional Drivers, Sources of Innovation, Pilots

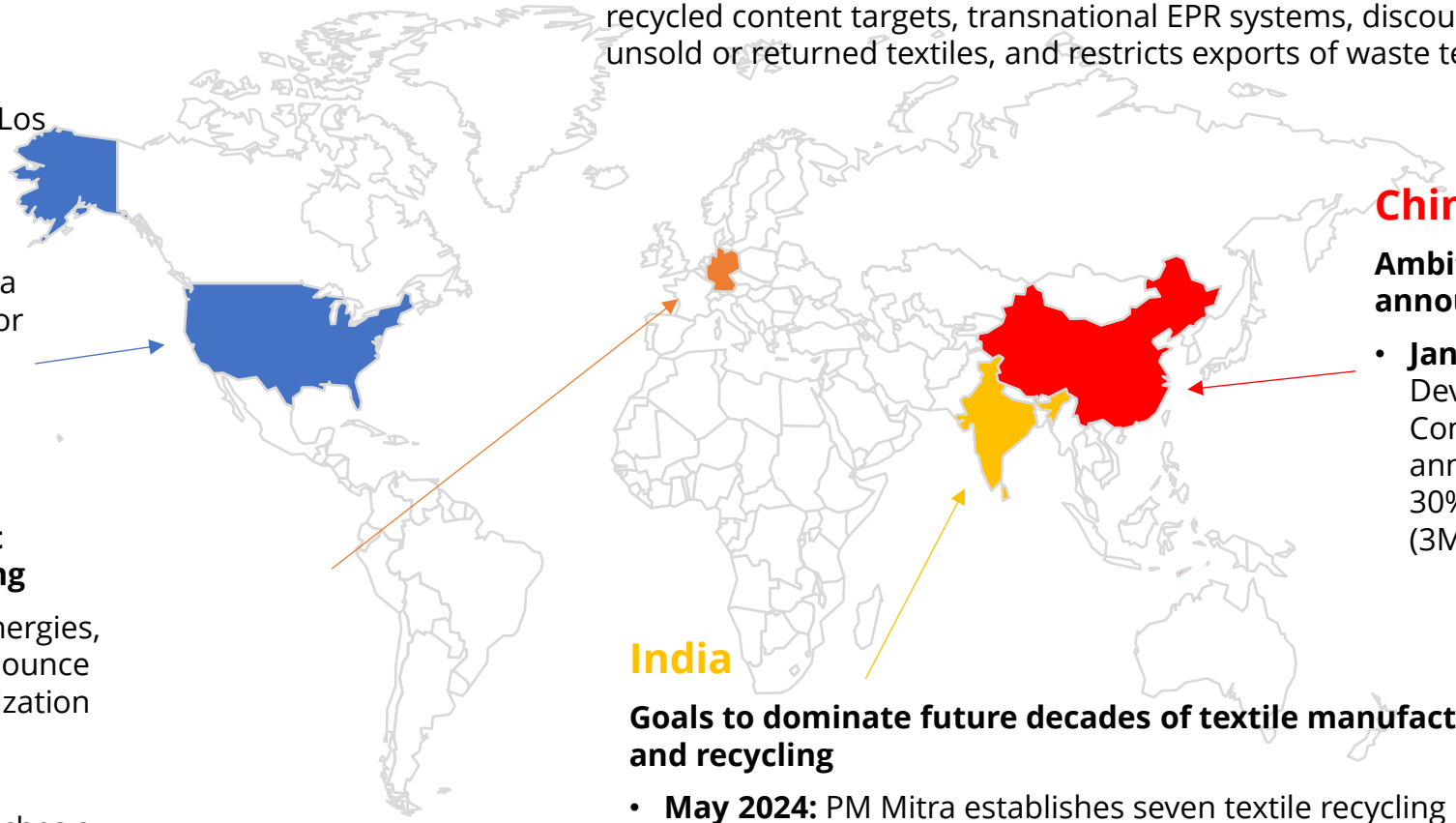
Transnational

- **November 2024: Lithuania** receives $11M from EU Waste Directive to modernize textile recycling and sorting facilities for intra-EU recycling capacity
- **July 2023: European Union's** EU Strategy for Sustainable and Circular Textiles set recycled content targets, transnational EPR systems, discourage the destruction of unsold or returned textiles, and restricts exports of waste textiles

United States

FOAK public and private scale-ups

- **November 2024:** WM, Gap, H&M partner with the city of Los Angeles on LASAN textile sortation facility
- **May 2024:** Syre announces construction of North Carolina pilot facility as well as plans for Vietnam and Iberian facilities



China

Ambitious goals but few announced facilities

- **January 2023:** National Development and Reform Commission (NDRC) announces plan to recycle 30% of waste textiles per year (3M tons) by 2030

Germany

Europe's collection stand-out accelerates chemical recycling

- **November 2023**: Technip Energies, IBM, and Under Armour announce launch of Reju, a depolymerization spin-out based in Frankfurt converting PET to Polyester
- **October 2023:** Germany reaches a high of 75.6% waste textiles collected

India

Goals to dominate future decades of textile manufacturing and recycling

- **May 2024:** PM Mitra establishes seven textile recycling parks with $542M through 2028
- **May 2022:** Production-Linked Incentive (PLI) scheme allocates $1.4B for textile import and export acceleration

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Textile Recycling: Technology Leading Innovator Examples

Positioning: Textile-to-textile recycler focusing on depolymerization as a solution to polyester waste

Market insight

- Recycling processes for PET are not true closed-loop recycling as they specialize in plastic bottle waste
- Polyester still has no commercial-scale solution, too large of an issue to ignore

Company insight

- Able to reduce polyester footprint by up to 85% compared to virgin production
- Solution remains focused on majority polyester blends, can handle up to 40% non-polyester content

Milestones:

- Finalizing North Carolina demonstration facility
- Planning to open 32 recycling facilities by 2032 with an ambition to produce over three million tons of recycled polyester annually
- Acquired recycling technology from Premirr in 2023, $600M offtake agreement with H&M

Capital: $100+

Contact: Ley Richardson, CTO

Positioning: Textile recycler primarily extracting PET and cotton using organic solvents DMSO, DMI, and Propyl benzoate

Market insight

- High contamination rates limit effectiveness of depolymerization on textile recycling
- Europe driving demand via recycled content mandates

Company insight

- Investment is not a necessity today but will require additional capital once commercial scale is validated
- Aiming to launch first commercial plant in 2027 to recycle 100,000 pounds of textiles

Milestones:

- Working with Sulzer and IWK to incorporate recycled PET into foam solutions
- Opened first demonstration plant, capable of recycling 2,000 pounds of textiles per year
- Offtake agreements with H&M, Kering

Capital: $48M

Contact: Mike Schwarz, Director of Operations

Positioning: Provider of PET depolymerization technology using glycolysis for bottles and clothes

Market insight

- Removing textile waste from PET fiber is an expensive process most companies disregard
- Industry standard is to extract only BHET from PET or dispose of non-polyester blends

Company insight

- Jeplan's BHET extraction process extracts valuable monomers while preserving monetary value of waste textiles like cotton
- Weighing licensing and constructing more facilities equally, looking at Asia and U.S. for next facility
- Achieved horizontal bottle and textile recycling

Milestones:

- Highest recorded commercial depolymerization yield (98%)
- Two commercial-scale facilities in Japan, partnerships with Nippon Sumitomo, Sojitz
- Licensing PET to BHET technology to Axens, Toray Films for European expansion

Capital: $32M

Contact: Masaki Takao, CEO

Textile Recycling: Enzymatic Depolymerization Innovator Examples

samsara eco

Positioning: Enzymatic recycler targeting PET and nylon with a proprietary selection of enzymes

Market insight

- Enzymatic recycling remains difficult to commercialize due to slow processing times
- Enzymatic recyclers failed to progress processing efficiencies, need to target commercial partners' understanding of runway first to secure future

Company insight

- Pursuing several plastic feedstocks while optimizing PET enzymes through AI
- Company is aiming to recycle 1.5M tons of plastic per year by 2030 first with a Melbourne plant, plan to finalize 20,000 tons per year facility in 2025

Milestones:

- Extensive waste-to-textile partnership with lululemon focused on nylon
- Partnering with NILIT to develop nylon recycling facility
- Spin out from Australian National University

Capital: $106M

Contact: Raoul McAlister, CTO

CARBIOS

Positioning: Enzymatic depolymerization recycler of PET producing recyclate at food quality standard using cutinase enzyme

Market insight

- Traditional and chemical recycling continue to struggle with contamination from dyes, additives, or impure waste streams, lowering yields

Company insight

- Cutinase enzyme achieves a 97% depolymerization yield for PET over a 16-hour process
- Engineered enzyme can recycle PET contaminated with dyes, additives, or waste
- Establishing recycling facilities in UK and France, licensing technology out in Turkey

Milestones:

- Partnered with Patagonia and Puma to produce full enzymatic textile-to-textile recycling, L'Oreal, Nestle, and Pepsi Co. to expand PET circularity
- Recyclate is 60% more expensive than virgin PET
- Broke ground on 50kt/year plant in April

Capital: $150M+

Contact: Pascal Bricout, CSO

PROTEIN EVOLUTION

Positioning: Enzymatic depolymerization recycler using artificial intelligence to engineer new enzymes

Market insight

- Enzymatic depolymerization traditionally struggles with long processing times
- Enzymatic recycling does improve recycling's energy requirement, emissions, and waste

Company insight

- Difficulty establishing plans for pilot and commercial facilities due to low output, feedstock acquisition, and low offtake demand
- Enzymes remain expensive to produce, especially to supply commercial-scale recycling plants

Milestones:

- Partnership with Stella McCartney for biologically recycled PET garment line
- Expanding feedstocks to nylon and polyurethane through AI-designed enzymes

Capital: $20M+

Contact: Anthony Young, Director, Investor Relations

Textile Recycling: Fashion companies investing in recycling to meet EPR frameworks

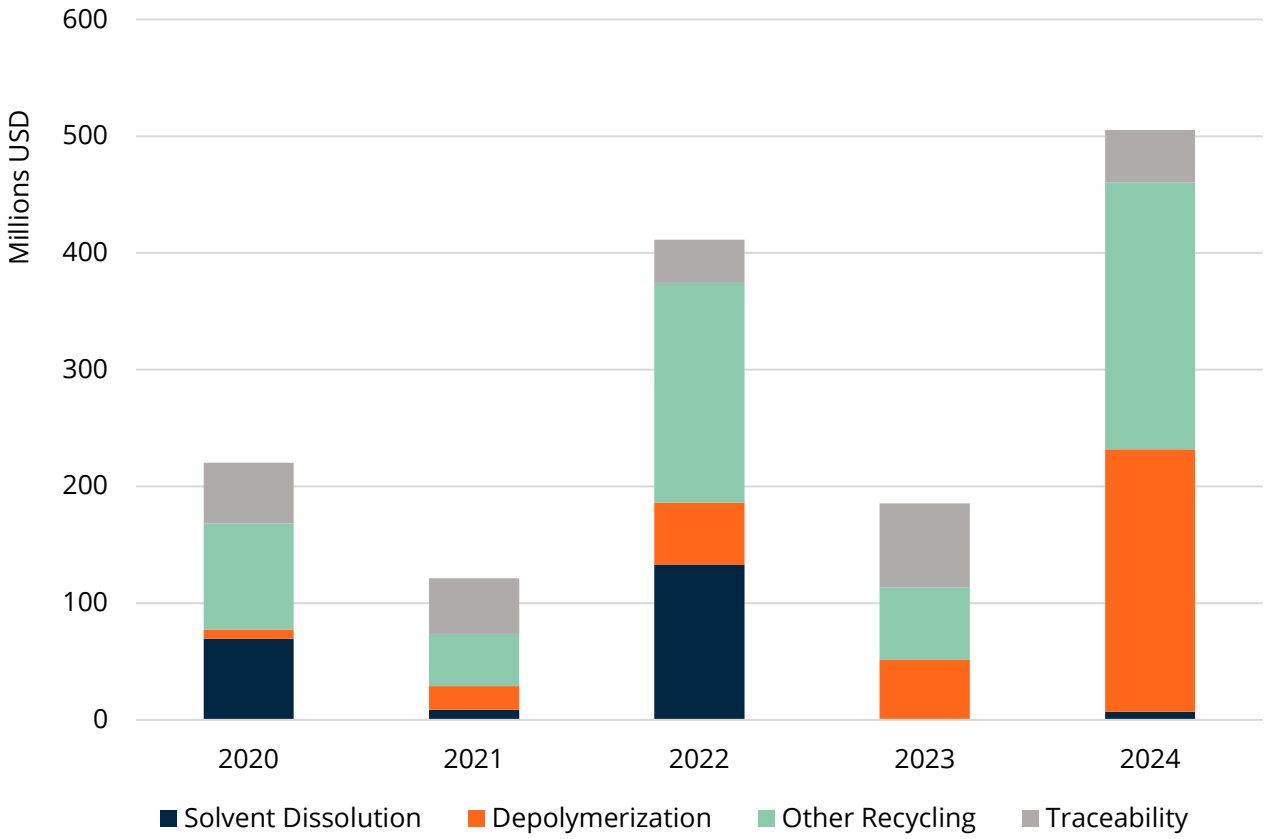
	Positioning	Engaging Innovation
H&M	▪ Multinational fashion retailer known for their success in the fast fashion business model ▪ Aiming to rectify their contribution to large growth in textile waste through recycling programs and investments into innovators	▪ Partnered with Vargas Holdings to launch Syre to scale polyester textile-to-textile recycling ▪ Agreed to a $600M, seven-year offtake agreement with Syre to incorporate recycled textiles into H&M's manufacturing in North America, Europe, and Asia ▪ Invested in solvent dissolution textile recycler, Worn Again Technologies, to advance contaminated PET polymer recycling ▪ Offtake agreement in place for Worn Again Technologies' 2027 commercial facility
INDITEX	▪ Multinational clothing company representing Zara and other brands with over 7,000 retail locations ▪ Aiming to replace 40% of textiles with recycled fibers, mostly using mechanical or depolymerization	▪ Joint research venture with BASF to recycle post-consumer polyamide textiles directly into new polyamide textile goods, currently being incorporated into several Zara products ▪ Signed three year, $74M recycled polyester offtake agreement with Ambercycle to purchase 70% of their recyclate output ▪ Member of textile recycling consortium, Whitecycle, alongside members aiming to expand European recycling capacity including Carbios, Michelin, Mandals, Kordsa, and five research universities
lululemon	▪ Multinational clothing company focusing on athletic and athleisure verticals ▪ Historically criticized for alleged greenwashing campaigns, making active efforts to improve sustainability of products and end-of-life collection	▪ Key investor and industry partner in Samsara Eco's $65M Series A round ▪ Manufacture suite of products using enzymatically recycled nylon fiber under multi-year nylon and polyester recycling partnership with Samsara Eco ▪ North American end-of-life collection and sortation partnership with textile logistics start-up Debrand

Textile Recycling: New Players Entering Textile Recycling Supply Chains

	Positioning	Engaging Innovation
goodwill	▪ American business focused on community development projects with an emphasis on veteran employment and clothing procurement ▪ Expanding into textile reuse and recycling services using national partnerships and software	▪ Leading a recycling pilot program funded by Walmart and partnering with TOMRA and Sortile as material sortation partners and the Rochester Institute of Technology ▪ Partnered with WM and textile recycler Reju on a multi-year pilot facility to advance textile recycling capabilities in North America ▪ Partnership with Harvest Nano to recycle cotton waste into nanocellulose for aerospace applications ▪ Aggressive EPR lobbying in New York and California to bolster feedstock access
WM	▪ Largest American waste collection company improving sorting to supply high purity plastic waste/resin ▪ Aiming for 200,000 tons of annual recycled resin production from their 500,000 tons of plastic waste by 2025	▪ Partnership with Goodwill and Reju (IBM, Technip and Underarmour) to establish a three-party supply chain focused on supplying Reju's developing U.S. facility with textile feedstock ▪ Investments in textile sortation company Debrand and recycler REPREVE ▪ Financial support for publicly-owned MRFs in Chicago and Los Angeles processing and sorting textile waste
EASTMAN	▪ Eastman is a chemical manufacturer providing industrial acids, adhesives, solvents, and other chemical solutions ▪ Set to own three of the world's largest chemical recycling facilities ▪ Specializing their depolymerization facilities on glycolysis and methanolysis to treat polyester	▪ Received $375M from the Department of Energy to support their Longview, Texas recycling facility capable of handling 110,000 tons of waste annually ▪ Partnered with Debrand, Patagonia on initial pilot to recycle pre- and post-consumer clothing waste ▪ Invested $2.5B to build three PET Methanolysis Depolymerization recycling facilities across France and the U.S. to process 400,000 tons PET/year

Key Trends: Investments in Innovators

Figure 7: Venture Investments in Textile Recycling



Source: Cleantech Group i3 database. Traceability includes feedstock sourcing and digital visibility along the supply chain. Other recycling primarily focuses on mechanical recycling but also includes thermal and pulping technologies.

Source: Cleantech Group

Investment Highlights

- Solvent dissolution and depolymerization moving into Series B, historic struggles between Series A and B rounds are the most frequent cause of company bankruptcies
- Lessons from Renewcell's bankruptcy
  - First-to-market in textile recycling is insignificant giving volume of waste and fragmented global markets
  - Global scaling is nearly impossible today; careful diligence over feedstock and offtake is imperative and difficult
- Future and present financing
  - Funding should be designated several years out for specific project goals with an emphasis on local supply chains and offtake
  - Large project financing rounds are incredibly uncommon with the last two coming in 2020 and 2021
  - Smaller, structured debt is more common with several rounds over the last five years, most often funding pilot facilities for innovative technologies
- Need for blended public/private financing
  - Public investment is uncommon with the European Innovation Council and Australian Government as the only two leaders in the space, Temasek is also a growing name
  - Venture funds are the most frequent investors in the space, corporates are increasingly active to meet EPR goals

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Waste & Recycling Sector Research

Recent Published Research

Spotlights

- Solvent Dissolution (Q3 2024)
- Residential Heat Pumps (Q4 2023)
- Cultivated Protein (Q4 2024)
- Plant Protein (Q3 2023)
- eJet (Q2 2023)
- Cathode Manufacturing (Q2 2023)

Insights

- Battery Recycling (Q2 2024)
- Plastic Recycling (Q1 2024)

Upcoming Topics

Spotlight

- PFAS Removal (Q1 2025)

Insights

- Wastewater Treatment (Q2 2025)

Upcoming Events

- **Cleantech Forum Europe** – Chantilly, France – November 5-7, 2024
- **Cleantech Forum North America** – San Diego, CA – January 27-29, 2025
- **Cleantech Forum Asia** – Singapore – May 7th-8th, 2025

Associate – Parker J. Bovée

- Focused on emerging innovation & trends across cleantech sectors, including water management systems and recycling technology.
- Prior to joining Cleantech Group, Parker developed wildfire prevention technologies with VegaMX and researched wildfire management at Duke University and the University of California, Berkeley.
- Parker earned a Bachelor's degree in History and Public Policy from the University of California, Berkeley where he specialized in the history of American environmental entrepreneurship.

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