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TEXTILE RECOVERY IN THE U.S

a roadmap to circularity

RRS

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ACKNOWLEDGMENTS

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- **Susan Inglis,** Executive Director, Sustainable Furnishings Council

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ABOUT RRS

Resource Recycling Systems (RRS) has been active for decades supporting the development of recovery solutions across the breadth of materials consumed in our daily lives: paper products, food and beverage containers, electronics, organics, durables, and more. From early adopters to fast followers to mainstreamers ready to scale, RRS has worked with private and public clients across the value chain to strive for more sustainable and resilient materials management systems. The firm has industry professionals, engineers, economists, technical analysts, and communication specialists who share the vision to effect change for the good, bringing a better tomorrow for our next generations.

WHO WE ARE

30+ years in recycling and managing resources

40+ employees in 4 countries

660+ years combined field experience

1,000+ projects across 9 markets

WHO WE SERVE

- PUBLIC AGENCIES
- MANUFACTURERS/ COMMERCIAL BUSINESS
- PARTNERSHIPS
- RECOVERY INFRASTRUCTURE
- TRADE GROUPS
- RETAIL
- UNIVERSITIES
- HEALTHCARE
- FUNDERS/INVESTORS

PREFACE

As one of the fastest growing waste streams, used textiles are a largely untapped resource. Recovering these fabrics and fibers as inputs to a variety of closed loop and cascading end uses presents the opportunity to develop more sustainable and resilient supply chains. The time is ripe for action throughout the industry value chain to transform textile manufacturing, use, and recovery into a truly sustainable and resilient system.

The development, successes, and failures of existing recovery systems for metal, glass, plastic, and paper can be applied to create successful circular systems for textiles, including the establishment of infrastructure, practices, corporate culture, and consumer mindset. The entire textile industry value chain has a part to play. The framework presented in this white paper, Textile Recovery in the U.S.: A Roadmap to Circularity, shows a path forward to this textile industry investment.

As evidenced by recent global economic and market disruptions from events like China's National Sword and COVID-19, the business case for more reliable, transparent, and domestically powered supply chains is stronger than ever. It is critically important that brands, retailers, manufacturers, suppliers, consumers and the emerging textile reuse and recovery value chain come together and take steps forward with the technical, business, and financial resources to get the job done. The path is before us and the time is now.

JIM FREY

CEO | RRS

INDUSTRY PERSPECTIVES

"TOGETHER, we have to create a more circular apparel industry, and efficient and scalable textile recycling is a vital part that."

–DEVON LEAHY, VP SUSTAINABILITY, RALPH LAUREN

"THIS COMPREHENSIVE STUDY is essential reading for anyone seeking to understand the fastest growing category of waste in the United States, and the opportunities for future-facing brands, innovators, and municipalities to transition from costly linear business models to efficient circular systems for textiles."

KATE DALY, MANAGING DIRECTOR, CLOSED LOOP PARTNERS

"AS AWARENESS AND UNDERSTANDING around textiles circularity has increased, the one area which has been somewhat overlooked is the end of use textiles supply chain, namely the sorters and collectors responsible for aggregating our 'future feedstock'. RRS's white paper report does an exceptional job at highlighting the gaps and evolution of this market segment which needs to take place in order to provide high volume supply of suitable feedstock to future regenerative recycling plants like ours."

CYNDI RHOADES, FOUNDER/CEO, WORN AGAIN TECHNOLOGIES

"IF CIRCULARITY IS OUR DESTINATION, we must have a roadmap. RRS has done great work to plot the industry's current position while outlining crucial paths for everyone to navigate a more sustainable way forward. Resources like this are invaluable to Tyton as we work to save the planet from human consumption."

PETER J. MAJERANOWSKI, PRESIDENT & CO-FOUNDER, TYTON BIOSCIENCES

"WE MUST ALL PLAY OUR ROLE to become a circular society and IKEA is determined to be a part of the solution. While we transform our operations to contribute to a circular economy, we embrace the opportunity to cooperate and collaborate with others to effectuate lasting change."

JENNIFER KEESSON, COUNTRY SUSTAINABILITY MANAGER, IKEA RETAIL US

"*TEXTILE RECOVERY IN THE U.S.: A ROADMAP TO CIRCULARITY* is a comprehensive review of the textile reuse and recycling industry in the United States and the need for collaboration among all stakeholders trying find a solution to the abundance of textile waste that ends up in landfills. The Secondary Materials and Recycled Textiles Association (SMART) and its members have been at the forefront of working on finding the best and highest use for all textiles going into the reuse and recycling stream from pre and post-consumer markets. *Textile Recovery in the U.S.: A Roadmap to Circularity* recognizes the vital role our members play in the sale, collection, sorting and processing of these materials helping to close the loop and provide circularity to textile reuse and recovery. This white paper is a great resource for anyone interested in understanding the problems associated with textile waste and the solutions needed to improve the reuse and recovery of textiles in the future."

JACKIE KING, SMART EXECUTIVE DIRECTOR

"RRS MAKES THOUGHT-PROVOKING POINTS and shows salient examples of what the current textile waste and recycling landscape looks like. This paper provides a road map to guide stakeholders across the value chain on who they can collaborate with to drive real material change in the textile industry."

NICOLE KENNEY, CO-FOUNDER, MATEREVOLVE

"IT IS URGENT the home furnishings industry learn to reduce waste - for the health of our businesses now as well as for the health of the world we leave for future generations. Turning waste to feedstock is our greatest hope. But it is also one of our greatest challenges. Daunted by our complex supply chains, we can begin to hope when we begin to understand how to leverage our existing relationships with suppliers and customers, as well as the potential in new relationships and technologies. With what we throw "away" having become our world's most abundant natural resource, we must focus on the potential in every aspect of textile recycling."

SUSAN INGLIS, EXECUTIVE DIRECTOR, SUSTAINABLE FURNISHINGS COUNCIL

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GLOSSARY OF TERMS

CIRCULAR ECONOMY
The Ellen MacArthur Foundation defines a circular economy as “a systemic approach to economic development designed to benefit businesses, society, and the environment. In contrast to the ‘take-make-waste’ linear model, a circular economy is regenerative by design and aims to gradually decouple growth from the consumption of finite resources.”

CIRCULAR TEXTILES
Textiles that are recovered, processed, and recirculated back into supply chains to make new textile products.

DIVERSION
Preventing waste going to disposal through recycling or other recovery methods.

DOWNCYCLING
The financial or structural value of a material is downgraded in the recycling process.

FIBER-TO-FIBER RECYCLING
In this report, the term “fiber-to-fiber recycling” is used to describe the recovery of raw materials from textile waste through the application of mechanical or advanced recycling technologies. Whereas the immediate outputs of advanced technologies may be intermediaries such as PET polymers, PET monomers, and/or cellulosic pulp, the intermediary raw materials are generally intended as inputs to fiber production for the textile industry.

LCA
Life cycle assessment (LCA) is a technique for evaluating the potential environmental impacts associated with a product (or service) by: compiling an inventory of relevant inputs and outputs; evaluating the potential environmental impacts associated with those inputs and outputs; and interpreting the results of the inventory and impact phases in relation to the objectives of the study [1].

MRF
A material recovery facility (MRF) is a facility that receives, sorts, and prepares recyclable materials for commodity end markets.

OFFTAKE PARTNER
In recycling, an entity committed through contract, agreement, or otherwise to purchasing recycled commodities from a recycler or other producer.

PET
Polyethylene terephthalate, commonly abbreviated PET, is the most common thermoplastic polymer resin of the polyester family and is used in fibers for clothing. Recycled PET is commonly abbreviated rPET.

PRE-CONSUMER TEXTILE WASTE
Generally refers to textile waste generated or consolidated at the retail level. Examples include overstock, deadstock, returns, damaged or defective goods, off-spec products, sample waste, and other goods that for one reason or another are unsalable.

POST-CONSUMER TEXTILE WASTE
Textile waste generated after consumer or commercial use. Examples include used clothing and home textiles and used textiles from the hospitality sector.

POST-INDUSTRIAL TEXTILE WASTE
Refers to textile waste generated during the manufacturing or production process. Examples include cut and sew waste, excess or damaged fabric, overruns, and off-spec material.

SECONDHAND
Textiles that have been used by the consumer.

UPSTREAM
A term that refers to a point in the supply or value chain that comes before referenced point.

EXECUTIVE SUMMARY

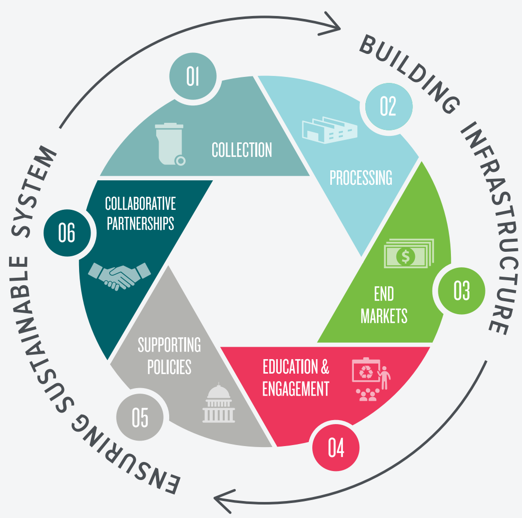
The growth of textile waste in the United States is outpacing the growth of every other major category of waste. This report evaluates the current state of textile waste in the U.S. waste stream and explores a future-state system in which textiles are maintained in best and highest use throughout the value chain.

Solving for textile waste in the United States can have a measurable global impact on the upstream investment of human and natural capital like oil, cotton, energy, water, and chemicals used to make textile products. Building systems to recover textiles requires strategic partnerships from across the recovery value chain. This paper outlines the essential elements of an ideal recovery system and describes a way forward to a circular textile economy.

Note: Textiles as a product category are defined as apparel and non-apparel products including home and hospitality textiles, commercial textiles, and indoor and outdoor upholstery fabrics. Throughout this paper, the term "textile waste" refers to both pre- and post-consumer material that is regarded as no longer usable for its original purpose by its owner. If only post-consumer waste is being discussed, the term post-consumer textile waste is used.

components of a successful textile recovery system

1. Widespread convenient collection systems;
2. Regional textile sorting facilities (textile MRFs) that generate readily accessible material volume and composition data, paired with mechanical and advanced recycling technologies to convert inputs into global commodities;
3. Robust end markets and brand uptake agreements that support a domestic recycler economy;
4. Compelling outreach that drives engagement with consumers, brands, and communities;
5. Thoughtful supportive policies that create a level playing field and incentivize textile recovery and infrastructure development; and
6. Innovative strategic partnerships that increase the circularity of pre-consumer and post-consumer textiles and decrease textile waste going to landfill.



TEXTILES IN THE U.S. WASTE STREAM

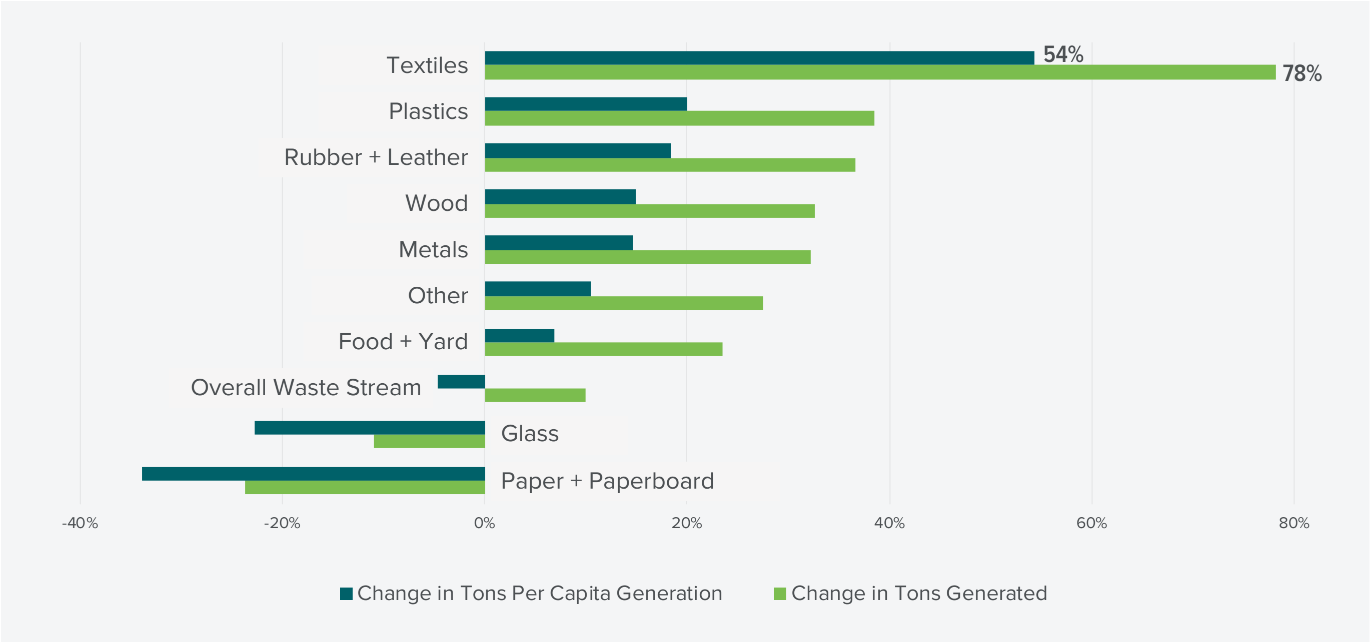
growth of textile waste

The growth of textile waste in the United States is outpacing the growth of every other major category of waste, with plastic waste second. Textile waste in the municipal solid waste (MSW) stream increased 78 percent by weight between 2000 and 2017 while the waste stream as a whole grew 10 percent over the same time period [2]. On a per capita basis, textile waste increased 54 percent per person, while overall waste generation per capita decreased by 5 percent (Figure 1).

The overall growth in disposal of textile waste is compounded by a stagnant diversion rate of around 15 percent. In 2017, only 2.6 of 16.9 million tons of textile waste was diverted from disposal [4].[1]

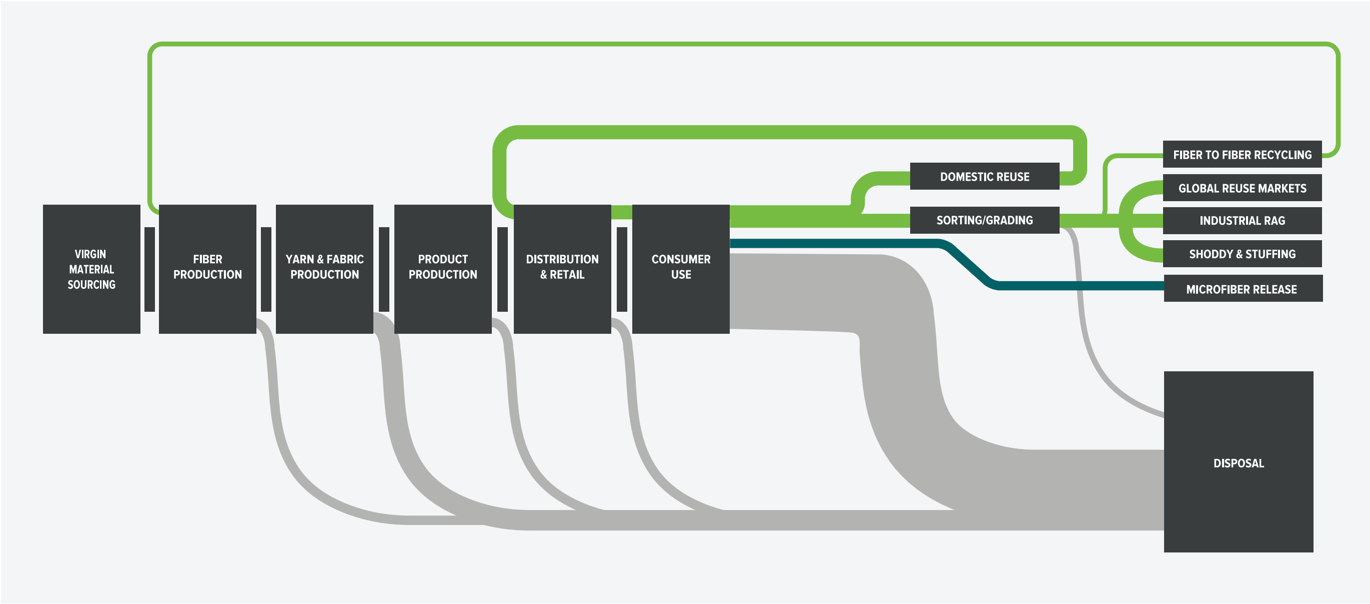
These figures account for both apparel and non-apparel textile waste such as home and hospitality textiles, healthcare textiles, and institutional textiles. The dataset includes textile waste generated by the residential,

Figure 1. Percent Change in Absolute Tons and Tons Per Capita Waste Generation 2000-2017 [3]



1. The U.S. Environmental Protection Agency (EPA) does not calculate the amount of textiles donated or resold in the United States for reuse. Reuse falls outside the EPA's definition of generation and EPA does not have estimates for the reuse of textiles.

Figure 2. Flow Diagram of Textiles in the U.S. [6]



commercial, and institutional sectors, but does not account for post-industrial textile waste [5]. Throughout the paper, the term "textile waste" will refer to both pre- and post-consumer material that is regarded no longer usable for its original purpose by its owner. If only post-consumer waste is being discussed, the term post-consumer textile waste will be used.

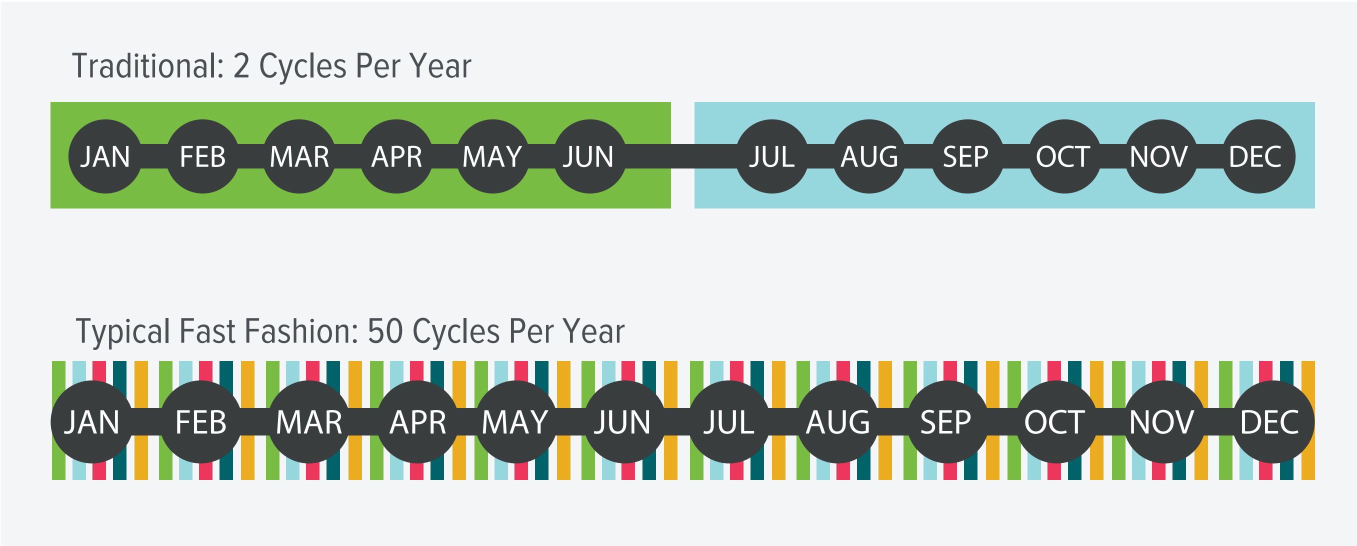
Textile losses at the post-industrial level are not reported or tracked reliably, but independent academic and industry sources estimate that losses at each stage of production range from 3-6 percent of total throughput. Figure 2 depicts the proportion of textiles that are lost or recovered at each phase along the value chain from post-industrial to pre-consumer to post-consumer [6].

With the projected rise in population and the emergence of a new global middle class, consumption of textile and apparel is projected to increase 63 percent by 2030 [7]. Along with that growth comes environmental, labor, and solid waste issues. Due to its size, solving for textile waste in the United States can have a measurable impact on the global upstream investment of resources, energy, water, and chemicals used to make textile products.

With the projected rise in population and the emergence of a new global middle class, consumption of textile and apparel is projected to increase 63% by 2030.

Action is needed across the textile and apparel value chain to address consumption and waste generation, reduce impact on the environment, and develop more sustainable models to manage this rapidly growing waste stream.

Figure 3. Traditional vs. "Fast Fashion" [8] [9]



fast fashion

The growth in textile waste over the past two decades can be partly or mostly attributed to a shifting consumer mindset about the durability of clothing. Once viewed as lasting goods, clothing and home textiles are now often viewed as disposable.

"Fast fashion" is the result of the apparel industry producing more styles of clothing at a faster pace and at lower prices. In fast fashion, there can be as many as 50-100 micro seasons, compared to two seasons per year in traditional fashion (Figure 3) [8].

In this era of fast fashion, consumer purchasing habits have driven average product prices down, and that price pressure has translated to price constrictions on materials. As a result, product quality suffers and less-durable materials have a shorter lifespan. In the United States alone, consumers buy a new garment every five days and keep these items for a shorter period of time; more than half of fast fashion produced is disposed of in under one year [10].

Whether this trend's peak has been reached remains to be seen. One sign of the changing textile retail environment is the recent Chapter 11 bankruptcy protection filing of the iconic fast fashion brand Forever 21 along with the company's announcement to improve the quality of their clothing to win back consumers [11]. At the same time, there is growing momentum within the industry to address the waste consequences of the fast fashion business model as H&M and others announce investments to support circular textiles. Evolving consumer attitudes are also driving change. According to ThredUP's 2019 Resale Report, millennial and Generation Z shoppers prefer to purchase from "sustainably conscious" brands and are 2.5 times more likely than other age cohorts to purchase second-hand clothing [12]. A 2019 McKinsey study found that 42 percent of millennials want to know what goes into products and how they are made before they buy, compared to 37 percent of Gen Z [13].

More than half of fast fashion produced is disposed of in under one year.

Fast fashion has consequences beyond its contribution to the growing volume of textile waste. Many of fashion's environmental impacts occur upstream during fiber sourcing, yarn spinning and dying, weaving, and garment production. The rapid pace and low cost of fast fashion is an enabler of overconsumption and contributes to a decline in environmental health and human safety. Fast fashion is fundamentally unsustainable.

Figure 4. Textile Fraction of U.S. MSW Over Time (By Material Type)

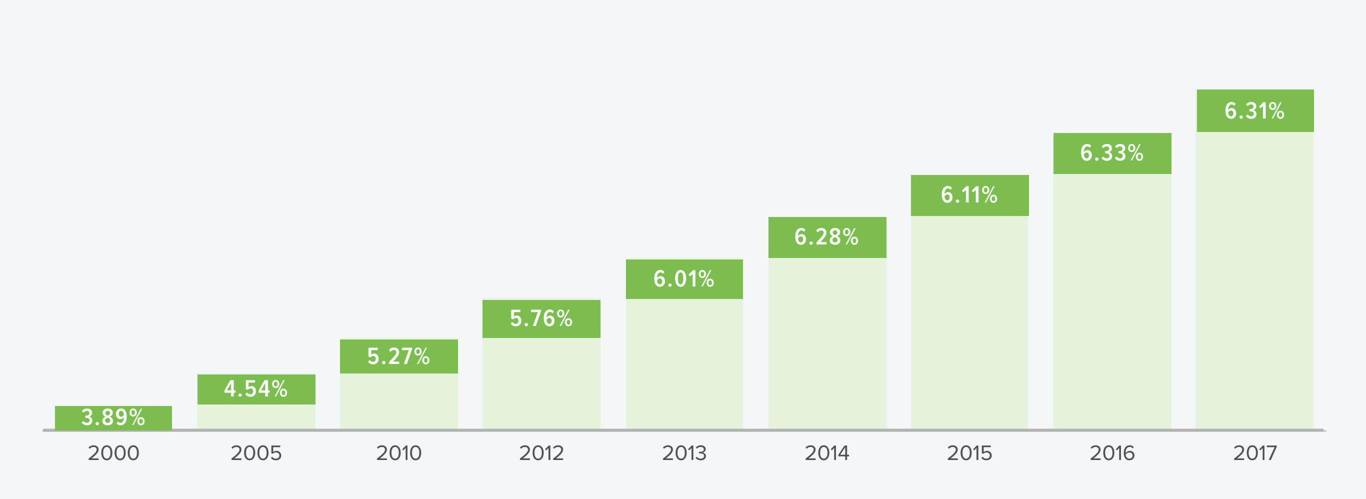
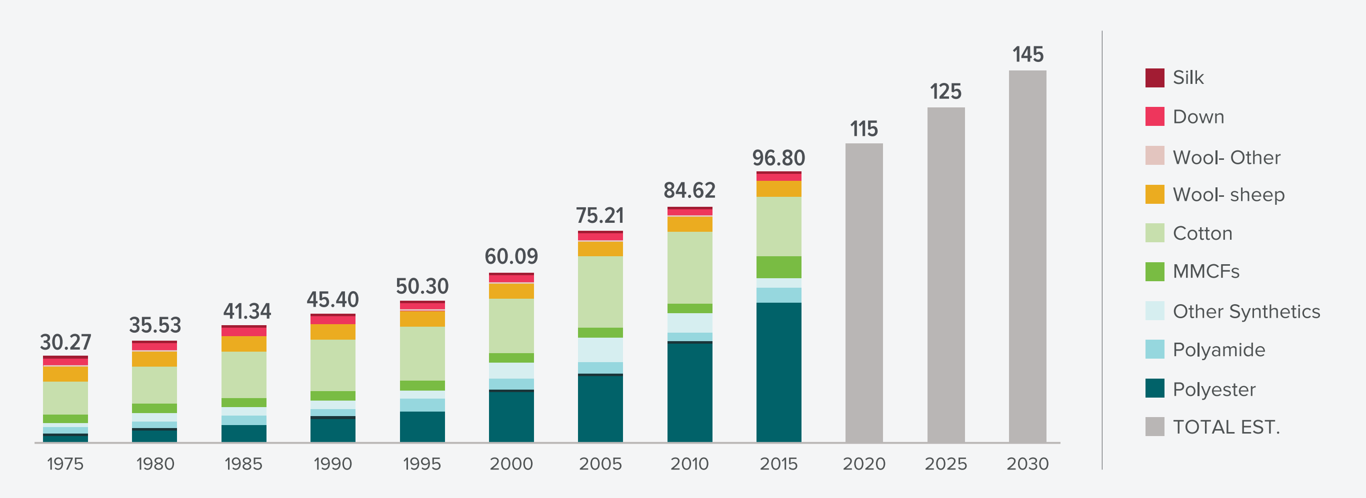


Figure 5. Global Fiber Production, 1975-2030 (projected) [14]



waste stream by material type

The U.S. Environmental Protection Agency classifies the waste stream by material type and by product type. Textiles comprised 6.31 percent of the waste stream by material type in 2017[2], for a total of 16.9 million tons (Figure 4) [4]. There are small amounts of clothing and home furnishing textiles found in the rubber and leather categories that are not accounted for in these estimates.

EPA estimates that textiles as a product category (defined as clothing, footwear, towels, sheets and pillowcases) comprised 4.5 percent of the waste stream in 2017, at a total of 14.3 million tons – 12.8 million tons of clothing and footwear and 1.47 million tons of towels, sheets and pillowcases [4].

fiber composition

Knowing more about the types of fiber present in the textile waste stream can help inform diversion decisions. However, detailed data do not exist for the fiber composition, fiber blends, and material blends of textiles and apparel consumed in the United States. Fiber composition can be gleaned at a high-level by looking at global raw commodity flows. The Textile Exchange's 2019 Preferred Fiber and Materials Market Report shows that the two primary fibers used today are polyester and cotton (Figure 5) [14]. According to the findings, polyester increased in usage from 1975 to become the dominant fiber type, followed by cotton. PCI Fibres projects that polyester will continue its growth in market share at least through 2030 [15].

2. *2017 is the most recent year of data as of the time of publication.*

THE U.S. TEXTILE RECOVERY LANDSCAPE

elements of a sustainable recovery system

For a recovery system to thrive it needs a strong foundation across six key elements: Collection, Processing, End Markets, Education & Engagement, Supportive Policies, and Collaborative Partnerships (Figure 6).

The first three components focus on infrastructure:

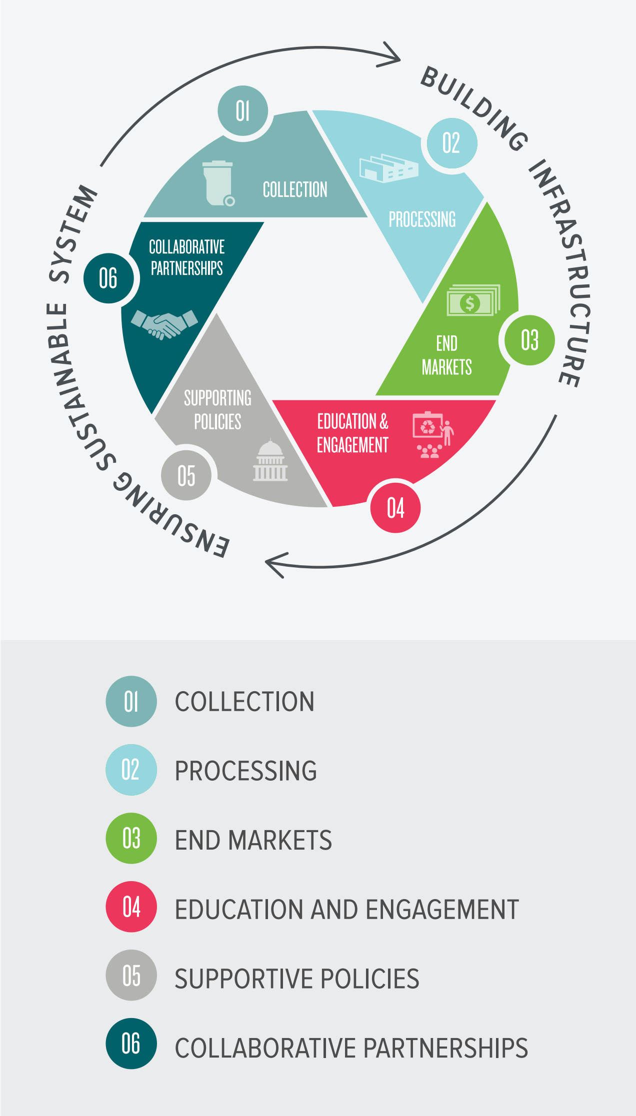
1. **Collection:** Access to convenient collection systems for similar groups of recyclables;
2. **Processing:** Technologically robust recycling facilities that can effectively sort and market the recyclables; and
3. **End Markets:** Strong end markets for recyclables.

The second three components focus on the long-term viability of the system – ongoing participation, informed recycling and funding:

4. **Education and Engagement:** Strong and consistent education and engagement that supports participation from stakeholders across the value chain;
5. **Supportive Policies:** Supporting state and local policies that encourage recycling; and
6. **Collaborative Partnerships:** Effective stakeholder coordination to develop and fund recycling solutions.

The following sections describe the current state of U.S. textile recycling within each of these parts of the sustainable recovery system model.

Figure 6. Six Elements of a Sustainable Recovery System



COLLECTION

There are two elements to textile waste collection – collection for disposal and collection for recovery.

Collection for Disposal

Currently, the majority of textile waste (85 percent) is discarded as trash and must be managed by municipal or regional government solid waste systems which will either landfill or incinerate the waste.

The management of textiles for disposal comes with a large price tag. The annual cost to collect and dispose of textile waste in the United States is estimated at $4 billion in 2020 based on national tip fees and industry-average collection costs (Figure 7) [16] [17].

Case Example – NYC

In New York City, waste characterization reports show that textiles in the waste stream rose 16 percent between 2005 and 2017 (Figure 8) [18]. Associated costs to collect, transport, and dispose of textile waste increased from $43 million to $93 million over that same time period (Figure 9) [18] [19].

Figure 7. Annual Cost to Collect Textiles for Disposal in the U.S., 2000-2020 [16] [17]

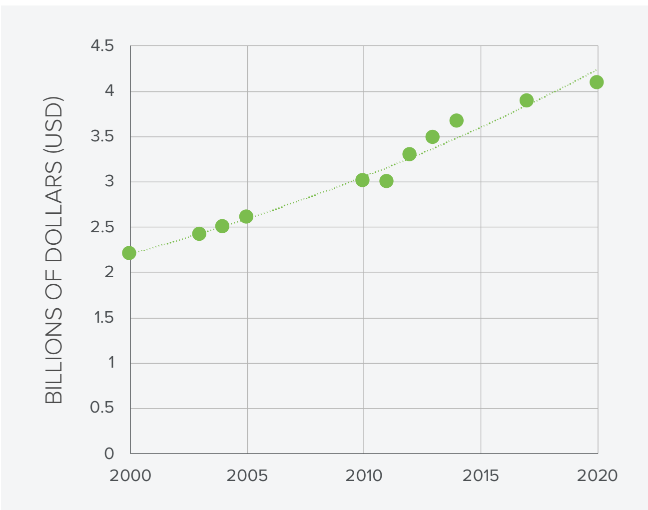


Figure 8. Textiles in New York City Municipal Solid Waste, 2005-2017 [18]

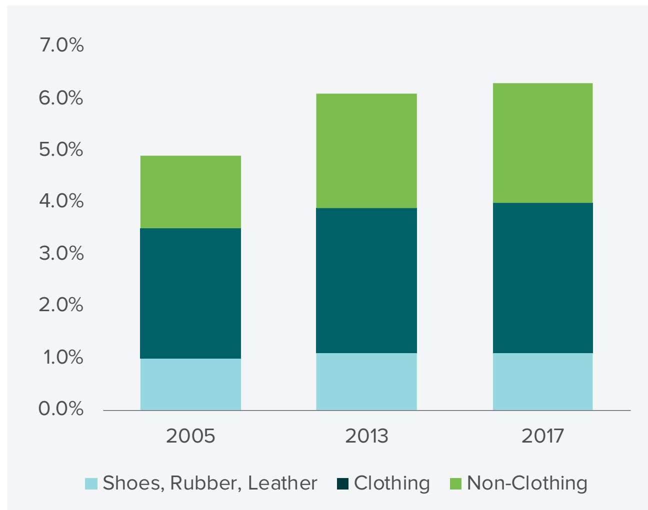
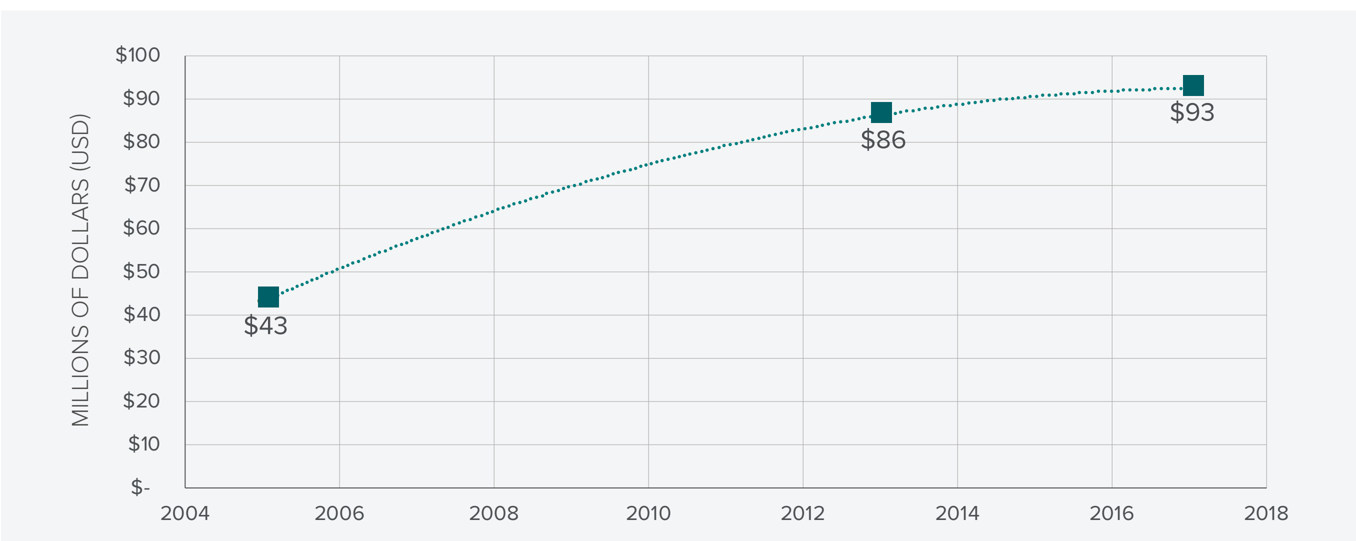


Figure 9. Collection and Disposal Costs for Textiles in New York City, 2000-2017 [18] [19]



COLLECTION FOR RECOVERY AND REUSE

Textile waste that is not discarded as refuse travels through a complex recovery network. There are many textile recovery and reuse practices including hand-me downs, charity donations, pawn shops, garage sales, clothing swaps, and peer-to-peer sales platforms. Charities and thrift stores were some of the first organized avenues to institutionalize clothing recovery and reuse. The thrift, vintage, and consignment market has also grown in prominence through organizations such as Goodwill, Savers, America's Thrift Stores, Salvation Army, and the thousands of private retail mom and pop stores that move used clothing and goods. According to Nonprofit Source, 52 percent of Americans donated clothing, food, or other personal items in 2018 [20]. IbisWorld Market Research estimates that between 2014 and 2019, the thrift store industry grew an annualized 2.3 percent reaching $10.2 billion [21].

Over the past decade, new approaches have emerged, including for-profit secondhand clothing companies collecting through publicly placed drop boxes; highly tailored resale markets such as high end consignment stores and thrift boutiques; brand-sponsored recommerce; retail-based collection boxes; and municipally-managed curbside recovery programs that often rely on logistics providers like Simple Recycling and Retrievr. Growing awareness of the textile waste problem has given rise to innovation in the collection for recovery field, including early leaders like FABSCRAP, a not-for-profit that aggregates and recycles excess fabric; Queen of Raw, an online marketplace for excess yardage from fabric mills and clothing manufacturers; service providers like The Renewal Workshop whose list of corporate clients engaging in the repair community is expanding; and recommerce – a new approach to traditional retail – in the likes of Stuffstr, Trove, and others.

These new business models are changing the way consumers can envision and interact with clothing and apparel. They also have implications for other large textile industries, including home furnishings and upholstery, as in IKEA's furniture sell-back and reuse pilot , currently available in select Ikea markets, such as Spain [22]. Some hotels already utilize rental services for their linens and towels.

The textile products consumers buy and love have life left to give; they carry embedded value for consumers and there is increasing evidence of financial benefit for brands and retailers to provide opportunities for recovery and reuse [12].

PROCESSING

Sorter-Graders

Much of the clothing donated is not directly reused as clothing [23]. Instead, the thrift industry is a large multinational supplier with multiple end use processing paths for used textiles. It is estimated that 80 percent of textiles that enter the thrift store circuit are sold directly to textile brokers, and sorters-graders, largely sight-unseen. Sorter-graders also receive material from other collection systems, including donation bin collections, curbside collections, and retail store takebacks. A sorter-grader is a company that sorts and grades used clothing based on quality, condition, format, and type (specific to end markets), and sells the sorted grades into reuse and recycling markets. There are a few dozen sorter-graders across the U.S. and Canada [24] and a large sorter-

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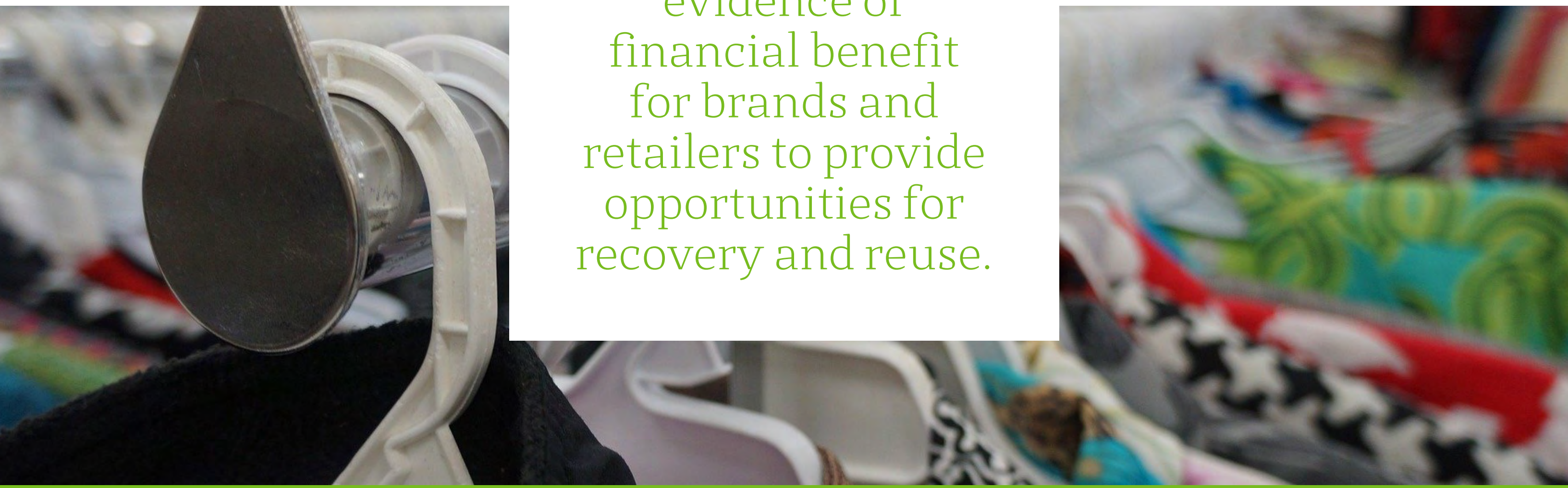
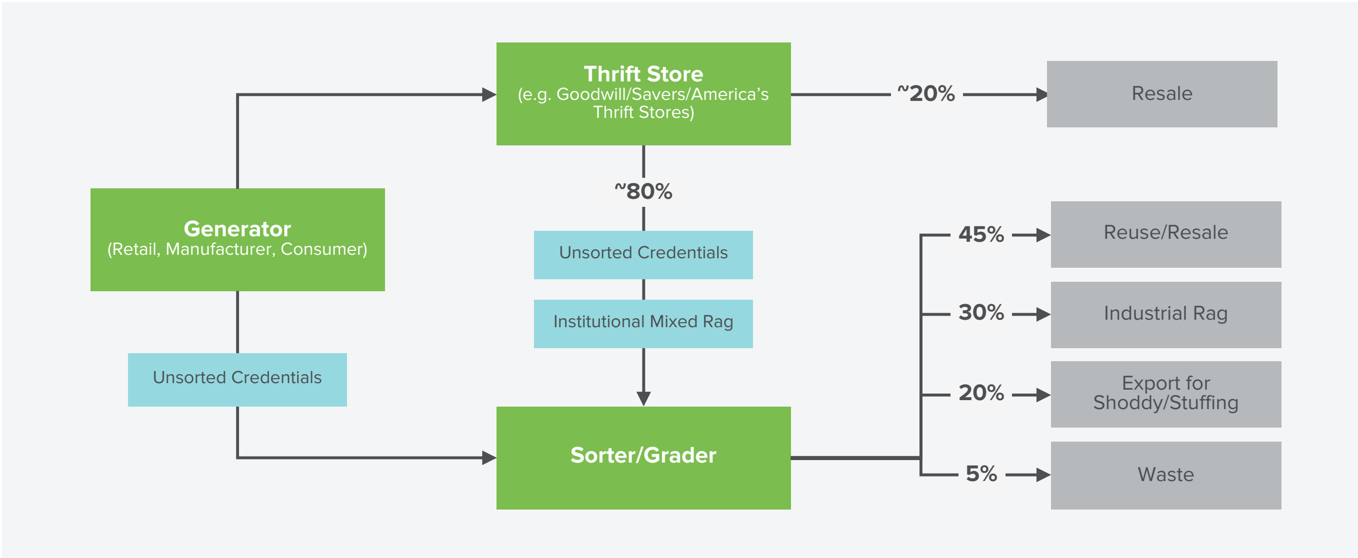


Figure 10. Current Post-consumer Textile Value Recovery Flow [6]



grader presence in India, Pakistan, and the United Arab Emirates, as well as Central and South America. The sorter-grader industry is one of small profit margins and is highly vulnerable to labor costs and market conditions. Brokers often serve as intermediaries.

END MARKETS

The Secondary Materials and Recycled Textiles trade group (SMART) reports that 45 percent of incoming material is sold for reuse, 30 percent is sold as institutional rag, 20 percent is sold into the stuffing, shoddy, and yarn fiber industry, and five percent is unrecoverable or unusable due to contamination. Less than a fraction of one percent is turned back into fiber for new textile production [25]. Figure 10 illustrates the flow of post-consumer textile waste through the sorter/grader network.

End Markets for Reuse – U.S. and Global Markets

Apparel designated for reuse by sorters-graders can be sold in the U.S. as described earlier or exported to the global market.

Among net exporters of used textiles, the U.S. is dominant, exporting $682 million worth of used clothing per year, followed by Germany ($386 million) and the United Kingdom ($346 million) [26]. Net importers include Pakistan (6.2 percent share), Malaysia (4.1 percent), Ukraine (4.1 percent), Ghana (3.4 percent), and Kenya (3.3 percent) [26]. In all, the secondhand market was worth $20 billion globally in 2015 and is projected to reach $41 billion by 2020 [10].

Clothing export is not without its challenges. First, temperature and climate differences between origin countries and destination countries render certain types of clothing less valuable for export. For example, winter clothing has little export value for warm climates.

Second, overseas reuse markets are at risk of diminishment as the quality of fast fashion declines and competition for new clothing at lower prices increases.

Third, in recent years, a subset of East African Communities (EAC) countries moved to close their borders to used clothing imports by raising import tariffs to prohibitive levels, citing concerns that the imports had outcompeted domestic textiles industries. Some argue that the decline of EAC countries' domestic apparel manufacturing industries is likely due to a combination of socio-political factors, not least of which is the decline in domestic cotton production and the large growth of Chinese clothing imports. A 2017 report by USAID found that:

> *"Chinese exports of ready-made clothes to the EAC reached $1.2 billion in 2016, dwarfing the value of used clothing imports by a factor of four. Although taxed at a higher ad valorem rate than used clothing, the vast majority of what enters EAC markets is undocumented and untaxed. Chinese imports, particularly the undocumented goods that flood the market, pose a much greater danger [than used clothing imposts] to EAC domestic industries." [27]*

End Markets for Institutional Rag

Materials that are not sold for reuse are classified as "institutional grade mixed rag". Mixed rag is generally comprised of items that did not meet thrift store specifications, did not sell, or are the unwearable portion of a load of unsorted credential clothing. At 30 percent of total donated textiles, this material is sold as industrial wiping cloths to commercial garages, public works operations, and/or for other industrial uses.

End Markets Using Mechanical Recycling to Produce Shoddy

The remaining 20 percent of donated textiles are sold to fiber converters who shred or otherwise break down the garments into shoddy for use as stuffing, padding, and insulation across several commercial industries. The shoddy process entails sorting by color, cutting with scythes, pulling the fibers, and spinning the fibers into shoddy. Shoddy is most often used to produce low quality woven blankets used for disaster relief [28].

Shoddy markets are saturated, and the global shoddy industry is in decline as it faces competition from low-cost virgin polyester fleece with faster production times from China [28]. Two-thirds of the shoddy mills in Panipat, India, the world's hub of shoddy mills, have closed in the past decade, leaving 200 of what was once 600 in operation [28].

End Markets Using Mechanical Recycling to Produce Fiber & Yarn

Not many mechanical recyclers produce new yarn using used textiles. Two examples of those that do include Hilaturas Ferre and Circular Systems. Hilaturas Ferre has been recycling textile waste into upcycled yarn since the 1940's. Based out of Spain and with locations in North Carolina and Mexico, the company's Recover Upcycled Textile System cuts, shreds, and spins used clothes and garment production waste into new Recover yarns [29].

Circular Systems, a recycling company headquartered out of Los Angeles, California, mechanically recycles post-industrial cutting-room textile waste into yarn that can be used in the manufacturing process for apparel. Circular Systems works with large brands like H&M, Nike, and Adidas to convert cut and sew manufacturing waste into yarn called Orbital hybrid yarn using a mechanical recycling process called Texloop. Through this process, Circular Systems is able to support highly strategic yarn spinning and customization [30].

PET bottles can also be used to produce recycled polyester using a mechanical recycling process. Unifi's REPREVE® yarn is an example of this [31]. However, PET bottles are in low supply and face high demand. See the section below titled Competition for Limited Supply of rPET for more on this topic.

Advantages and Limitations of Mechanical Recycling

Mechanical recycling is a process that converts materials from their original form and function into a different form and function through mechanical means such as shredding without changing the basic molecular structure or chemistry of the material. Mechanical recycling has many benefits but also inherent limitations. Among the benefits of mechanical recycling, cost and energy intensiveness are usually lower than alternative forms of recycling. Additionally, there may

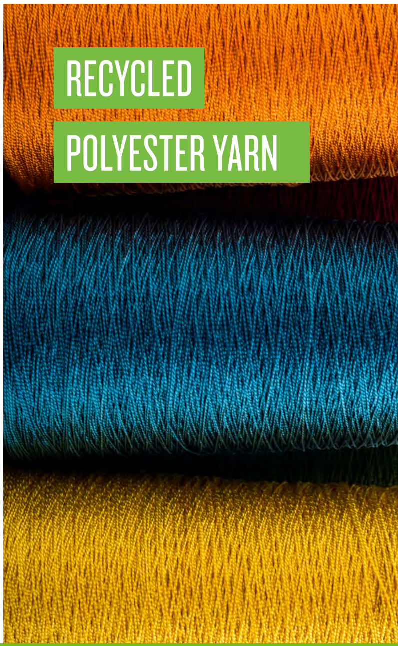


Table 1. Forms of Mechanical Recycling – Advantages and Challenges

DESCRIPTION	INPUTS	PROCESS	END MARKETS	ADVANTAGES	CHALLENGES
Garnetting	Wool and cotton rags and cuttings	Shredding into fluffy, fibrous condition and re-spinning so yarn can be reused in blends, or in some cases alone [32]	New textiles	• Widely available • Established end markets • Retains natural fiber aesthetics and quality. • Retains original color, minimizing the need for dye • Reduces use of energy, water, and emissions compared to virgin	• Mechanical recycling cannot separate fibers. Final product may contain presence of other fiber types • Unable to remove colorants, dyes, finishes, toxic chemicals, and other additives • Results in loss of fiber length, evenness, fiber length uniformity, and material strength • Must be supplemented with 50 percent or more virgin cotton to match the quality and integrity required for new garments [33] [34] • Cannot be recycled infinitely • Restricted end-use applications • Higher cost than virgin
Shredding for Shoddy & Stuffing	Used clothing, fibrous material and textile manufacturing scraps	Shredded into fibrous form, combed, carded	Emergency blankets, insulation, stuffing (mattresses, furniture, stuffed animals), car interiors, carpet and roof felts, etc.	• Established supply chains and end markets exist • Offsets use of energy, water, and emissions compared to virgin production	• Down-cycling (not best and highest use) • Shoddy markets are saturated and may be in decline [28]
Cutting for Rag & Wiping Cloths	Different classes of used clothing according to hydrophilicity, oil repellency, and water absorption properties	Hardware (metals, buttons) removed; Cut into sized rags and wiping cloths	Rags and wiping cloths for various industries	• Established supply chains and end markets exist • Fulfills an existing niche • Offsets use of energy, water, and emissions of producing new rags and wiping cloths	• Down-cycling (not best and highest use)
Mechanical Recycling of PET Bottles into Fiber	PET bottle flake or mono-material polyester textiles	Melted, pelletized, and extruded into new polyester fibers	Carpet, new apparel	• Established supply chains and end markets exist • Offsets use of energy, water, and emissions compared to virgin production	• Not widely available • Unable to remove colorants, dyes, finishes, toxic chemicals, and other additives • Textile inputs are rarely used and when they are, they are limited to color sorted postindustrial materials • rPET from bottles is in limited supply and faces competition from food/beverage companies

be less need for dyes since the fibers retain their original colors. On the other hand, mechanical recycling is limited in the color, aesthetic, and quality of outputs compared to virgin. This is one reason less than one percent of post-consumer textiles captured for recycling makes its way back into textiles and apparel. A summary of mechanical recycling processes is described in Table 1.

EDUCATION AND ENGAGEMENT

Education about the lifecycle impacts of textile waste is largely provided by advocacy organizations like The Story of Stuff Project, the Ellen MacArthur Foundation, Global Fashion Agenda, and the Secondary Materials and Recycled Textiles Association. Education efforts are primarily focused on the downstream effects of consumer choices and behaviors, though some campaigns are working to educate consumers about curbside collection and drop-off bins from various operators (see Figure 11 for an example) [35].

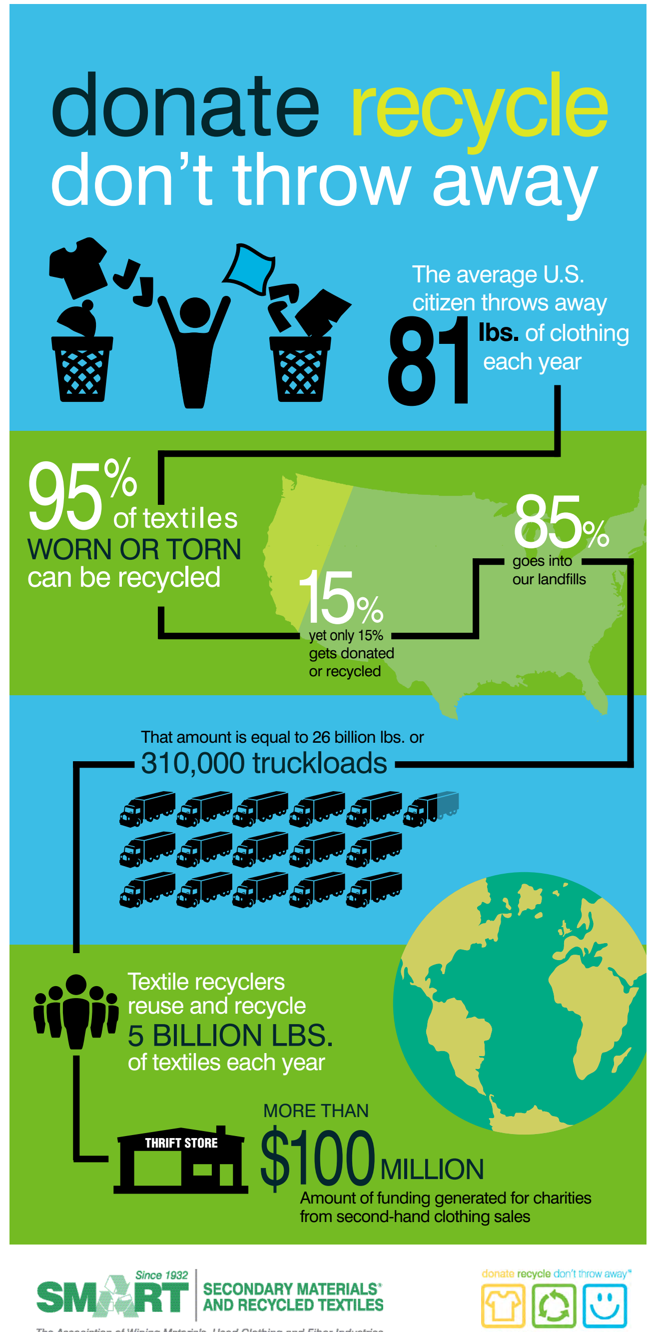
SUPPORTIVE POLICIES

Due to increasing costs of handling textile waste and the negative upstream impacts of the textile and apparel industries, a handful of states are exploring policy for textiles and textile waste [36]. In addition, Montreal is considering a retailer disposal ban on clothing that would prohibit clothing stores and textile companies from throwing out unsold clothing.

California requires labeling for all products containing 50 percent or more polyester. In December 2019, CalRecycle hosted a full day workshop to discuss the need for regulatory oversight for textiles. Additionally, the California Product Stewardship Council [37] has noted several policy discussions under development around:

1. Microfiber washout prevention and capture
2. Mandatory apparel takeback
3. Recycled content standards
4. Improved labeling for accurate sorting
5. Bans on curbside collection for landfilling
6. Eco-modulated fees (i.e., varying levels of fees on virgin raw materials and products that do not meet different thresholds of minimum recycled content criteria)
7. Mandatory recycling
8. Banning PFAS and other toxics (e.g. silver, DWR water repellent)
9. Bills on e-waste and Lithium-ion batteries in wearable tech

Figure 11. SMART Donate Recycle Infographic



PARTNERSHIPS

To date, several high-profile public-private partnerships have started to pave the way for textile recovery. The City of New York, for example, contracts with Housing Works to provide in-building textile collection to residents across the city [38]. Dozens of cities and towns work with Simple Recycling to collect used textiles from households at the curb for reuse and recycling [39]. In 2019, U.K.-based WRAP awarded £4.7 million in capital funding for infrastructure projects for the recycling of plastic packaging or textile waste [40]. Brand and retail foundations have funded research, as well. One example is H&M Foundation's Recycling Revolution project, which is a partnership with The Hong Kong Research Institute of Textiles and Apparel to develop methods for recycling blended textiles [41]. Another is the C&A Foundation's collaboration with Fashion For Good, which supports and funds innovative fashion sustainability startups [42].

A number of brands and retailers offer in-store collection of used apparel for reuse and recycling in partnership with service providers like I:Collect (I:CO), which provides collection boxes and organizes the transport, sorting, and recycling of collected textiles, while others are developing capacities for resale and repair, with partners like The Renewal Workshop.

Industry Collaborations

Several industry groups are pursuing efforts to address textile waste, from working groups to pilots to recycled content standards. The Textile Exchange has made great strides through the development of the Global Recycled Standard (GRS) and the Recycled Content Standard (RCS) for textiles, as well as through its Home and Hospitality Recycling Project Working Group and Recycled Polyester Working Group. The Retailer Industry Leaders Association (RILA) covers the topic of textile waste on its Zero Waste Committee, and the Sustainable Furnishings Council convenes manufacturers, retailers and designers across the home furnishings industry to solve for home furnishings textile waste. The Sustainable Apparel Coalition integrated some end of life indicators into the Higg Index, and the Ellen MacArthur Foundation's Make Fashion Circular campaign works to raise the profile of textile waste at the global level. Circle Economy in Europe has done work to advance a textile sorting technology called the Fibersort, and Fashion Positive works to certify cradle-to-cradle inputs.

Due to increasing costs of handling textile waste and the negative upstream impacts of the textile and apparel industries, a handful of states are exploring policy for textiles and textile waste.

BUILDING A NEW U.S. TEXTILE RECOVERY SYSTEM

the way forward

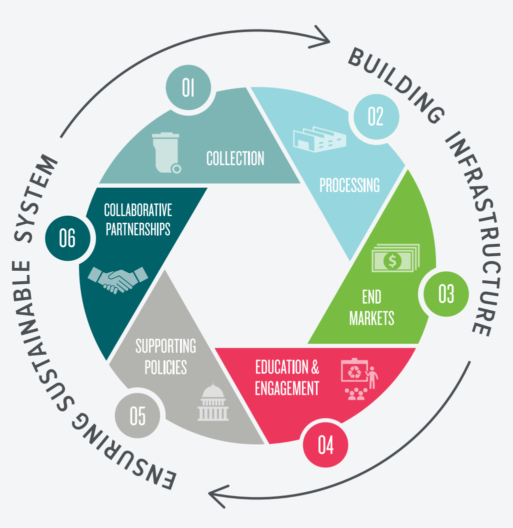
Sustainability in the textile supply chain has received increasing attention in recent years. Amid growing awareness of the high levels of pollution associated with textile production [43] and disposition as well as the wide-ranging impacts of fast fashion, many brands are feeling an increased urgency to reduce consumption and waste and move toward a circular economy for textiles. Robust innovation in the six elements of a sustainable recovery system could be the way forward to build a textile recovery system that manages materials sustainably at each point along the pathway (Figure 12).

COLLECTION

Convenient and wide-spread access to collection is essential to make a dent in the mountains of textiles sent to disposal each year. To surpass a 15 percent textile waste diversion rate, collection efforts must become more widespread than current charity donation and in-store collection box options. For example, H&M captured 26,000 metric tons of clothing worldwide in 2018 through its in-store collection program. Compared to an estimated 1.3 billion garments sold in a year [44], that is less than 10 percent.[3] Ease of collection is vital to help consumers overcome barriers that prevent

Figure 12. Six Elements of a Sustainable Recovery System

- 01 Widespread convenient collection systems;
- 02 Regional textile sorting facilities (textile MRFs) that generate readily accessible material volume and composition data, paired with mechanical and advanced recycling technologies to convert inputs into global commodities;
- 03 Robust end markets and brand uptake agreements that support a domestic recycler economy;
- 04 Compelling outreach that drives engagement with consumers, brands, and communities;
- 05 Thoughtful supportive policies that create a level playing field and incentivize textile recovery and infrastructure development; and
- 06 Innovative strategic partnerships that increase the circularity of pre-consumer and post-consumer textiles and decrease textile waste going to landfill.



3. Assuming the weight of a garment is between one-half pound and one pound, that collection is the equivalent of between 57 million and 114 million garments, or 4-9% of annual sales.

them from diverting textile waste in the first place. Textile collection must be as accessible to consumers/generators as disposal.

In the hospitality sector, linens and towels are a low hanging fruit for collection and recycling. Hotel linens are often generated at predictable frequencies due to standard turnover practices and they are largely homogenous in weight and fiber type. Furthermore, large quantities are managed by a relatively small number of generators – usually the hotel itself, third party linen rental companies, or commercial laundries, with which hotels have quality assurance agreements that dictate quality thresholds for what they do and do not want back [45].

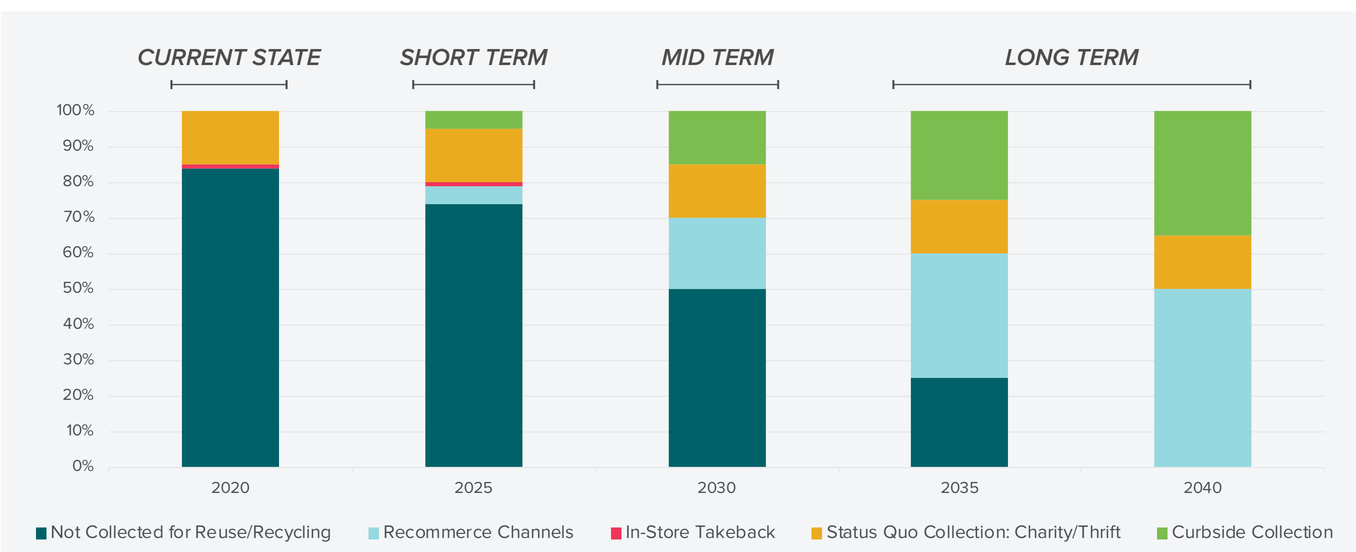
Medical linens from the healthcare industry may be another low-barrier opportunity. According to a study conducted by TRSA, a trade organization for companies that supply, launder, and maintain linens and uniforms, almost 90 percent of hospital linens are lost from rotation before reaching the the end of their useful lifespan [46]. The main reason for this loss is attributed to premature disposal by healthcare workers, costing the healthcare industry $840 million a year. With employee education and revised handling protocols, hospitals can minimize losses and prolong use. When medical linens are no longer fit for use, they can be aggregated and collected for recycling from laundry facilities and/or linen rental companies depending on the applicable arrangement. Like in the hospitality sector, medical linens are generated in regular homogenous quantities.

For consumer textiles, curbside collection is convenient and its message is simple – all clean and dry textiles go into the same bin, no separating into different containers for different types. Simple Recycling is an example of a company that operates a curbside collection service for textiles. It contracts free of charge with municipalities, provides free collection labeled bags to residents, and schedules collection on the same day as trash collection using its own trucks. The service has expanded quickly over the past few years [39]. The value of the collected textiles covers the cost of operations.

Another convenient direct-to-consumer collection method is mail-in. Online shopping, or more accurately, online returns, have acclimated U.S. consumers to shipping products back to retailers. With the emergence of retail clothing rental and resale platforms, this practice is becoming more common and more streamlined.

Figure 13 shows a possible combination of collection approaches that could comprise an ideal future state textile recovery system (percentage splits are conceptual – optimal collection methods require study). The weight of textiles not recovered for reuse/recycling would decrease from 84 percent to zero, while new curbside collection systems, new recommerce collection services and traditional collection channels (charity/thrift) absorb the volumes previously going to disposal. In-store retail collection would be phased out, saving brick and mortar retailers coveted floor space and backroom space. The 20-year timeline is reflective of the time that new fiber sorting and recycling technologies will take to reach commercialization, as it is the end market

Figure 13. Ideal Shifts to Achieve Full Collection for Post-consumer Textiles



THE ROLE OF RECOMMERCE IN TEXTILE RECOVERY

The emergence and projected growth of recommerce makes it an attractive prospect as part of the recovery infrastructure for post-consumer textiles. According to ThredUp's 2019 Resale Report, apparel resale has grown 21 times faster than traditional retail from 2015 to 2018 and is valued at $24 billion (Figure 14) [47]. It is slated to reach $51 billion in the next five years.

As a tool in the recovery system, recommerce can play a role through prolonging the useful life of a textile product, whether garment or home furnishing. Recommerce outlets create a strong end market for branded items and widespread consumer awareness. Instead of brand-by-brand or retailer-by-retailer takeback programs, recommerce may be better served (or enhanced) by an aggregated management system such as a regional textile MRF with brand-sorting capabilities built in [44]. Table 2 summarizes several emerging recommerce models and partnerships.

Stuffstr is a recommerce platform that has partnerships with Amazon, H&M, and The North Face [49]. Stuffstr gathers product data from past and current purchases to populate a consumer's Stuffstr profile so consumers can see current resale value and find disposal-alternatives [49]. A benefit for retailers is a steady flow of product back into existing retailer-managed recirculation channels giving retailers the ability to extend the number of revenue transactions associated with one product. Transparency into consumer usage behavior and product post-sale lifecycles is another benefit, lending insights about product quality and lifespan. The Stuffstr model can drive store traffic when gift cards and rewards are offered for new purchases.

Trove (formerly Yerdle) provides full-suite logistics on behalf of retailers using its specially developed technology interface [50]. It owns and operates a warehouse to accept, inspect, repair, list, and prepare items for resale. The online interface is integrated with a retailer's website so that products are resold under a retailer's own brands and warranties; even product packaging is consistent with a retailer's branding. For example, Patagonia's Worn Wear website is powered by Trove, and other retail partners include Eileen Fisher, REI, Arc'teryx, Taylor Stitch, and Nordstrom. Trove accepts products from retail stores, distribution centers, and directly from customers.

CaaStle, which is a play on Clothing as a Service or CaaS, assists retailers in the clothing rental marketplace by using its technology platform and warehousing facilities to power the process [51]. CaaStle manages garment handling and cleaning as well as tracking customer feedback. CaaStle's retail partners include American Eagle, Scotch & Soda, Bloomingdale's, Banana Republic, and Express.

Repair partners such as The Renewal Workshop assist in making the recommerce business model work. The Renewal Workshop works with The North Face, Prana, Mara Hoffman and more, proving the value proposition for repair and refurbishment [52]–[54].

A re-imagined recommerce model is breathing new life into brick and mortar stores. J.C. Penney, Macy's, Stage, and Madewell are partnering with ThredUp to sell used merchandise within their department stores [55]–[58]. The stores serve as ThredUp drop-off locations for customers to return used clothes.

Table 2. Select Examples of Recommerce Models

	RESALE	LEASE/RENTAL	REPAIR/ REFURBISHMENT	TAKEBACK
RETAILERS	Eileen Fisher Filippa K H&M Icebreaker J.C. Penney Macy's Patagonia Prana REI Stage The North Face Zalando	Ann Taylor Club Monaco Express Filiwppa K Gwynnie Bee Lauren New York & Company Polo Rebecca Taylor Tchibo Urban Outfitters Vince Y Closet	Amazon Apple Best Buy IKEA Patagonia Taylor Stitch Verizon Walmart	& Other Stories Adidas American Eagle Outfitters Chantelle Lingerie Columbia Eileen Fisher Forever 21 G Foot Guess H&M intimissimi Jacadi Paris Kenneth Cole Levi's Madewell Marine Layer Patagonia Puma Suitsupply The North Face Timberland Vagabond Shoemakers Zara
SERVICE PROVIDERS	Circlarity Stuffstr ThredUp Trove	CaaStle Rent the Runway	ReStitch The Renewal Workshop	I:CO

Figure 14. Growth of the Resale Market [44]

that would inevitably create the pull through the system to enable collection at scale.

The cumulative lifecycle impacts of different modes of collection are unknown – whether it is curbside collection, mail-in, store take back, charity donation, or bin drop off. A review of the comparative logistics between the e-commerce industry and traditional retail may provide a parallel avenue of study. As reported in Resource Recycling (November 2019), e-commerce generates a higher number of touch points from the supplier to the customer than does traditional retail [59]. Instead of a product traveling from supplier to distribution center to retailer, the product in an e-commerce system travels from the supplier to a fulfillment center where it is broken down, shelved, repackaged, picked up by a transport provider, delivered to a sortation center, and distributed through parcel carriers. The result is that a single product is handled more than twenty times, whereas in traditional retail it is handled about five times. Product mail-back or retail drop off would likely include the same process but in reverse leading to more touchpoints than traditional curbside collection.

Leveraging technology to develop collection infrastructure and a network of consolidation points through companies like Optoro will be key to building an innovative collection system. A tech company with a cloud-based software program that uses machine learning and predictive analytics, Optoro assists retail partners in real-time to redirect returns and excess inventory for maximum utility, which might be to divert certain textile returns for recycling [60]. Optoro also manages remarket websites for clients and operates its managed service out of two domestic warehouses.

All of these options can contribute to significantly strengthening or innovating collection practices for textiles. A uniform collection system can be rolled out across the U.S., especially if a universal processing system like a textile MRF is made available.

PROCESSING

Sorting: The Textile MRF

Once collected, textile waste needs to be sorted for end markets. At present, sorters-graders perform this activity, but they are not usually equipped for advanced sorting by fiber type for the purpose of fiber-to-fiber recycling. A facility that has this kind of capability looks much more like the material recovery facilities processing mixed recyclables from the curb using advanced sorting technologies than it does the current-day low-tech sorter-grader facilities.

PRE-PROCESSING

As with the collection and sorting technology, recycling technology is informed by the needs of the end markets. In the case of circular textiles, those end markets are mainly yarn and fabric producers. Specifications must work their way backward so that the recyclers can hone their processes and yield outputs that are relevant to and usable by manufacturers.

Recyclers will likely need to pre-process the materials arriving in bales from the textile MRFs. Most recyclers will be unable to feed whole or even partially shredded garments into their recycling systems. Hardware, like buttons, fasteners, and zippers will need to be removed, and the textiles might need to be manipulated in shape or form or reduced in size before it can be introduced into the recycling process.

Some recyclers may decide to incorporate pre-processing into their front-end systems, whereas in other circumstances, stand-alone pre-processors may fill this gap and create a niche market. Alternatively, the textile MRF may be incentivized to process the sorted materials, if enough demand is present.

The aspirational textile MRF includes a quality sort first, followed by a fiber sort (Figure 15). Given that technology does not currently exist to recognize rewearability (this still requires the human eye), there is an attractive opportunity to rely on existing labor sources for this, such as sorter-graders and/or thrift-store or charity associates. An organization like Goodwill could fulfill this function as its employees have the skill set and its mission is to provide job training and placement.

The quality sort would segregate materials according to traditional grades used by sorters-graders, and potentially sort by brand for delivery back into brand resale channels. A certain portion of re-wearable textiles would be funneled directly into the sorting partner's inventory. If Goodwill is providing the sorting labor, it would also receive high quality rewearables for sale in its thrift stores. It's a win-win.

Items not pulled during the quality sort would continue along conveyers for optical fiber sorting. Today, two equipment providers that are developing optical sorting systems for fiber-sorting include Valvan Baling Systems and Tomra. Valvan Baling Systems is the manufacturer behind the Fibersort, a project led by Circle Economy, with additional partners including Salvation Army ReShare, Procotex, Smart Fibersorting, Wieland Textiles, and Worn Again Technologies [61]. The other is the Autosort, a technology developed by Tomra Sorting Systems [62]. They both lend new insights into the challenges and possibilities of optical sorting for textiles. For example, Fibersort in its current form can process 60 picks per minute, and items must be mono-materials containing no more than two fiber types. For comparison, optical sorters utilized in container recycling lines are capable of around 1000 picks per minute [6]. Fibersort can sort by material composition and color into 45 fractions [63]. Future refinements include adding capability to discern between knitted and woven materials and improving sorting accuracy.

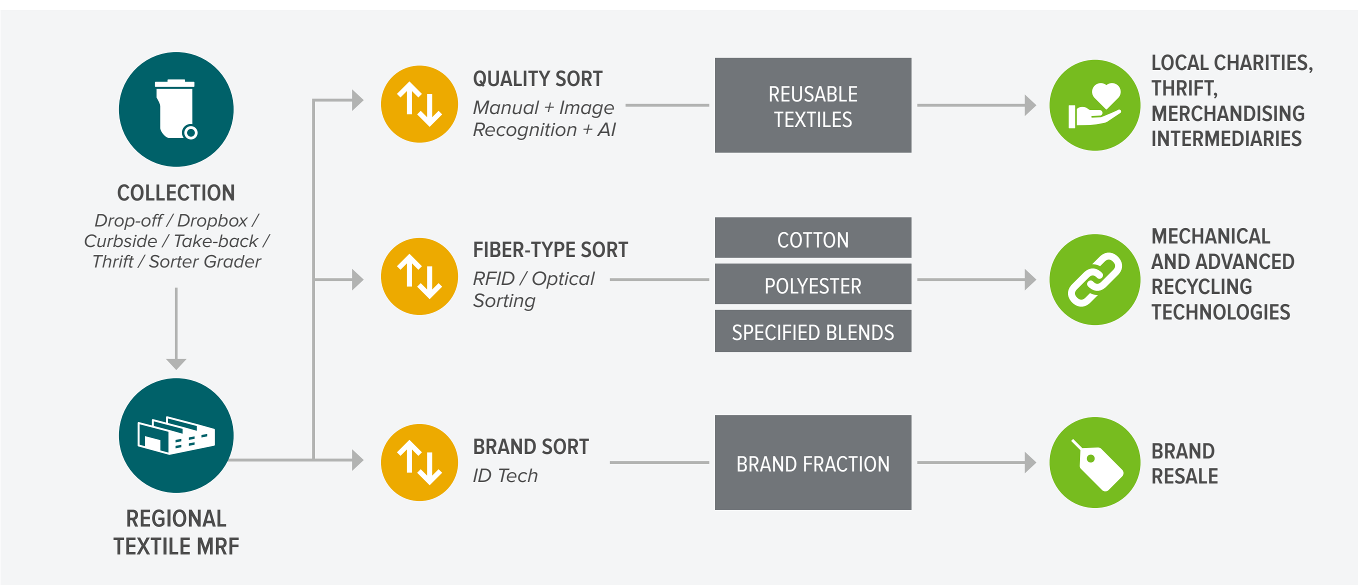
In addition, Hong Kong-based Novetex Textiles launched an automated system in 2019 called the Billie System that cleans and color-sorts used textiles. Combined with manual hardware removal the system prepares textile waste for recycling with minimal handling [64].

These new technologies could be paired in a textile MRF with hoppers, feeders, conveyors, robotics, blowers, sensors, and other ancillary equipment, to ensure proper throughput volumes, speeds, spreads, and picking. Systems like the Fibersort, Autosort, and Billie System offer promise in working toward a circular textile economy.

The textile MRF must also have the capacity to adapt to new industry developments. Given the difficulty of identifying fiber types in recovered clothing, Natasha Franck, founder and CEO of fashion technology company EON, launched CircularID as part of the Connect Fashion Global Initiative [65]. CircularID is a digital ID that encodes product data like origin and fiber composition into a digital identity stored in an online database and accessible for future use. The ID enabler, a piece of technology that stays with the garment, such as an RFID tag, is used to access the digital database. Information about the item's product journey can be updated in its CircularID as it passes through the textile MRF, providing valuable lifecycle, usage, and material flow data back to the brand and/or retailer. Another example is Applied DNA Sciences, who's CertainT platform enables a unique molecular identifier to be embedded in raw materials and products which can then be tested throughout a global supply chain [66].

Adoption of digital identification and tracking technologies like RFID, NFC, QR codes, nanoscale trackers, molecular tagging, digital product birth certificates, product passports, and blockchain could provide additional prospects for the process of waste sorting, especially to the extent these technologies integrate automatically with information

Figure 15. Future Desired Textile Value Recovery Flow



systems, i.e. the Internet of Things (IoT). Smart technologies could assist in cataloguing fiber blends and other textile waste composition data to inform continuous textile MRF improvements and guide the appropriate development of infrastructure and recycling technologies. Brands stand to benefit from this information as well to inform decisions around material choice and design for durability and recyclability.

Several emerging technologies focus on recovering fibers from used textiles to serve as feedstock for new textile production.

EVRNU recycles old cotton textiles using a solvent-based pulping process to create virgin-like cellulosic fiber, marketed as NuCycl [69].

TYTON BIOSCIENCES is a fiber-to-fiber recycler that recovers cotton and polyester from used textiles. Their closed loop hydrothermal process creates dissolving pulp from cotton textiles while depolymerizing polyester to recover its monomers [70].

WORN AGAIN TECHNOLOGIES, based in the United Kingdom, uses a solvent-based polymer recycling technology to separate, decontaminate and extract PET and cellulose (from cotton) to produce virgin equivalent PET pellets and cellulosic pulp [71].

Without using an open platform like CircularID, this approach may require the manual integration of brand information systems with textile MRF information systems or the ability to ensure access to product data in some other way.

Textile MRF Outputs

The final step in the textile MRF would be baling and marketing the sorted fiber grades. The textile MRF of the future requires relationships with offtake partners, buyers of the MRF's generated commodities. These offtake partners would have long term agreements with the textile MRF and function as partners rather than price-influenced buyers. In fact, offtake partners could work with textile MRFs to ensure that the MRFs have the information they need to generate bales of appropriate quality and composition for their particular needs. Offtake partners and MRFs working together can develop standardized bale specifications and make those for use across the industry. These specifications would create ripple effects back through the supply chain so that designers can design with recyclability in mind. With RFID, bales can also be sorted by brand and returned to those brands for reuse and repair.

The textile MRF may be a standalone facility or its functionality can be incorporated into existing sorting facilities. A vast infrastructure of sorting facilities of varying capabilities is in place across the country from sorters-graders to charities like Goodwill to resale and recommerce warehouses. With coordination, textile MRF technology can be incorporated into this network of existing textile sorting infrastructure.

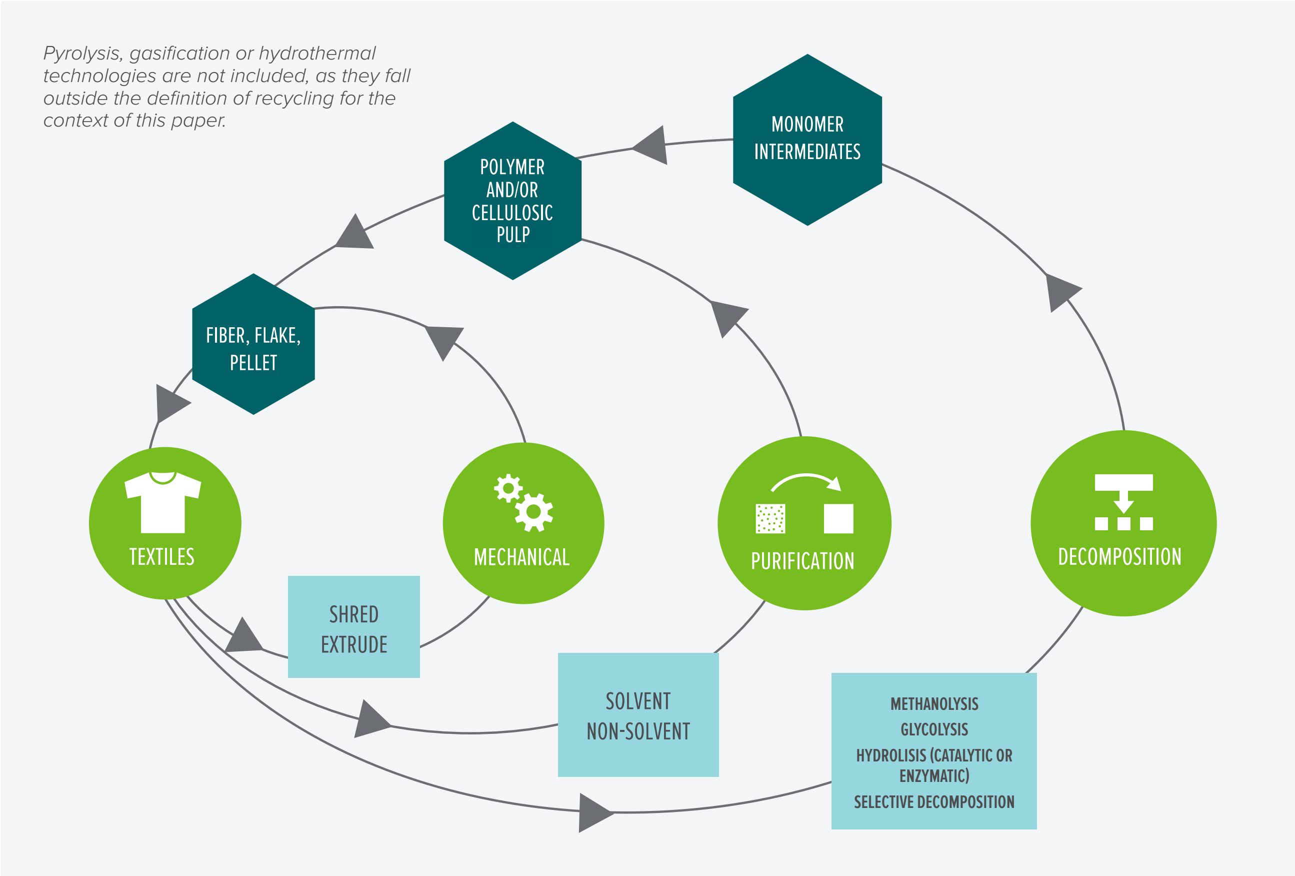
Recyclers – Fiber-to-Fiber Recycling

Fiber-to-fiber recycling can be accomplished using mechanical, chemical, thermal, and/or enzymatic processes. Each approach has its own strengths and weaknesses regarding cost, energy usage, and resulting quality. While traditional mechanical recycling is generally lower cost, advanced recycling technologies can generate virgin-like raw materials from pre-consumer and post-consumer textile waste and can be more forgiving of contaminants. As a result, the increased value of the high-quality fiber feedstocks can offset the higher cost of advanced recycling processes.

Benefits of Domestic Sorting and Processing

Domestic sorting and processing can lead to reduced international shipping, fewer intermediaries, less handling, a reduced carbon footprint, and cost savings from avoided export, allowing for a higher recovery value of textile feedstocks.

Figure 16. Textile Recycling Technologies Diagram



Advanced Recycling Technologies

Advanced recycling technologies are classified into three types: those that purify, those that decompose, and those that convert as a means of recovering the targeted material (Figure 16). Purification removes contaminants, decomposition breaks materials down into their building block for rebuilding at a later stage, and conversion transforms materials from one form into another, with a primary application for it being the fuel industry. These technologies can be engineered to recover specific compounds and molecules and hold the potential to extract value from a variety of textile types. Most current technologies focus on polyester, cotton, and poly/cotton blends.

Advanced recycling technologies allow processors to:

1. Remove inks, dyes, chemicals, and other additives
2. Handle elastane in quantities over five percent
3. Separate compounds from blended and multi-materials textiles
4. Retain virgin quality

The removal of toxic chemicals from textiles is a growing concern as companies adopt stricter chemical standards for new products. A new study by IKEA and H&M found chromium compounds (a carcinogen) and alkylphenol ethoxylates (an endocrine disrupter) in a portion of sampled pre- and post-consumer clothing. These toxic chemicals are mainly associated with dyes and pigments [67]. There is also increasing concern over PFAS, a group of more than 5,000 per- and polyfluoroalkyl substances that can be applied to textiles for their stain- and water-repellent properties. PFAS are bio-accumulative and bio-persistent chemicals linked to increased cholesterol levels, low infant birth weights, effects on the immune system, cancer (for PFOA), and thyroid hormone disruption (for PFOS) [68].

Dozens of companies are researching, designing, testing, and scaling technologies to recycle a variety of materials, including polyester and cotton.

Table 3. A Comparison of Mechanical Recycling and Advanced Recycling Technologies

DESCRIPTION	INPUTS	PROCESS	END MARKETS	ADVANTAGES	CHALLENGES
Mechanical recycling	Wool and cotton rags and cuttings PET bottles	Garnetting Mechanical PET recycling	Carpet New apparel Packaging	• Widely available • Established end markets • Retains original color, minimizing the need for dye in new manufacturing • Reduces use of energy, water, and emissions compared to virgin	• Mechanical recycling cannot separate fibers. Final product may contain presence of other fiber types • Unable to remove colorants, dyes, finishes, toxic chemicals, and other additives • Results in loss of fiber length, evenness, fiber length uniformity, and material strength • Must be supplemented with 80 percent or more virgin cotton to match the quality and integrity required for new garments [33] [34] • Cannot be recycled infinitely • Restricted end-use applications • Higher cost than virgin
Advanced Recycling Technologies	PET bottles and thermoforms Polyester textiles Cotton textiles Poly / cotton blends Nylon	Purification Decomposition Conversion	Carpet New apparel Packaging	• Removes inks, dyes, chemicals, and other additives • Some can handle elastane in quantities over 5 percent • Separates compounds from blended and multi-materials textiles • Retains virgin quality	• Not yet commercialized • Not yet proven cost-effective at scale • Will requires significant investment to scale • Price parity TBD

A Comparison of Recycling Technologies

Advanced recycling technologies have both benefits and drawbacks compared to traditional mechanical recycling (Table 3).

END MARKETS

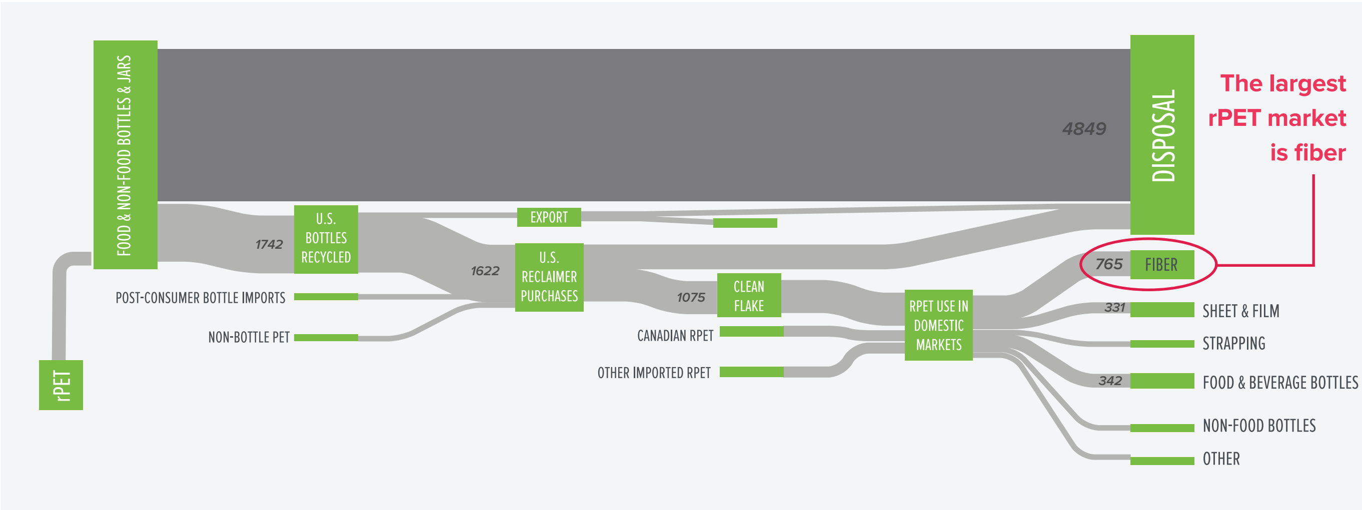
Once yarns and fabrics are produced, they can be sold on the global market to garment manufacturing hubs all over the world, contributing to a vibrant domestic recycler economy.

Because advanced recycling technologies are several years away from scale (and have not been proven economically feasible yet), it is likely that emerging textile recovery and sorting schema will primarily rely on mechanical recycling. Even when advanced recycling technologies scale, mechanical recycling is likely to continue to play an integral role.

Mechanical Recycling for Polyester Textiles and Recycled PET

Mechanical recycling for polyester textiles does not widely exist; recycled polyester is made from PET bottles, PET thermoforms, and polyester carpet. In 2017, fiber was the largest end market of U.S. recycled PET (rPET), followed by food and beverage bottles (Figure 17) [73]. The greater flow of rPET into fiber markets is largely because the fiber market is more forgiving and has a more favorable cost structure than food-grade rPET end markets. However, rPET prices are on the rise, and will likely continue to go up as competition increases [74]. To further intensify the price disparity, virgin PET prices are forecasted to decrease as oversupply floods the market from overproduction, and the gap in pricing between rPET and virgin PET will grow [74]. It is important for the textile and apparel industry to unlock more rPET fiber supply through the form of waste polyester textiles.

Figure 17. PET Material Flows in the U.S. 2017 (in MM LBS) [73]



Competition for Limited Supply of rPET [4]

Despite price premiums, competition for rPET is real and growing as brands and retailers across industries pursue their public commitments to incorporate more recycled content into products (Figure 18). The Ellen MacArthur Foundation's New Plastics Economy initiative has garnered more than 400 signatories, including top companies representing 20 percent of all plastic packaging produced globally [75]. New demand for rPET from the apparel, home and hospitality sectors is growing at a rapid pace. Brands like Adidas, IKEA, H&M, Walmart, and a host of others have committed to reducing the use of virgin fibers in favor of recycled ones. The top eight brands consuming recycled polyester, by volume, in 2016 were Nike, The North Face, Decathlon, H&M, Target, Patagonia, Williams Sonoma, and Timberland [76].

Figure 18. Brand Recycled PET (rPET) Commitments

4. *In the packaging industry, recycled PET is referred to as rPET. As the textiles industry moves from bottle rPET inputs to recovered textile rPET inputs, there may be a benefit to changing the nomenclature of 'rPET' to distinguish between inputs (bottles versus textiles).*

Today's recycling system in the U.S. is a long way from being able to meet this growing rPET demand. Mechanical recycling is limited in its ability to produce virgin-equivalent outputs and so reclaimers chase clean high-quality PET bales (primarily bottles) with preference given to bales generated from deposit states because they are generally the least contaminated. Higher quality inputs yield higher quality outputs at lower costs.

Post-consumer PET supply is governed by recycling behavior as opposed to demand, and therefore supply quantities are relatively inelastic to price. In this supply-constrained setting, increased demand for rPET translates to increased competition and therefore quickly increasing price. The rPET supply could improve by introducing other forms of post-consumer polyesters into the recycling system, such as polyester textiles. This future state, made possible by cutting edge mechanical recycling and other advanced recycling technologies, would require a re-imagining of existing infrastructure, material flows, and business models.

While it is less onerous and less expensive to channel recovered bottles into fiber instead of back into bottles, there is no scaled solution for doing the opposite – converting polyester textiles into food-grade rPET for beverage bottles. Advanced recycling technologies may offer this possibility and would hypothetically enable beverage companies to realize their ambitious recycled content goals.

> "There is an exceptional amount of work to be done, particularly around increased collection volumes and the adaptation of sorting facilities, to supply our future plants with high volume and reliable quality non-rewearable textile inputs. By sharing our feedstock specification requirements with collectors and sorters, we are collaborating to establish a phased approach and business case that provides them with a timeline for adapting and investing in the required changes. Wider collaboration with policy makers and brands is also key to shaping this market and ensuring the 'economics of feedstock' work for all stakeholders in the value chain."
>
> *CYNDI RHOADES, FOUNDER/CEO, WORN AGAIN TECHNOLOGIES*

EDUCATION AND ENGAGEMENT

Educating all players in the value chain – from manufacturer to consumer to collector – on how to prevent waste is a critical step in the path forward to better textile recovery. Limiting the amount of material entering the system by curbing consumption of newly manufactured textile products is the most effective way to reduce the current growth trajectory for textile waste.

Brands and retailers have a role in educating and engaging consumers through supply chain transparency, demonstrating the benefits and efficacy of circular raw materials, and shifting toward restorative business models, such as recommerce. Patagonia is an example of a brand making efforts to educate consumers with the "Don't buy this jacket" campaign [77].

Municipalities also have an important role to educate residents on available methods for recycling used textiles, just as municipalities educate residents on the proper disposal of other wastes like trash, recyclables, e-waste, and household hazardous waste. Consumers need to know that there are outlets apart from the trash bin. The development of a "how-to guide for consumers" can be a useful resource for municipalities.

With proper education, consumers can make choices to prioritize reuse, rental, and repair over buying new, and selecting products manufactured from recycled fiber when they do buy new.

SUPPORTIVE POLICIES

In industry sectors where policy governs the end of life management of products, a common sentiment among stakeholders (e.g., producers and/or waste generators) is the importance of having a level playing field. When policy is thoughtful, intentional, and developed through a multi-stakeholder process, it can be a force for good. Policy can help create incentives to spur material recovery and it can stimulate needed investment in recycling infrastructure.

The type of policy that will best support a circular economy for textiles in the most constructive way remains to be determined, whether it takes the form of extended producer responsibility (EPR) or incentivizes a shift in consumer and manufacturer behavior through tax/deposit programs or tax breaks on sustainable practices, secondhand purchases, etc. Regardless, it is unlikely that textile waste will evade oversight and legislation moving into the next decade and the opportunity for an industry-led and industry guided conversation on the topic is strong.

All stakeholders in the value chain have an opportunity to chart their course through helping to develop the policy landscape that will provide structure and resources for textile recovery.

PARTNERSHIPS

There is a lot of exciting progress being made at each interchange along the textile recovery value chain from collection systems to fiber sorting technology to recycling technologies. Innovators are creating solutions and implementing new ideas to bridge gaps and create effective textile recovery systems. Strategic partnership that leverage these crucial and oftentimes proprietary insights can help unlock momentum and create solutions tailored to specific business needs.

first steps: filling the information gaps and testing the system

RESEARCH, MAPPING, AND WASTE CHARACTERIZATIONS

Building a new textile recovery system starts with understanding the location, composition, and volumes of textile waste; this lays the foundation necessary to identify a set of immediate solutions and actions that can be taken to address textile waste and generate innovative solutions.

For residential and commercial waste streams, this means conducting waste characterization studies in enough key markets to understand regional and seasonal variations. Additional information that is beneficial to understand relates to how macro-trends such as economic recessions impact the volumes and characterization of the waste stream. In the experience of Marcus Gomez, owner of California Clothing Recyclers, donation volumes, quality, and export value of used textiles increase during a healthy economy [78]. This may be because in strong economic times consumers shop more leading them to be more likely to discard items that are in relatively good condition. During economic slowdowns consumers may be less likely to spend and opt instead to prolong the use of items they already have. When the item is discarded, there is more wear and tear.

SMART TECHNOLOGY LEVERAGED FOR RECOVERY

As described in the textile MRF section above, smart technology is being embedded in the textile supply chain. A connected landscape can better inform opportunities for recovery and if adopted widely can replace the need for manual waste characterization studies. Instead of evaluating garments and other textile products for fiber composition and using those data to inform the geographic opportunities and economic potential for recovery, aggregated cloud-based data can help plan textile recovery networks. It is important, also, to remain aware of how embedded technology impacts the recycling process and ensure that any electronic components can be recovered safely.

Detailed waste characterization studies of textiles in the municipal solid waste stream can help fill the gaps in knowledge on the types, amounts, composition, and variations of U.S. textile waste to best inform an effective recycling system for textile waste. Volume, fiber/material composition, generation frequency, geographic distribution, form and format are key pieces of information needed by mechanical and advanced recycling technologies to assess the potential of textile waste feedstocks, determine compatibility with their technologies, identify pre-processing needs, and develop a business case for action.

SPECIFICATIONS DEVELOPMENT

To scale new textile recovery systems, clear specifications for major classes of traded fibers are needed. For recycling technologies to be economically sustainable and scalable, recyclers need reliable access to appropriate volumes of fibers of known specification. In turn, textile sorting facilities need to determine if they can economically sort to meet those specifications.

Defining standards for fiber bales and aligning textile MRFs with those bale standards will allow recyclers to level-set feedstock expectations and define suitable pre-processing for their specific needs. Depending on the end market for the bales, pre-processing may be incorporated at the back end of the textile MRF.

Developing bale standards requires collaboration between textile MRF operators, equipment manufacturers, recyclers, and a standards-governing body, such as the Institute of Scrap Recycling Industries.

Similarly, the new textile recovery system must develop specifications for recycled fiber inputs so that outputs from mechanical and advanced recycling technologies can be easily fed back into textile manufacturing supply chains. Ideally, mechanical and advanced recycling technologies would organize around a set of standardized industry-defined specifications, thereby limiting unnecessary variability in composition and quality and allowing for applicability to a larger number of fiber, yarn, and textile manufacturing processes. Specifications for recovered raw materials are likely to follow those for virgin raw materials, and the closer the specifications are, the easier it will be to integrate recovered raw materials into established fiber spinning processes.

Specification development will be an iterative process requiring close coordination between manufacturers, brands, sorters, recyclers, and supply chain intermediaries to test and validate standards at each juncture in the recovery value chain.

PILOTS AND TESTING

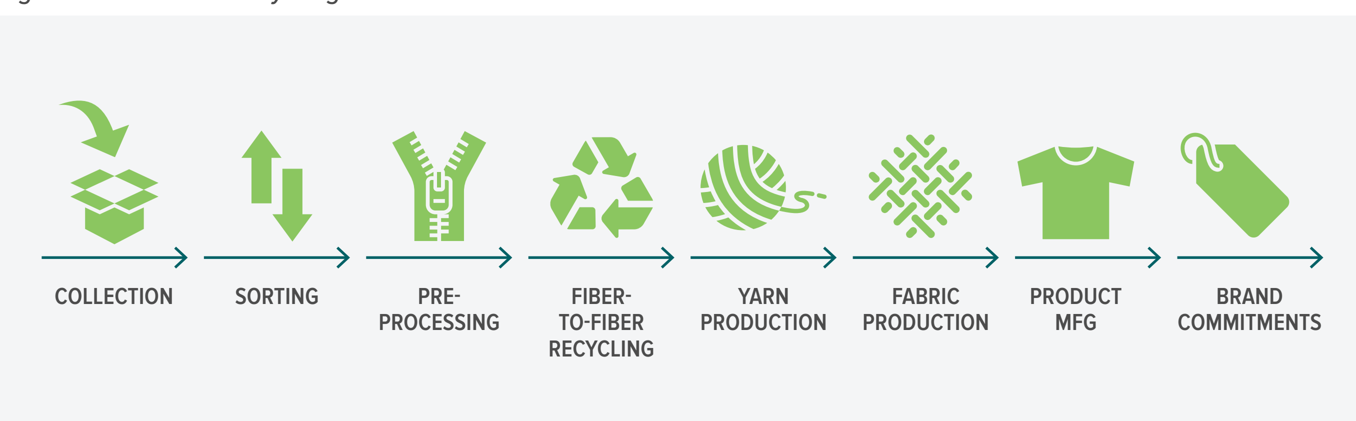
It will be necessary to develop a pilot program in or near a dense population center to prove the technical, operational, and economic viability of each element of a textile recovery program (Figure 19).

A facility is needed that can serve as a demonstration plant and proof of concept textile MRF. Such a facility would serve to establish, test, refine, and optimize textile waste aggregation and sortation processes (for reuse and recycling), equipment, configurations, and systems. It would provide the demand-pull needed to stimulate textile waste collection systems and the supply necessary to attract mechanical and advanced recycling textile recyclers domestically and regionally. It will also likely uncover weaknesses in the value chain where supportive policy can fill gaps.

The business case and logistics at each point along the pilot textile recovery system must be developed. Processes to sort textiles must be created, starting with reuse and repair, then brand identification and RFID or Circular ID recognition, and finally automated fiber sorting in addition to any other categories deemed necessary. Manual labor practices to sort and triage incoming materials must be thought through, as do reuse offtake partnerships, logistics, and agreements with supporting organizations like Goodwill and other local charities and not-for-profits (who may also be prime candidates for sorting, given their vast experience in the field to date). Offtake agreements and brand commitments to circular raw materials must be secured, and to feed this facility, curbside textile collection and transfer practices must be established and tested.

A pilot scale textile MRF is the lynchpin that can catalyze testing of the entire recovery process and lead to the development of procedures and technology refinement that leads to a scalable and replicable model.

Figure 19. Textile Recovery Program Elements



DETERMINING ECONOMIC VALUE AND BUILDING THE BUSINESS CASE

For circular textile recycling technologies to be economically sustainable and scalable, they need access to reliable volumes of fiber as well as an understanding of the relative value and cost of getting to fiber streams with known specifications. Economic development and investment are currently hampered by the lack of financial insights.

Knowing the availability of fibers in the waste stream and how easily recoverable and sortable they are will help inform the value proposition for recovery both across the whole recovery chain and for each player within it, including collectors, aggregators, textile MRFs, recyclers, and ultimately brands, manufacturers, and suppliers.

Based on currently available data and informed assumptions, a series of economic scenarios can be performed to determine ways to optimize value creation from mixed textile waste. Collection modelling involves assessing the range of costs associated with various collection methods from mail back to curbside collection and the mixture of methods in between. This can be applied both to the city/regional level (for post-consumer textile waste) and to the level of a commercial waste shed (for pre-consumer textile waste).

Another key piece of this puzzle is modelling sorting/textile MRF costs and projecting cost-revenue ratios. In 2019, traditional MRFs saw a rise in cost-revenue gaps as the result of increased spending on new technologies to stay competitive, adapting to a changing materials stream, and meeting increasingly stringent bale-quality standards [79]. As the textile MRF concept develops, it will be important to understand how the textiles value chain can avoid some of the same challenges faced by traditional MRFs by evaluating processing costs, equipment needs, maintenance costs, capabilities of sorting technology, possible levels of automation (versus manual labor), reliability of incoming textile waste feedstock, levels of contamination in the incoming feedstock, bale specifications, commitment of offtake partners, the pace of the textile industry's evolution, and other variables. This analysis will help shape an approach that allows textile MRFs to evolve with the industry and flex with market forces.

The result of these analyses is a business model that illustrates costs to collect waste textiles and sort them according to a set of end market specifications.

The value proposition for manufacturers, brands, and retailers must also be explored. Crafting the business case for individual brands and retailers to embrace textile recovery includes estimating the financial investment necessary to develop and scale infrastructure, including new collection networks and regional sorting facilities/textile MRFs as well as complementary technologies; and then measuring these costs against benefits, which include improvements to brand reputation, reduced supply chain risk, progress toward sustainability goals, and more. In doing so, questions around the value, reliability, and performance of recycled raw materials need to be answered. A new textile recovery system must identify the case for investment and develop a call to action to scale fiber-to-fiber recycling and other textile waste solutions. At the same time, recycling facilities are reliant on feedstock availability and offtake commitments, and brands can play a proactive role by starting to evolve collection and aggregation systems, document the fiber composition of their textile products, track internal points of textile waste generation, and plan for the integration of recycled raw materials into their supply chains.

Finally, it is important that no single stakeholder bear all the burden of risk. Risk and profit should be distributed across the value chain.

As the textile MRF concept develops, it will be important to understand how the textiles value chain can avoid some of the same challenges faced by traditional MRFs.

CONCLUSION

The growth of textile waste in the United States is outpacing the growth of every other major category of waste and can be partly or mostly attributed to a shifting consumer mindset that once viewed clothing as a durable good and now views this item as disposable. Many brands and retailers seek ways to move toward a more circular business model and many industry innovators are developing solutions at various points along the textile recovery value chain. By leveraging strategic partnerships, companies can merge key insights and build scalable systems to effectively recover and recirculate the value of their textiles. Progress toward this ideal future state starts with establishing foundational elements and developing sustainable solutions step by step.

components of a successful textile recovery system

- Widespread convenient collection systems;
- Regional textile sorting facilities (textile MRFs) that generate readily accessible material volume and composition data, paired with mechanical and advanced recycling technologies to convert inputs into global commodities;
- Robust end markets and brand uptake agreements that support a domestic recycler economy;
- Compelling outreach that drives engagement with consumers, brands, and communities;
- Thoughtful supportive policies that create a level playing field and incentivize textile recovery and infrastructure development; and
- Innovative strategic partnerships that increase the circularity of pre-consumer and post-consumer textiles and decrease textile waste going to landfill.

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