NIST Special Publication 1500-207

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This publication is available free of charge from:
https://doi.org/10.6028/NIST.SP.1500-207

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

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Facilitating a Circular Economy for Textiles Workshop Report

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https://doi.org/10.6028/NIST.SP.1500-207

May 2022

U.S. Department of Commerce
Gina M. Raimondo, Secretary

National Institute of Standards and Technology
Laurie E. Locascio, NIST Director and Under Secretary of Commerce for Standards and Technology

National Institute of Standards and Technology Special Publication 1500-207
Natl. Inst. Stand. Technol. Spec. Publ. 1500-207, 62 pages (May 2022)
CODEN: NSPUE2

This publication is available free of charge from:
https://doi.org/10.6028/NIST.SP.1500-207

Executive Summary

Textile production has increased dramatically over recent decades, particularly with the rise of 'fast fashion'. Simultaneously, increased production of synthetic, fossil-based fiber (e.g., polyester, nylon) due to their cost-efficiency and performance characteristics (e.g., stretch, durability, shrink resistance) has resulted in a large volume of synthetic fibers in the marketplace. The value chain of textiles is characterized by vertical dis-integration and global dispersion of successive processes that span several industries including agriculture (natural fibers), petrochemical (synthetic fibers), manufacturing, distribution logistics, and retail [1]. In the current linear economic model, textile products are produced, used, and disposed. In fact, it is estimated that in the U.S. a mere 15 % of discarded clothing and textiles are collected for reuse, recycling, or downcycling, while the remainder is sent for landfill and incineration [2]. This represents not only a tremendous loss of economic and material value, but also has severe social and environmental impacts.

A circular economy (CE) approach aims to extend the life of textile products through reuse and repair and keep end-of-life (EoL) materials in the economy through recycling. Transitioning to a CE is, therefore, essential to reduce pressure on natural resources, create domestic and sustainable growth and jobs, and thereby ensure our Nation's security and economic prosperity. However, several challenges face the adoption of a circular economy for textiles. In September 2021, The U.S. National Institute of Standards and Technology (NIST) held a three-day workshop entitled "Facilitating a Circular Economy for Textiles" aimed at identifying specific challenges and needs to overcome those barriers. Nearly 150 stakeholders participated in the event including brands/manufacturers, recyclers, non-profit organizations, industry associations, and researchers who discussed the current state, bottlenecks, and opportunities for circularity.

The current textiles recovery system in the U.S. includes collection, sorting, grading, and to some extent, recycling. That said, a majority of the 15 % of textile products collected are exported to low-income regions for resale, although there is skepticism regarding the sustainability and benefit of this practice. While several methods of recycling exist, they are at different stages of maturity and face many barriers. Key challenges facing the current system identified in the workshop include:

- Infrastructure and systems for collection of waste textiles are not well established and do not support consistent, convenient, widespread collection of the quantity and quality (clean, dry) of textiles needed to retain value.
- Sorting and grading of textiles rely on expensive manual labor, even though it is not possible to visually identify fiber composition. No harmonized sorting standards or criteria exist, challenging downstream markets.
- Commercial-scale recycling processes for textiles are fiber-type dependent, require pure, reliable, high-volume feedstock, and generally cannot process mixed material inputs (fiber blends). Separation of blends and removal of dyes, additives, and finishes (e.g., functional coatings) often requires or generates hazardous substances that require proper disposal. Limited recycling processes exist for select fiber types.
- Textile circularity is not economical in the current system. Large-scale reuse, repair, and recycling is hindered by high transportation, labor, and processing costs and decreasing quality and cost of new products.

To address these challenges and improve the sustainability and circularity of the textiles industry requires a harmonized, systems-level, collaborative approach. Several opportunities for advancement were identified in the workshop, including the following:

- Harmonization of terminology, definitions, classifications, documentary standards, and industry tools are necessary to facilitate consistency, transparency, circular business, and to track progress.
- Increased data collection and access. Significant data gaps exist throughout material, product, market, and system levels, fostered by a general lack of transparency across the industry. Publicly available databases, registries and repositories need to be developed following FAIR data principles of findability, accessibility, interoperability, and reusability. Strategies need to be advanced that support transparency while protecting proprietary information.
- Advanced labeling strategies to facilitate and communicate textile traceability throughout the value chain and lifecycle of products. Such strategies could include digital product identification that provides access to the data needed to support circular pathways.
- Technological development to improve sorting-grading and preprocessing. Development of high-speed automated sortation systems is needed that is capable of rapidly identifying fiber compositions and separating textiles based on desired characteristics. Development of separation methods for blended fibers as well as multi-material components (e.g., carpets) is necessary.
- Advanced recycling process development, particularly for low-value textiles and non-cellulosic/polyester fibers (e.g., elastane), which are currently difficult to recycle.
- Brands play an integral role and can improve circular textiles through product design, recycled content requirements, as well as alternative businesses models (e.g., takeback programs for repair, resell, or garment renting).
- Industry standards can establish requirements and consistency for products, feedstocks, principles, and processes. Examples of areas in need of standards development include collection, recycling feedstock, sustainable procurement, and microplastic fiber testing and monitoring. CE standards should be harmonized and interoperable.
- Policy approaches to facilitate a CE for textiles that span local, state, and federal jurisdictions and include economic incentives, public procurement, disposal bans, recycled content mandates, and extended producer responsibility.
- Education and outreach across all ages and sectors of the population is needed to support sustainable consumption, product life extension (e.g., through repair or donation and thrift), and awareness of pathways for unwanted products.
- Research needs include economic assessment of current and potential domestic infrastructure and market developments; waste composition audits; consumer behavior studies; microfiber identification, quantification, and source reduction; and separations science of blends and recycling of currently unrecyclable fiber types.
- Collaboration and increased communication across industrial sectors and throughout the value chain is necessary to understand different dimensions and recognize the diverse perspectives and needs of various stakeholders.

NIST could support the needs and opportunities identified above through the development and hosting of data registries and repositories; development of standards, specifications, and guidelines; and applied research including materials and separations science, economic assessment, and digital tracking and traceability. NIST could also facilitate the development of a Circular Economy for Textiles Roadmap: A clear plan mapping out the timeline and path to transition to highly optimized sorting systems and materials circularity. Further, NIST is well-suited to serve as a convener of the wide range of stakeholders included in the textiles CE, both public and private, and across the social and technical disciplines.

List of Acronyms

AI	Artificial intelligence
CE	Circular Economy
CO_{2eq}	Carbon dioxide equivalent
DfR	Design for recycling
DIY	Do it yourself
EoL	End-of-Life
EPR	Extended producer responsibility
EU	European Union
GHG	Greenhouse gas
Kg	Kilogram
Lbs	Pounds
LCA	Lifecycle assessment
MFA	Material flow analysis
MMF	Manmade fibers
MPF	Microplastic fibers
MRF	Material recovery facility
MSW	Municipal solid waste stream
NFC	Near-field communication
NIR	Near-infrared spectroscopy
NIST	National Institute of Standards and Technology
PET	Polyethylene terephthalate
PFAS	Per- and Polyfluoroalkyl Substances
QR	Quick response
R&D	Research and development
RFID	Radio frequency identification
SMART	Secondary Materials and Recycled Textiles Association
TEA	Techno-economic analysis

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1 Introduction

1.1 Motivation

The National Institute of Standards and Technology (NIST) initiated a Circular Economy (CE) program in 2019 to coordinate NIST resources to support the Nation's need to transition away from a linear – take, make, use, waste – economic model toward one in which materials repeatedly cycle within the economy. For NIST, this involves inter-agency collaboration, identification of external stakeholder needs, and innovations in measurements and standards that enable decreased dependence of economic activity on the consumption of virgin resources.

The NIST program defines a circular economy as an economy which aims to keep atoms and molecules cycling within the economy and out of unwanted sinks (e.g., land, air, and water systems). This necessitates a transition away from the current linear economic model toward a regenerative model based on principles of material circularity and designing out waste and pollution. A circular economy therefore entails extending the life of products and materials for as long as possible. This is performed through design for durability, reuse, repair, and remanufacturing, as well as recovering materials at end-of-life (EoL) through recycling. A circular economic model also mitigates many of the risks posed by resource depletion, unmanaged disposal, adverse environmental impacts, and social and environmental injustice while creating value and new business opportunities.

Initially, NIST's CE program focused on polymers due to the increasing awareness and scale of plastic leakage to the environment, the rapid development of alternative polymer types (e.g., bio-based polymers) as well as the advancement of chemical recycling strategies. The direct relationship between plastics and textiles lead to the exploratory work on textiles in the CE and the workshop discussed herein. Other nascent areas included in NIST's CE program include 'high-tech' products including solar panels, electronics, batteries (workshop hosted January 2021 [3]), concrete (future topic), and biomass (e.g., food waste; future topic).

NIST has expertise in several areas that will contribute toward the field of circular textiles, including materials, chemical and biological sciences, reference material development, sorting and identification technologies, data repositories and support for data standards, and life cycle assessment tools. While other Federal partners are investing in this area, NIST is uniquely poised to provide the measurement and standards capabilities that are needed to promote widespread adoption of the technologies developed. Additionally, the U.S. has the capability to create a robust circular economy, but lacks any unified infrastructure for collecting, sorting, identifying, and transporting waste streams. NIST can address these areas with appropriate attention to stakeholder engagement to understand community needs through workshops as well as program alignment with critical partners.

1.2 Workshop Overview

To better understand the needs to overcome key challenges and NIST's role in this area, NIST held a virtual workshop entitled "Facilitating a Circular Economy for Textiles" on September 21-23, 2021. The purpose of the workshop was to convene stakeholders associated with textiles, waste management, and associated industries to identify key challenges facing a circular economy for textiles as well as needed advancements to overcome those barriers. Participants included representatives from industry, academia, government, trade associations, national laboratories, and non-governmental organizations.

Workshop planning and organization involved outreach to stakeholders to identify core areas of interest. The resulting agenda included three plenary presentations, six topic-specific sessions, and three discussion sessions. Each session included a series of presentations by experts on a given topic followed by a question-and-answer session. The plenary presenters included a textiles recycling consultant, an "EcoFashion" innovator and educator, and a professor specializing in sustainable textile systems. In total, the workshop brought together approximately 150 participants including 30 speakers. The workshop agenda and speaker/participation list are provided in Appendices A and B, respectively. Additionally, Appendix E provides a list of CE resources compiled throughout the workshop. Following are the plenary, sessions, and discussions topics.

WORKSHOP TOPICS

Plenary Topics

- Current landscape, bottlenecks, and critical gaps
- Consumer challenges and opportunities
- Sustainable textile systems

Session Topics

- Boundary-spanning tools to facilitate a circular economy for textiles
- Challenges with collection, reuse, and repair of textiles
- Challenges to mechanical and chemical recycling of textiles
- Environmental impacts of textiles
- Brand responsibility and best practices
- Legal and regulatory barriers and opportunities

Discussion Topics

- Data, Standards, and Terminology
- Reuse, Repair, and Recycling
- Policy Approaches and Needs

This workshop report summarizes the presentations and breakout group discussions that took place at this event. The viewpoint of the experts attending the workshop are presented here. They may not reflect the views of the broader community or NIST.

2 Current Status of Circularity in the Textile Industry

This section aims to define textile materials and products in conjunction with their rate of production and resulting waste generation.

2.1 Textiles Defined

Textiles are a broad category of flexible materials made through spinning raw fibers into long and twisted lengths that are interlocked into bundles of yarns or threads and woven, knitted, matted, or otherwise bound together into fabrics [4]. Fibers generally are categorized by their chemical origin, falling into two classifications: natural and manmade/manufactured/synthetic fibers. Figure 1 provides the classification of fibers based on origin.

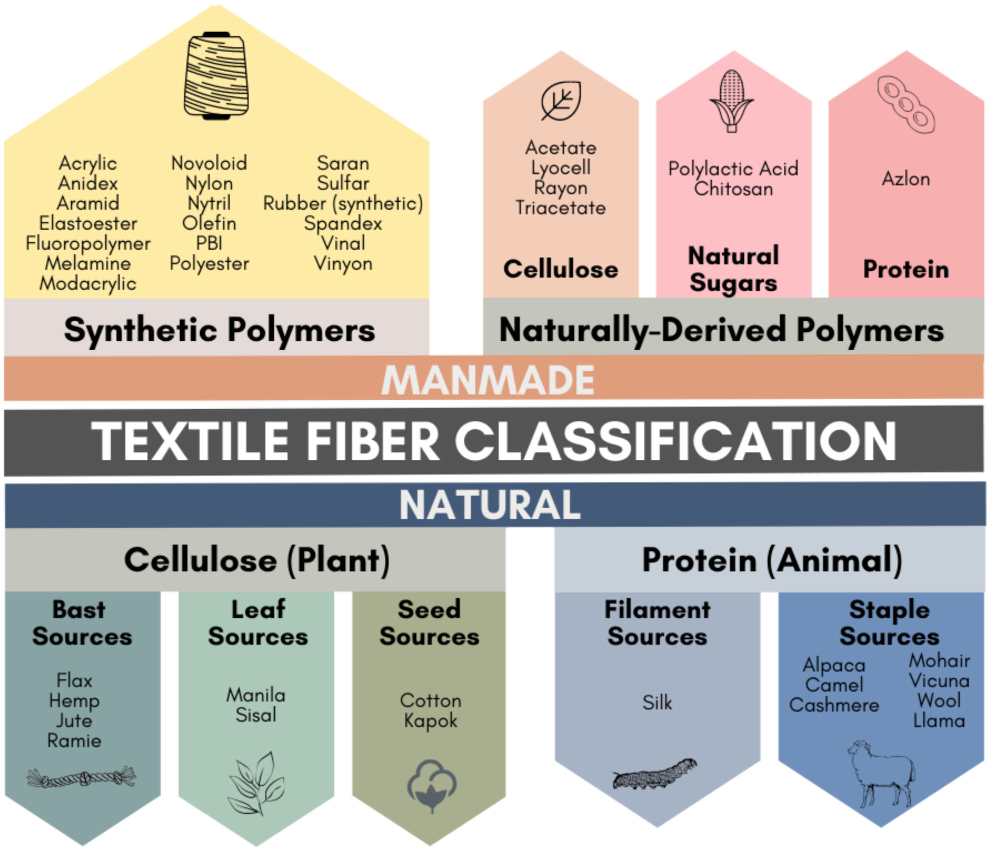

Figure 1: Classification by fiber type (adapted from [5, 6])

Textiles are comprised of single fiber types or a blend of two or more fiber types depending on the desired product characteristics (stretch, stain and/or water resistance, durability, expense, etc.). Many products utilize textiles, and several (e.g., mattresses) have developed individual supply chains and management programs at EoL. For this reason, *textiles* in this report refers to those used in clothing and apparel, outdoor equipment (e.g., tents), home and hospitality (e.g., towels, linens, etc.), upholstery fabrics, stuffed toys, as well as post-industrial textiles such as manufacturer clippings, overstock, deadstock, off-spec, and returns.

2.2 Textiles Production

The textile industry is a complicated manufacturing industry due to its fragmented and heterogeneous nature dominated by small and medium enterprises (SMEs) [7]. In the current linear model (Figure 2), the value chain of textiles is comprised of successive processes which span several industries including agriculture (natural fibers), petrochemicals (synthetic fibers), as well as manufacturing, distribution logistics, and retail [1]. This global dispersion and dis-integration challenges circularity, as it thwarts efforts to improve consistency and harmonization across the textiles industry.

Figure 2: Current value chain of textiles (used with permission from [8])

Textile production has increased dramatically over the last two decades, particularly with the rise of 'fast fashion'. Figure 3 displays the growth in global textile production by fiber type in relation to population growth. Based on the Figure, it is apparent that fiber production increased significantly in the late 1990s, irrespective of population growth, which remained constant. This signifies an increase of per capita production, which is often attributed to global economic development and expansion of higher living standards.

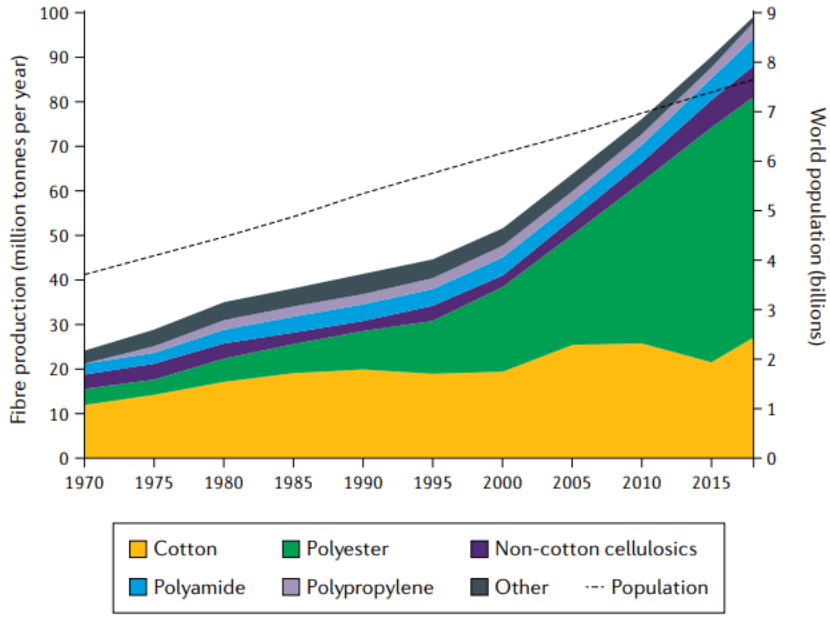

Figure 3: Growth in textile production by fiber type and total world population (used with permission from [1])

While production of cotton, wool, and cellulosics has remained fairly stable over the decades, production of synthetics, especially polyester, has increased tremendously. It is estimated that today 60 % of clothing and 70 % of household textiles are comprised of synthetic fibers, and this trend is expected to increase into the future as consumers in emerging economies adopt Western lifestyles and attire [9, 1]. Currently, 60 % of global fiber produced is destined for the fashion industry, the remainder used for interiors, industrial textiles, geotextiles, agrotextiles, and hygienic textiles, among other uses [1]. The United States, which represents only 4.2 % of the global population [10], now accounts for approximately 8 % of global fiber production and 14 % of global end-use demand [11].

Along with the growing production of textiles there has been a global shift of textile and apparel production to developing countries which generally have a competitive advantage in manufacturing and labor costs. China now dominates the production market, annually exporting an estimated $109.9 billion of textiles generally, and $158.4 billion of apparel specifically [12]. Other major textile and garment producing countries include India, Turkey, South Korea, Bangladesh, and Vietnam [1]. More than 90 % of apparel sold in the U.S. is now imported from other countries [13]. The United Nations Alliance on Sustainable Fashion reports that the clothing and textile industry today employs 300 million people worldwide across the value chain, many of them women [14]. This global shift in production has led to increased complexity and reduced transparency of supply chains as each step of the supply chain often occurs in a different country [1]. Altogether, the textile and clothing industry is a major contributor to economies around the world and is estimated to be worth well over $3 trillion [8].

2.2.1 Fast Fashion

The increased fiber production shown by the inflection point in the late 1990s in Figure 3 is likely due to the rise of fast fashion. Taxes on imports/exports diminished at that time, and manufacturing moved to countries with lower labor costs and reduced regulatory requirements [15]. The term *fast fashion* therefore describes the mass manufacturing and marketing of low-cost clothing that is quickly transferred from a design concept to retail stores. It is thus 'fast' in several ways: the rate of production, the number of fashion cycles, delivery, consumers' decision to purchase, and the rate at which garments are worn and disposed [16]. Workshop speakers provided several statistics regarding fast fashion, including:

Fast Fashion Claims Stated in Workshop*: CLAIMS

- Traditionally, 4 fashion cycles produced per year, today fast fashion produces 50+ cycles/year
- 100 billion items of clothing are produced each year
- Fashion brands produce almost 2x the amount of clothing today than they did before the year 2000
- On average, consumers wear a garment seven times before getting rid of it
- More than 50 billion garments are thrown away within 12 months of being made

Social media has also been a driver of fast fashion, speeding the rate at which trends come into style through increased visibility. From a business model perspective, fast fashion has been exceptionally successful, however, it has caused negative social impacts, particularly on the workforce, and has resulted in a situation where inexpensive products drive unsustainable consumption behavior and ultimately fuels a culture of consumption and disposal. Additionally, fast fashion products tend to be lower in quality, and therefore are often not suitable for resale, repair, or repurposing into alternative textile products (e.g., wiping rags). As a result, the overproduction and consumption of low-cost, low-quality clothing has significant social and environmental implications.

2.3 Textile Waste Generation

Textile waste includes clothing and apparel, home and hospitality textiles, contract textiles, uniforms and workwear, upholstery fabrics, as well as manufacturer or retailer overstock, deadstock, off-spec, damages, and returns [17]. Distinctions are often made between categories of textile waste generation, such as the following:

Post-industrial:	Waste generated before it reaches the consumer, i.e., during the manufacturing process. Often called pre-consumer waste [18]. Tends to be the cleanest and easiest stream of which identify material compositions.	DEFINITIONS
Post-consumer:	Waste generated by the consumer after use. Highest volume stream but includes blends of all fiber types and often contain contaminants.	
Residential:	Post-consumer textiles worn by general consumers or used in residential settings	
Non-residential:	Post-consumer textiles used for professional uniforms, hospital linens, and industrial, commercial, and institutional (ICNI) applications	

* Claims stated in this table were presented by workshop participants, have not been verified by NIST, and are not the official view of the U.S. Government.

The rate of textile waste generation has increased significantly over the last two decades, in line with fast fashion. According to U.S. EPA data, textiles comprised 5.83 % of the total municipal solid waste (MSW) stream generated in the U.S. in 2018 (roughly 17 million tons), a linear increase of 80 % on a per tonnage basis since 2000 [19]. This is a drastic increase compared to the overall waste stream which increased only 20 % over the same timeframe (Figure 4). On a per capita basis, textile waste grew 55 % over the same period, indicating that the increased textile waste generation is not only due to population growth [17]. Per the U.S. EPA's waste statistics and US Census data, each American discarded an average of 103.5 pounds (47 kg) of textiles in 2018. By comparison, the annual per capita discard rates in Finland and Sweden are 37.5 and 53 pounds per capita, respectively [15]. It must be noted that the U.S. EPA does not track or measure the volumes of textiles sent to charities for reuse, which potentially comprises a large, unrepresented segment of the total volume of discarded textiles. Additionally, insufficient data exists to confidently measure textile waste generated through different supply chain production stages (e.g., fiber processing, textile production, garment manufacturing). That said, it is estimated that somewhere between 2 % to 20 % of all textiles ends up on the cutting room floor, representing a significant generation of post-industrial waste [20].

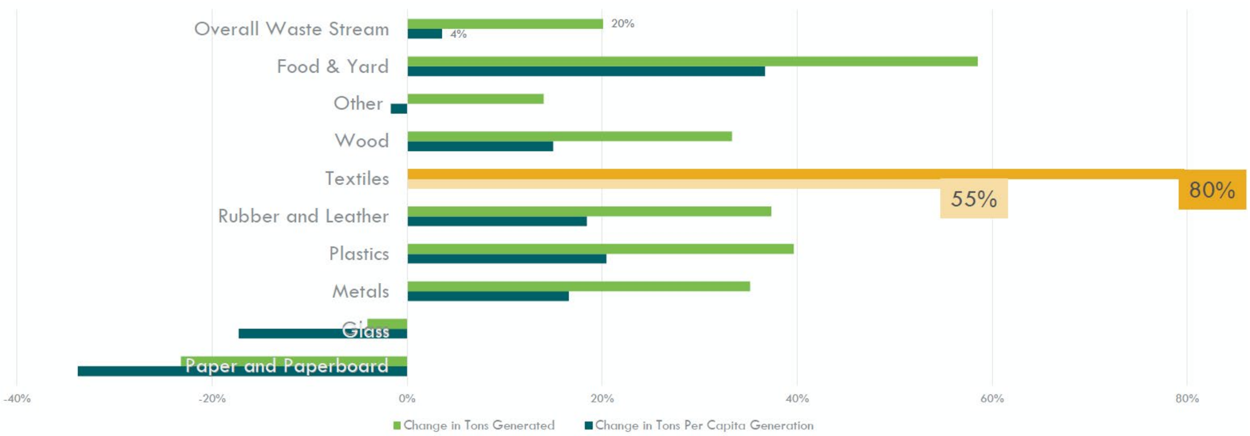

Figure 4: Percent change in absolute tons and tons per capita waste generation 2000-2018 (used with permission from [17])

The current recovery rate for textiles in the U.S. is approximately 15 %, while the remaining 85 % of discarded clothing and textiles are sent for landfill or incineration [2, 21]. The volume recovered are collected either through donation to thrift stores or donation bins or collected through curbside collection programs and retail store takebacks (Figure 5) [22]. It is estimated that thrift stores sell approximately 20 % of textile donations, while the remainder are sold to sorters and graders who assess and sort the textiles based on quality, condition, and format to be sold to appropriate downstream markets, such as reuse/resale in domestic or international markets, turned into industrial rag, stuffing, or shoddy (i.e., low-quality yarn or fabric made from shredded fiber of discarded woolen cloth), or sent for disposal [17, 2]. Industry experts claim that there is a significant amount of textiles that do not get sorted or graded before being exported and sold internationally [20]. Currently, less than 1 % of textiles collected go to fiber-to-fiber recycling [17].

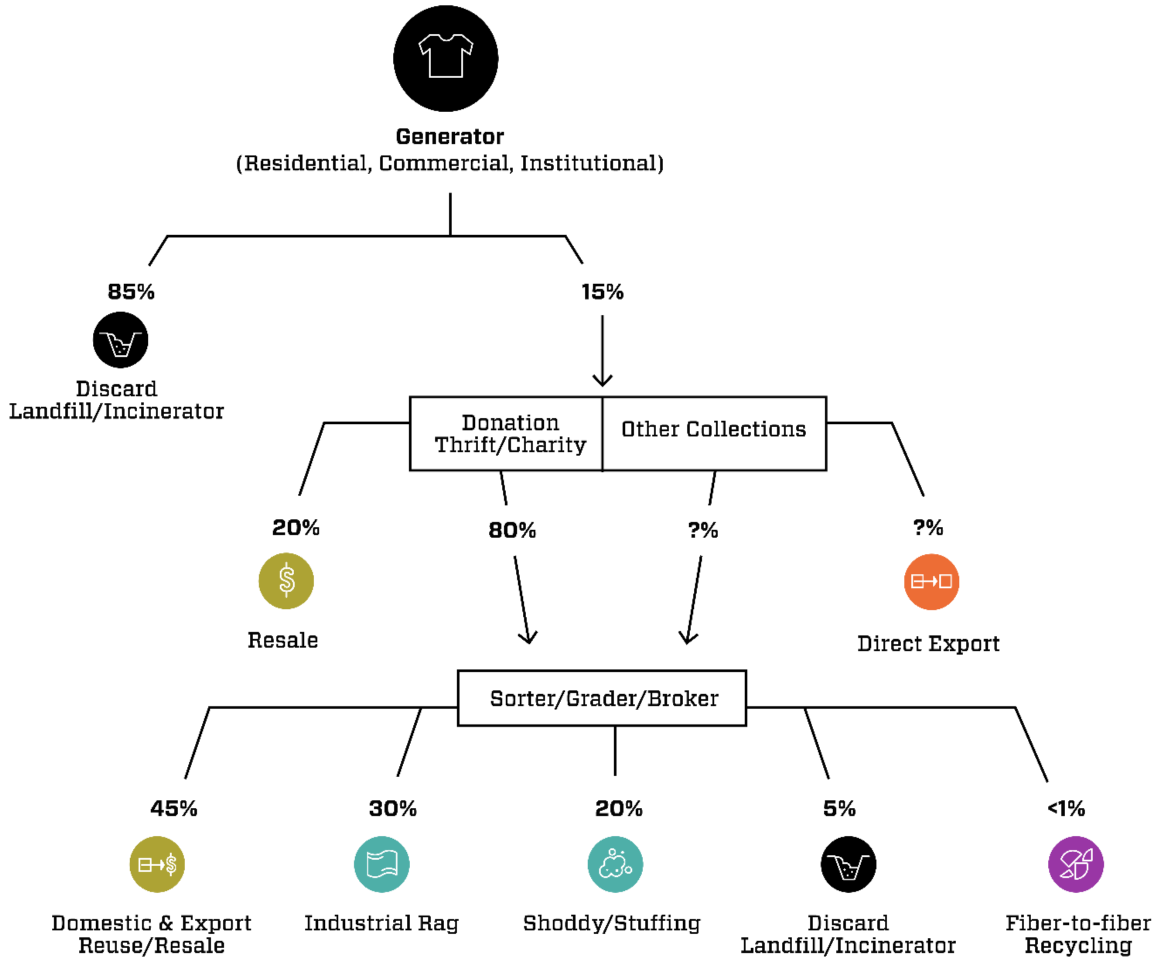

Figure 5: Current fate of used textiles in the United States. Question marks indicate flows for which reliable data are unavailable. Shoddy is made from shredded fibers and used for insulation and stuffing. Based on data from [17, 20, 21].

Export of used clothing to low-income regions is a common practice for garments that do not have a market in wealthier nations. The major importing countries are in Africa, Asia, and Central America and there is a lot of discussion and differing opinion around the benefits and detriments of exporting used textiles [17]. Several countries in Eastern Africa have collectively banned the import of used textiles to protect their own domestic textile industries [23].

The cost of managing textile waste in the U.S. is significant and increasing. In 2020, it was estimated that textile collection and disposal cost Americans over $4 billion based on average landfilling/incineration tip fees and collection costs [17]. This cost will likely increase as transportation costs rise and available landfill capacity is reduced.

2.4 Environmental and Social Impact of Textiles

The textile industry is rife with social and environmental impacts due to unregulated material processing and manufacture, high usage of energy, water, and chemicals, and the leakage of pollutants to environmental sinks (air, water, soil). However, specific estimates of these impacts vary widely, and the underlying sources are often difficult to ascertain, or not based on science, actual data collection, or peer-reviewed research, but rather anecdotal evidence, extrapolations, and assumptions. This section aims to discuss key environmental and social impacts of the textiles industry presented in the workshop, while also highlighting areas where this data is lacking or exhibits discrepancies.

2.4.1 Raw Materials

All textile materials, whether natural or manufactured, have environmental impacts. Natural fibers, especially cotton, require large amounts of land for production. Some argue that increasing cotton production is not possible due to the lack of available suitable land [15]. The cultivation of textile fiber crops has the potential to compete with the production of food crops, as both sectors compete for arable land [24]. The production of other raw materials also has environmental implications, including deforestation, overgrazing of pastures, and soil and water contamination due to chemicals and pesticides.

Figure 6 displays the relative environmental impacts associated with manufacturing the most common synthetic fibers and cotton. While cotton production has low climate change impacts, its production requires significant amounts of land, water, and mineral resources as well as contributes to eutrophication. Nylon, by comparison, has the highest impact per kilogram for climate change and fossil resource use, but has lower impacts in the other categories. A similar comparison can be made between polyester and cotton. It is important to note that impacts also depend on the volume of fiber production. For instance, the manufacture of polyester requires less energy than nylon, however, its annual production rate is much higher, thus resulting in higher overall impacts [25]. A portion of textile polyesters are recycled from polyethylene terephthalate (PET) bottles, which reduces the extraction of raw materials and associated climate impacts but may not influence other impacts such as toxicity. The key takeaway is that all textile materials have environmental impacts, so shifting away from one to another may only serve to shift the environmental burdens. Ultimately, efforts need to focus on reducing the impacts of all fiber types.

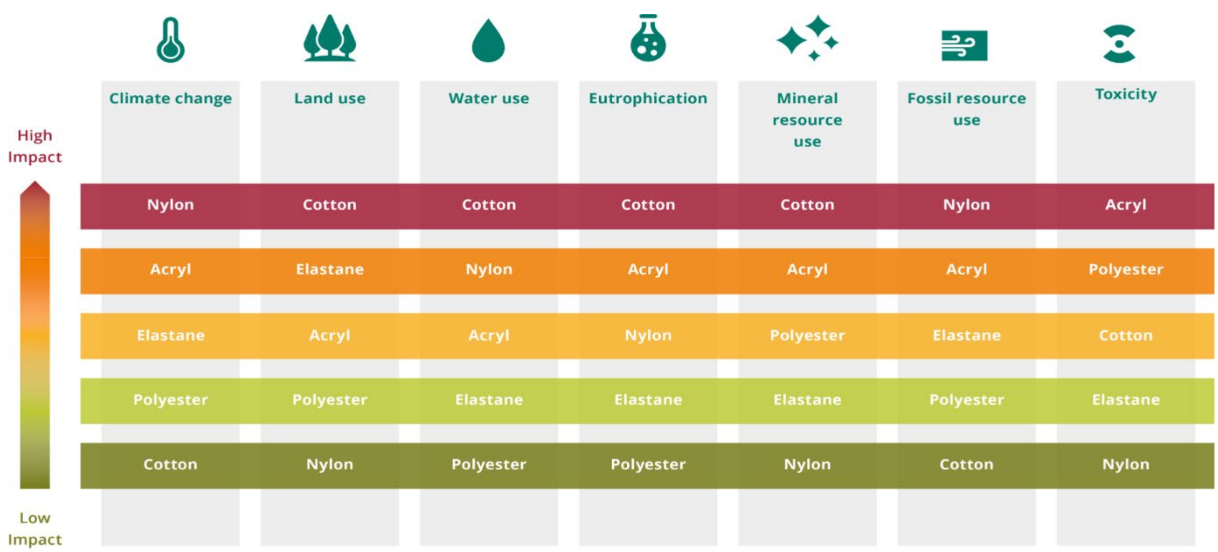

Figure 6: Impact of manufacturing of 1 kg dyed woven fabric (used with permission from [9])

A full lifecycle approach is needed to effectively compare textile fibers and products. This requires a thorough understanding regarding the relevant flows of materials throughout the lifecycle. Transparent harmonized accounting tools that are supported by data are also necessary. Due to the fragmented and dispersed nature of the textiles value chain, such information, if available, is difficult to obtain. Advancements are needed to improve data collection and transparency, as well as advanced lifecycle analysis methods and tools.

2.4.2 Climate Impacts

The textile industry consists of a large number of production and manufacturing plants that together consume a significant amount of energy. Many of these facilities are in regions of the world where fossil fuels dominate the energy supply and as a result are a substantial source of greenhouse gas (GHG) emissions. Therefore, to address climate change necessitates reducing emissions associated with textiles production and use. Climate claims reported by workshop speakers included the following:

Climate Impact Claims Stated in Workshop*:

- Annually the industry consumes 1 trillion kilowatt hours of electricity
- GHG emissions from textile production total 1.2 billion tons of CO2 equivalent
- The fashion industry contributes around 10 % of global GHG emissions annually
- Textiles is the 5th leading industry in terms of GHG emissions in the European Union
- Industry emissions are projected to increase more than 60 % by 2030

CLAIMS

Many of the above claims are not well supported or the underlying data are not available. For instance, in the resource stating that emissions from textiles production total 1.2 billion tons of CO_2 equivalent (CO_{2eq}) (calculated for the year 2015), two sources are identified for this calculation, yet neither include documentation or information pertinent to this calculation or access to the underlying data [26]. Similarly, another documented source estimated emissions from the global footwear and fashion industries at 3,990 million metric tons of CO_{2eq} (3.99 billion metric tons) in 2016, representing 8.1 % of global emissions [27], however, underlying data sources were not provided. Another major entity claims that the textile industry contributes 10 % to global GHG emissions, yet the method and scope behind this calculation is also unclear [28]. While it is logical that the textiles industry would have a significant carbon impact, clearly more transparency is needed as to how these determinations were made in order to make measurable progress from a foundation of common understanding.

2.4.3 Water Impacts

The textile industry is a major water consumer. Nearly all phases of the supply chain utilize water in some capacity, and the water demand of textiles use, particularly for clothing, is also high due to laundering. Furthermore, some areas of the world where fibers and textiles are produced are already facing water stress, which is exemplified by the fact that many of these regions do not have the water purification infrastructure in place to properly treat and recirculate water [8, 1]. The amount of water used in the textiles industry is expected to increase, which combined with population growth, will further stress water availability.

The textile industry is also a significant source of water pollution. Much of this pollution comes from agrochemical runoff from natural fiber crop production or wastewater effluent from textile and garment production facilities where a number of chemicals are typically used (see Section 2.4.4). Microplastic fibers shed from polymer-based textiles (particularly during laundering) are an increasing form of water pollution (see Section 2.4.5). Staggering statistics provided by workshop speakers regarding water impacts include the following:

* Claims stated in this table were presented by workshop participants, have not been verified by NIST, and are not the official view of the U.S. Government.

Water Impact Claims Stated in Workshop*:

CLAIMS

- The fashion industry is the world's second largest consumer of the world's water supply
- 20 trillion liters of water are used by industry every year
- Water use in the fashion industry is expected to increase by upwards of 50 % by 2030
- 20 % of water pollution is from textile treatment and dying
- 17 % to 20 % of ALL industrial wastewater comes from the textile industry (citing the World Health Organization (WHO))
- Fashion is the second biggest polluter of clean water in the world, after agriculture (citing the WHO)
- In China, the textile industry is the leading cause of water pollution

Annual global water consumption estimates used by the industry range significantly, including, for example, 20 trillion liters (L) [8], 79 trillion L [1], 93 trillion L [29], and 215 trillion L [14]. Similar discrepancy exists in estimates of water usage for specific garment types, for example estimates of water used to make a pair of jeans include 3,781 L [30], 7,500 L [31], 10,000 L [32]. Such inconsistency could be a function of the diversity of processes and facilities and is indicative of the lack of data transparency across the supply chain and lifecycle of textiles. This may be due to a reluctance from industry to share proprietary information about their processes.

2.4.4 Chemicals

Chemicals are used or applied in nearly every stage of the textile supply chain. While agrochemicals are used on natural fiber crops, synthetic fibers necessitate different degrees of chemical engineering. Textile manufacturing processes, such as spinning and weaving, utilize lubricants, accelerators, and solvents, and wet processing of fabrics uses chemicals such as bleaches, dyes, processing aides, and water and stain repellents, among others [1]. Some of these chemicals can be harmful for the environment, factory workers and local communities, as well as consumers. For example, per- and polyfluoroalkyl substances (PFAS) are widely used synthetic chemicals that make clothing, carpets, and other products "waterproof," "water resistant," or "stain-resistant," yet are of concern because of their persistence in the environment, solubility in groundwater, and potential adverse health effects [33, 34].

Estimates of the total number of chemicals used in textiles production varies widely, with examples including over 8,000 [35], 15,000 [1], and 20,000 [36]. Additionally, specific chemicals used in textile production and applied to garments are often not identified or tracked through the supply chain, and as a result, their potential for toxicity is also lost. Without such information it is impossible to make adequate risk management measures to reduce the toxicity of textile production and consumption.

2.4.5 Microplastic Fiber

Microplastic fibers (MPF), also known as microfibers, are small (less than 5 millimeters in length) plastic threadlike fibers that are increasingly being recognized as a source of environmental pollution. The predominant leakage pathway is expected to be through the laundering of synthetic clothing, where abrasion causes the shedding of MPF to the water effluent. While many modern wastewater treatment plants can effectively capture MPF, they generally do so in the sewage sludge which, in the US and Europe, is then often used on agricultural soils, thus directly releasing the MPF

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* Claims stated in this table were presented by workshop participants, have not been verified by NIST, and are not the official view of the U.S. Government.

to the environment [37]. Furthermore, many low-income countries do not have modern wastewater treatment facilities and thus wastewater is often directly discharged to waterways without treatment [38]. Other sources of MPF leakage are expected to be through textiles production (wastewater effluent from production facilities), as well as the degradation or fragmentation of textiles during use and at EoL (i.e., in landfills) [39, 40]. Discarded fishing nets, which are made of nylon, polyethylene, or polypropylene fibers, are also expected to be a significant source of MPF in the oceans [40].

Microplastic Impact Claims Stated in Workshop*:

- Emissions are mainly from China, with large percentages from North America, Southeast Asia, and Western Europe
- Fashion accounts for 20 % to 35 % of microplastic flows to the ocean (citing McKinsey)
- At least 35 % of microplastics in our oceans, drinking water, and air are from textiles
- Microfibers are in our food (salt, beer, tea, drinking water, seafood), air, water, ingested by organisms across the planet and found in our feces

CLAIMS

While it is increasingly understood that textiles are a major source of MPF in the environment, testing standards and measurement methods do not yet exist to accurately quantify the extent of contamination. Nor can current methods readily detect specific polymer types of MPF. Furthermore, the impact of MPF on ecosystems and human health are not yet understood.

2.4.6 Social Impacts

Although estimates of employment in the textile industry vary greatly (e.g., 65 million people, 85 % of whom are women [41]; 300 million people worldwide (many of them women) [14]), it cannot be disputed that the growth of textile production has undoubtedly provided many jobs, particularly in low-income regions of the world. However, these regions often lack occupational health and safety regulations, minimum wage requirements, or child labor restrictions, and therefore labor justice is an issue. The collapse of the Rana Plaza building in Dhaka, Bangladesh, which housed five garment factories and resulted in the death of over 1,100 people, has become a symbol of the working conditions of garment manufacturers and has spurred movements to improve labor standards, although many still face resistance [42].

While any country producing textiles and textile products may experience negative social impacts, the globalization of the textile and fashion industry has resulted in the uneven distribution of environmental consequences. Low-income countries are those largely responsible for producing textiles and clothing, and thus most exposed to the impacts associated with production. As such, they bear the burden for wealthy countries, who represent the largest share of consumers. Further, chemical pollution, and thus exposure, is greatest in countries where cotton is cultivated, but also in countries where wastewater from the textile industry is not purified properly [1]. It is important to note that the donation of post-consumer textiles to charities has significant positive social impacts. This practice supports charities' fundraising efforts, provides reliable jobs (often to marginalized populations), and enables them to extend the life and retain the value in textiles while supporting their social missions.

* Claims stated in this table were presented by workshop participants, have not been verified by NIST, and are not the official view of the U.S. Government.

3 Challenges and Opportunities with the Current System

This section presents current practices employed, challenges, and opportunities for advancement regarding the collection, sorting-grading, and recycling of textiles, with a primary focus on the U.S. system. Further, we discuss the complex market relationship between the plastics and textile industries, particularly with respect to the demand for recycled PET.

3.1 Collection

Current textile collection generally includes thrift stores and charities (e.g., Goodwill, Salvation Army), drop-off centers (e.g., municipal or county waste/recycling centers), curbside collection programs, donation bins, and retail store takeback programs. However, availability of these programs differs greatly across the country. Furthermore, as mentioned previously, only 15 % of textile waste is currently recovered in the US, the remainder going to incineration/landfill. This represents a significant need to educate consumers on the value of post-use textile products and available collection alternatives. Specific challenges and opportunities facing textiles collection include the following:

CHALLENGES & OPPORTUNITIES

Challenges to Textile Collection

- No established infrastructure for convenient, consistent, widespread, and reliable collection
- No harmonized textile collection rules or standards
- Materials must be clean, dry, and have no odor or hazardous chemicals to maintain value
- High transportation costs

Opportunities to Advance Textile Collection

- Need significant evolutionary change, not incremental improvement
- Expanding collection on the scale necessary requires involvement from brands, retailers, as well as legislation
- Need harmonized collection rules with an emphasis on preserving the quality without contamination
- Consumers need to recognize the value of used textiles and know options and best practices for collection

Widespread access to consistent collection services is essential to support downstream markets for used textiles. Textiles cannot be readily added to existing recycling services (e.g., curbside recycling) due to contamination and because municipal recycling facilities are not equipped to separate out textiles. Textiles could potentially be collected separately as part of waste/recycling collection services (e.g., in a separate plastic bag), but this comes with increased cost and logistics [43]. It is argued that if the downstream processes (e.g., recycling) and end markets are improved, waste management haulers can readily extend collection services to include textiles but implementing collection programs before end markets are ready for large volumes can be catastrophic for local programs [43].

That said, recyclers are hesitant to invest in large-scale infrastructure without major improvements in collection to provide reliable, high-volume feedstock streams. For example, a major recycler will not invest the required $20-25 million in a plant without knowing it can be collecting 75-100 million pounds of textiles. Increasing collection to this scale requires a combination of brands and retailer takeback programs, charity, for profit, and municipal collection programs as well as legislation to stimulate the necessary investment.

3.2 Sorting and Grading

Currently, approximately 20 % of collected textiles are rehomed through domestic resale (Figure 5) and some is directly exported and sold internationally [17, 20]. Products not sent or sold through resale are sorted and graded for cascading uses and end markets (such as wiping materials, shoddy, fiber recycling). This involves the identification and categorization of textiles based on quality, condition, and format for sale in downstream markets [17]. According to SMART, while some sorting and grading is done in the U.S. (namely in Texas and California), much of it is done in the United Arab Emirates, India, Pakistan, and Central America where labor costs are lower [2]. However, freight costs for overseas shipping have increased significantly in recent years along with decreased availability of shipping containers. These factors, together with the import bans discussed previously, could influence the export of textiles for these practices.

At present, sorting and grading is primarily performed manually, although technologies are increasingly being employed, particularly to aid in fiber identification. Near-infrared (NIR)-spectroscopy is one such technology, which is widely used in automated sorting applications for other segments of the recycling industry, such as PET recycling. Challenges ensue, however, as post-consumer textiles increasingly consist of different fiber blends. At present, the margin of error for fiber identification technologies is still too large for many recyclers (namely chemical recyclers) who require very pure feedstock. As a result, many identification technologies on the market still require some level of human labor.

Challenges to Textile Sorting and Grading

- Currently relies on manual labor, which is expensive
- Human eye is incapable of identifying fiber composition
- Existing technologies are incapable of screening for current styles and trends or identifying rips, stains, or wear
- No harmonized sorting standards or criteria
- Fiber identification, especially with fiber blends

Opportunities to Advance Textile Sorting-Grading

- Development of high-speed automated sorting systems
- Dedicated domestic sorting facilities
- Digital identification on products

CHALLENGES & OPPORTUNITIES

A need exists for the development and expansion of high-speed automated sortation systems. This is necessary to reduce the cost of manual labor, especially given the volume of textiles required to support large-scale textile-to-textile recycling, as well as rapid fiber identification. Such a system would ideally combine NIR and robotics; the former to both identify fiber types and provide percentages of polymer/material compositions, and the latter to separate the textiles based on desired categories (e.g., fiber composition, color, etc.). Efforts are underway in this regard (e.g., [44]) and necessitate the simultaneous expansion in collection for feedstock as well as growth in demand of outputs. Automated sorting systems could be included in domestic textile sorting facilities (e.g., textile material recovery facilities, MRFs) distributed across the country to allow for the development of regional textile recovery hubs and increased waste diversion [17].

Digital identifiers (IDs) on textile products could also increase the speed and efficiency of textile sorting. Including some form of marker technology on each textile product that includes identifying information such as fiber composition, chemical additives, etc., would greatly enhance the sorting-grading process. More on this topic in Section 4.4.

3.3 Reuse and Repair

Reuse of used textile products is the highest value approach when compared to alternative pathways (e.g., repurposing or recycling) and lowest impact from an environmental standpoint [2]. However, several challenges currently face reuse and repair industries, including:

CHALLENGES & OPPORTUNITIES

Challenges to Reuse and Repair

- Lagging consumer and industry acceptance that reuse is the preferred path with the least social and environmental impacts
- Materials must be clean and dry and have no odor or hazardous chemicals
- People throw unwanted materials away and do not understand reuse capabilities
- General public lacks knowledge, tools, interest, or time to repair garments
- High transportation costs – especially if dealing with large volumes
- Disenfranchised repair industry
- Fast fashion clothing quality is inferior, not suitable for resell or conversion and appropriate only for lower uses, e.g., wiping rags

Opportunities to Advance Reuse and Repair

- Education regarding garment repair, as well as sources for repair support
- Consumer education on donating and purchasing used products
- Build industry acceptance and support for resell and repair industries

As previously mentioned, 85 % of post-consumer textiles are currently discarded in the municipal waste stream, eliminating the potential for reuse, repair, repurposing, or recycling. This signifies a lack of consumer knowledge about the continued value and reuse capabilities. Furthermore, today's consumers lack the ability/interest/time to repair broken or damaged products and prefer to discard and buy new rather than seek repair support.

According to discussion in the workshop, the repair sector is largely a disenfranchised industry, comprised of communities of minorities who may not be familiar with government protocols or paperwork, and often do not speak English as their first language. No publicly available data could be found to support this, including U.S. labor statistics (e.g., [45, 46]), yet that could be a result of the disenfranchisement. While this sector is integral to the circularity of textiles, forming partnerships and collaborations may take additional effort (see Section 5.2 for more on this topic). Further, large-scale, franchised textile repair is not economical in the current system due to increasing transportation costs, time consuming processes, decreasing quality of clothing due to Fast Fashion trends, and low cost of new garments. Efforts must be made to educate consumers on the value and pathways for used products, as well as build industry acceptance for reused and repaired garments (e.g., brand takeback and resell programs).

3.4 Recycling

Recycling is the next approach to retain value in textile products and, thus, after reuse and repair, the remaining waste textiles should be directed towards recycling. In general, textile recycling involves reprocessing post-industrial or post-consumer textiles into new products. While several definitions and classifications of textile recycling exist, the following were identified in the workshop:

Recycling:	Converting textile waste into something of roughly the same value; Often referred to as fiber recycling (e.g., recovery of fibers back into fibers). This term is often also used as a catch-all for all forms recovery pathways (whether up-, down-, open-, or closed-loop).	DEFINITIONS
Upcycling:	Turning wasted textile material into something of higher value; Often referred to as fabric recycling (e.g., making new garments with materials from allegedly old or used textiles)	
Downcycling:	Turning wasted textile material into something of lower value (e.g., industrial rags, shoddy/stuffing, carpet padding, insulation)	
Closed-loop recycling:	The material from a product is recycled and used in a similar or identical product	
Open-loop recycling:	Material from a product is recycled and used in different products (often referred to as cascade recycling)	

Textile recycling generally includes mechanical and chemical processes that turn textile fabrics back into their fiber components. Mechanical recycling processes generally include shredding waste textiles into small fractions, heavy carding in a Garnett machine to release the fibers, bleaching, and then re-spinning those fibers into new yarns. This process is best suited for mono-fiber materials (e.g., acrylic, pure cotton, and wool) due to their fiber yield. That said, mechanical recycling shortens the staple fiber length, compromising the strength and softness of recycled fibers. As a result, fabrics that include mechanically recycled fibers can generally only use 20 % to 30 % of recycled fibers before the quality of the fabric is reduced [47]. Post-consumer waste in particular does not produce high-quality recycled fiber due to degradation during wear and, as a result, only pre-consumer waste is typically mechanically recycled [47].

Chemical recycling refers to the process of using chemical methods to disassemble textiles back to their basic fibers or monomers. Most chemical recycling technologies are in the start-up Research and Development phase (technical readiness level 3-7) with only a few operating at scale (e.g., [48, 49]). Chemical recycling approaches for synthetic, polymer-based textiles (e.g., polyester, nylon), typically include depolymerization via hydrolysis, methanolysis, or solvolysis down to the monomer or oligomer constituents which can then be repolymerized and re-spun into new, virgin-like fibers [50]. Natural or cellulosic fibers (e.g., cotton, viscose) approaches include dissolution in solvent systems or derivatization into viscose compounds. The former produces cotton fibers that can be re-spun into recycled fibers while the latter produces viscose products that can be used for fiber production as well as other applications [47]. It is worth noting that due to the nature of chemical recycling, where recycled polymers become indistinguishable from their virgin counterparts, accounting tools such as Mass Balance accounting will be required to trace recycled content through the process [51].

Recycling routes often consist of a combination of mechanical and chemical processes. For example, garments must go through mechanical pretreatment to remove items such as zippers and buttons, size reduction through shredding or grinding, and, in some cases (e.g., carpet recycling) separation and debonding of components using mechanical methods (e.g., loop-clipping, density separation, centrifuge) [50]. In this regard, chemical recycling still requires pre-processing for most raw materials to meet input specifications and material handling requirements, which generally includes mechanical processes.

Challenges to Textile Recycling

- Recycling economics require subsidization *[Both]*
- No dedicated funding for scaling of recycling technologies *[Both]*
- Removal of dyes, additives, finishes (e.g., functional coatings) *[Both]*
- Only conducive for pure fiber (not blends) *[Mechanical, some Chemical]*
- Degradation of fibers (length, strength, softness) during processing *[Mechanical]*
- Post-consumer textiles do not produce high-quality recycled fiber *[Mechanical]*
- High temperature, pressure, time, and cost requirements *[Chemical]*
- Some processes use/produce hazardous chemicals *[Chemical]*
- Requires pure, reliable, high-volume feedstock *[Chemical]*
- Separation of poly/cotton blends *[Chemical]*
- No processes for select fiber types (Nylon 6,6, elastane) *[Chemical]*
- Unknown energy consumption and overall environmental impacts *[Chemical]*

Opportunities to Advance Recycling

- Development of post-consumer textile supply chain
- Development of domestic recycling options
- Advancements in separation of components (e.g., carpets)
- Advancements in separation of blended fibers
- Standardized methods for removal of buttons, zippers, etc.
- Methods to separate and process non-cellulosic/polyester content (e.g., elastane)

CHALLENGES & OPPORTUNITIES

Both chemical and mechanical recycling processes are sensitive to feedstock purity. Current recycling technologies cannot process mixed material inputs (e.g., garments made from two to three fibers or more) nor can they process chemicals and finishes applied to garments. As such, un-processable fractions, or low-purity, low-value feedstocks must be removed and disposed of properly, which represents considerable waste by itself [52]. In general, the higher the feedstock purity, the lower the availability, and vice versa, and lower feedstock purity generally results in higher processing costs. Purity requirements of feedstock for chemical recycling range from 80 % to 95 %+, depending on the method employed [53]. Color-agnostic processes naturally increase the feedstock availability. This reinforces the need for identification and composition of fiber types and blends (e.g., percent of fiber composition).

Modern consumers particularly enjoy stretchy fabrics and, thus, products increasingly include small amounts of elastane. This practice is problematic for recycling as elastane is difficult to separate from other fibers and current technologies are not capable of recovering elastane. Therefore, a need exists for processes to separate and recycle elastane.

Currently, post-industrial (or pre-consumer) streams are the most successful for both mechanical and chemical recycling because they comprise a designated stream with known characteristics and have not lost quality due to wear and laundering. However, they also represent a smaller volume than post-consumer waste streams, which comprise a mixture of garment types, fiber types/blends and quality, colors, additives, and finishes/coatings. However, as discussed previously, the post-consumer textile supply chain is currently not capable of supplying future recycling plants (namely chemically recycling plants) with the volume needed to drive circularity. Further, due to high processing costs, recycled fibers are often more expensive than their virgin-based counterparts. Therefore, to increase the uptake of recycled textiles requires market acceptance of a premium cost associated with recovered textiles, increased support and demand for recycled content from brands, and/or subsidies to support the development and expansion of recycling infrastructure.

3.5 Plastics vis-à-vis Textiles

While ‘fiber-to-fiber’ recycling is not yet widely practiced, ‘bottle-to-fiber’ is common practice, in which PET bottles are mechanically recycled into polyester textiles. Nearly all recycled polyester is derived from PET bottles, and as a result, textiles are currently the largest outlet for recycled PET, ahead of bottle-to-bottle recycling. This is largely due to the more forgiving fiber market and favorable cost structure compared to food-grade end markets [22]. Polyester currently constitutes the most widely used fiber in the apparel industry and, while only 14 % of polyester currently comes from recycled inputs, industry stakeholders are aiming to increase that to 45 % by 2025 [54]. However, as food and beverage brands commit to more and higher recycled content targets, and regulation of packaging companies increases, competition for recycled PET will increase and recycled content for textile and apparel brands will be harder to achieve. This tremendous crossover between recycled polyester and PET packaging must be considered and both systems need to be addressed holistically to ensure adequate supply for all end uses and selection of the most efficient circular pathways for all sources of material.

3.6 Economics

Textiles circularity is not economical in the current system. As indicated above, large-scale textile reuse and repair is hindered by high transportation and labor costs and decreasing quality and cost of new clothing. Similarly, the cost to collect and recycle textiles exceeds the price end users are willing to pay for the product. Even if the U.S. were to expand collection systems, processing systems, and market demand, the economics do not currently support the business model [55]. Options to address this concern include industry or public policy requirements for mandatory post-consumer recycled content, or policies such as Extended Producer Responsibility (EPR). The latter may allow for a funding mechanism that supports circular business models through options such as 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), which could drive design for recyclability. This may be an approach to balance textile performance and fashion with EoL considerations.

4 Actions to Facilitate a Circular Economy for Textiles

Addressing the above challenges and opportunities requires several actions which are graphically displayed in Figure 7 and discussed in the following sections. Collaboration across the textiles value chain can support system harmonization and the collection and exchange of data and information, which are all necessary for the steps in the inner circle. The following section explains each of these steps in greater detail and it should be noted that all the steps are necessary to realize a circular economy for textiles and thus are not presented in any prioritized order.

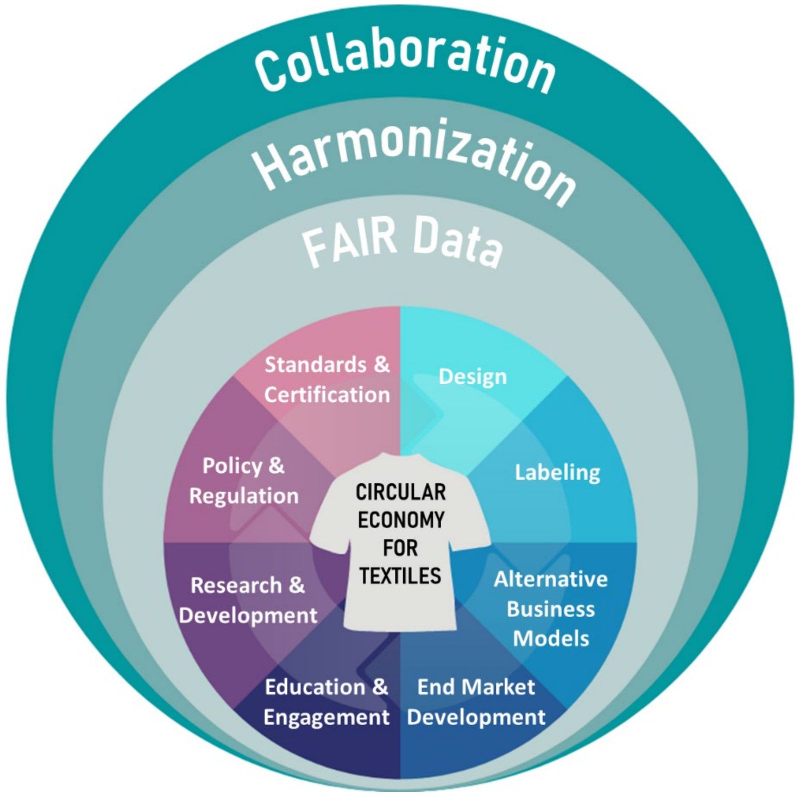

Figure 7: Actions necessary to facilitate a circular economy for textiles, where collaboration can support system harmonization and the exchange of findable, accessible, interoperable, and reusable (FAIR) data. Those three activities underpin the others outlined in the inner circle.

4.1 Collaboration

Transitioning to a circular economy for textiles requires non-traditional cross-sectoral collaboration. This action underpins all other actions needed to facilitate a CE, because re-engineering the current linear system to a circular economy cannot be done by individual actors but rather requires a unified effort. Increased communications between stakeholders throughout the value chain and reverse logistics is necessary to understand different dimensions and recognize the diverse perspectives and needs of various stakeholders. Innovative strategic partnerships including public-private partnerships are powerful tools in developing recovery systems, advancing successful business models, and raising capital and financing for public and private infrastructure. Collaboration can drive information sharing, organizational learning, and technology exchange, and thus requires trust and transparency. As such, communication channels must be enabled and supported which are participatory and inclusive. Collaborations must include the following the stakeholders:

COLLABORATION

Stakeholders to be Included

- Charity and thrift sector
- Sorters/graders (domestic & international)
- Global reuse end markets
- Technology providers (sorting and identification technologies)
- Equipment manufacturers
- Textile and apparel brands, manufacturers, and retailers
- Small and medium-sized enterprises (SMEs), including designers and intermediaries (e.g., wholesalers, distributors)
- Local repair businesses
- Local environmental community
- NGOs and advocacy groups
- Haulers, collectors, and bin operators
- Regional waste and recycling managers and waste auditors
- Academic institutions
- Professional experts in textile production and recovery
- Industry associations such as SMART, the Council for Textile Recycling, Textile Exchange, etc.

Several challenges face this collaboration, particularly for select stakeholder groups. Often, repair businesses are disenfranchised, they are communities of minorities, who may not be familiar with government protocols or paperwork and may not speak English as their first language [80]. Also, collaboration with the government generally requires a business license and insurance requirements, documentation many stakeholders in the repair, alteration, and reuse sectors may not have. Some stakeholders are unable to participate in external events such as NIST's textile workshop because they do not have the computing capability, access, or the time. Despite these challenges, collaboration with these communities is vital to the successful transition to circularity and as such, may require additional effort and outreach (e.g., visiting stores or operations in person, lessening restrictions, providing access and translation services, etc.).

4.2 Harmonizing Communications and Systems

There is a significant need to harmonize the system: common language, definitions, classifications, industry tools, and standards, must be agreed upon. For example, the very definition of textiles is not well established: different organizations include such items as shoes and fishing nets in their definition while others do not. Definitions and classifications of waste, second-hand, and materials for recycling is particularly ambiguous across countries (e.g., in trade codes) and need to be further clarified [56]. Classifications for waste audit studies must also be harmonized to enable comparisons and compilation. Following are several ill-defined terms identified in the workshop:

Unclear or Controversial Terms

- Biodegradable vs bio-based plastics
- Contaminant (e.g., chemicals introduced by design vs result of product use)
- Downcycling vs upcycling
- Open loop vs closed loop recycling
- End-of-life
- "Made with recycled materials"
- Pre-consumer, post-consumer vs post-industrial
- Recycling vs reuse vs repurpose
- Recycling rate
- Residential, non-residential vs commercial waste
- Sustainable
- 'Waste' vs 'secondary raw material'

TERMINOLOGY

Current organizations with defined terminology identified in the workshop include the US EPA, Ellen MacArthur Foundation, Textile Exchange, Salvation Army, US Federal Trade Commission, and the National Association for Charitable Textile Recycling (NACTR). Strategies to harmonize terminology could include a workshop dedicated to the effort and/or gathering input from the community at large and publishing guidelines for terminology.

Product-, process-, and principle-based standards and certifications related to a circular economy for textiles are emerging at various levels around the world. Harmonization of these standards at the international level is needed to promote interoperability and facilitate trade for businesses with circular modes of operations [56].

Additionally, tools to characterize and model textiles circularity must be comprehensive, consistent, and transparent. Lifecycle assessment (LCA), techno-economic analysis (TEA), and material flow analysis (MFA) are examples of systems-level assessment tools that can serve as a baseline for environmental impacts, identify supply vulnerabilities, and support cost-benefit analysis, policy evaluations, supply-demand scenarios, and economic feasibility studies. However, to be accurate and useful, these tools need significant improvement. Applied to the textiles industry their usefulness is low due to inconsistency between data inputs, system boundaries, functional units, and assumptions. As a result, any comprehensive assessment of the circularity of textiles will require significant advances in the tools and data currently available to evaluate the entire economic, manufacturing (including design), social, and environmental landscape.

4.3 FAIR Data and Information Exchange

Significant data gaps currently inhibit the advancement of many CE efforts. As alluded to in Section 2.4, the underlying data sources for many environmental impact claims are unavailable, unsubstantiated, and/or outdated. Without quality and available data, it is not possible to reduce the industry's environmental footprint, design effective policy, or drive social change.

Access to or collection of reliable data is a significant challenge for several reasons, including opaque supply chains, proprietary information, lack of data tracking by brands, cost of data collection and reporting, lack of resources or knowledgeable personnel, inconsistent use of terms, and a general lack of transparency across the industry. Furthermore, while many companies and organizations (e.g., Producer Responsibility Organizations) are collecting significant amounts of data, they are often proprietary, splintered, and/or not interoperable across the industry. Table 1 provides specific data needs identified in the workshop:

Table 1: Data Needs to Facilitate a CE for Textiles

Material Level	- Waste composition by fiber type - Prevalence of different blends - Feedstock availability and quality (for recyclers) - Current and projected fiber demand/usage - Chemicals/additives content and associated risk
Product Level	- Regionally distinct data on sales, collection, and disposition - Product lifespans - Chemicals, additives, and finishes used during production and applied to products - Waste composition by product type, quality, and condition - Supply chain tracking/traceability
Market Level	- Quantity of textiles reused (thrifted), exported, recycled - Quantity of post-industrial scrap use - Reuse markets, formal and informal (e.g., charity/thrift, peer-to-peer) - Recycler market economies - Industry employment - Cost of manual sorting - Industry data on yield ratio - Waste generators (residential, commercial, industrial) - Fate of exported used textiles
System Level	- Lifecycle inventory data (e.g., inputs of energy, water, and raw material, outputs to air, soil, water) - Microplastic emission estimates - Mapping of textiles processors and infrastructure (e.g., locations and processes associated with collection, reuse, and recycling) - Current and future technology options for product and material recovery - Losses at each node in the supply chain and EoL - Data on behavior and programs for collection

A need exists for a unified system for collecting and managing significant amounts of data. Publicly available databases, repositories, and registries can be managed by private and/or public institutions for use by industry stakeholders but they must be harmonized (e.g., consistent terminology) and interoperable. Data publishers and stewards should follow the FAIR Data Principles of Findability, Accessibility, Interoperability, and Reusability to ensure effective data discovery and application [57]. Additionally, access to data and databases needs to be available and affordable to all stakeholders, including resource-limited local governments.

Improving traceability and transparency has become a priority in the textile industry to manage supply chains more effectively and to identify and address social and environmental impacts. A garment is said to change hands 7 to 10 times in the supply chain, each time undergoing some level of alteration [58]. Development of traceability platforms is necessary to track and trace products through development and provide the data necessary to enable downstream decision-making.

Transparent information exchange can enhance system performance, stimulate investment, and help strengthen relationships of stakeholders across the lifecycle of products and thereby promote circularity. However, strategies are needed to facilitate data transparency while protecting proprietary information. Such strategies could include the development of a data framework to guide establishment of data standards, auditable data protocols, and other data tools suited to the needs and integrity of the entire supply chain.

Information sharing also necessitates increased connectivity between stakeholders across the CE. This is necessary to understand different dimensions and recognize the diverse perspectives of various stakeholders. Communication channels must be enabled and supported that are participatory and inclusive.

4.4 Labeling

Much of the data necessary to drive circularity could come in the form of improved labeling on textile products. In the US, Customs and Border Protection (CBP) and the Federal Trade Commission (FTC) enforce labeling laws and acts which, in general, require that textile and apparel products sold in the in the country be labeled with the following information: fiber content, country of origin, manufacturer or dealer identity, and the care instructions [59, 60, 61]. Only fibers that comprise 5 % or more of a product need to be identified (<5 % should be disclosed as "other fibers") and nonfibrous materials such as plastic, glass, wood, paint, metal, or leather, do not have to be included on the label [62]. While states and localities are preempted from implementing tag and label laws, they can require disclaimers for things like recycled content and toxic substances [63].

Current labeling does not provide the data necessary to support decision making for appropriate reuse and recycling pathways. Despite fiber content requirements, more than 40 % of garment labels contain inaccurate fiber composition information [64]. Additionally, current labeling is designed for the consumer, not circular partners, and are often removed prior to reaching post-consumer stakeholders.

CHALLENGES & OPPORTUNITIES

Labeling Challenges

- Fiber composition on labels is often inaccurate
- Labels are designed for consumer, not circular partners
- Labels are often removed
- Only fibers that comprise 5 % or more of a product need to be identified
- Non-fibrous materials not required to be identified

Labeling Opportunities

- Digital product identification/product passport
- Transparency of materials and chemicals in products

Alternative labeling strategies are necessary to support and communicate textile traceability throughout the lifecycle of products. Such a strategy could include digital product identification (often called a digital passport) in which a garment is equipped with a permanent digital identifier such as a Quick Response (QR) code, Radio Frequency Identification (RFID) tag, watermark, or Near-field Communication (NFC) technology to allow access to data collected at each stage of the supply chain. Such identifiers could provide the necessary data to support reuse/recycling decision-making including brand identification, product characteristics (year, size, gender, style, etc.), and production information (fiber origin and composition, chemicals/additives/dyes, certifications). Naturally, such digital identification requires an online database to host the data. Efforts of this nature are already underway (e.g., [65, 66]) however they have not reached widespread application and have been criticized for their cost and network structure being prohibitive to resource-limited stakeholders. Future research is necessary to explore appropriate hardware options for the digital identifier, for instance to understand how they can endure wear and tear and how they impact the recycling process as well as standards and/or policy development to ensure accuracy through conformity assessment.

4.5 The Role of Brands

Brands have a significant role in facilitating a CE for textiles. This section discusses design strategies that brands can employ to drive circularity as well as alternative business models that can help to curb textile waste generation as well as support their bottom line.

4.5.1 Design

Brand designers have a significant influence on the circularity of textile products, including upstream innovations and fiber sourcing, manufacturing quality, as well as product durability and recyclability. However, in general, current design practices fail to consider the full lifecycle of products. Below are several design challenges and opportunities identified in the workshop:

CHALLENGES & OPPORTUNITIES

Design Challenges

- Contradiction between design for durability and design for recycling (DfR)
- Current design does not consider the full lifecycle of product
- How to include EoL procedures into design?

Design Opportunities

- Need to commit to purity (not mix fiber types)
- Increase demand for sustainable fiber types (e.g., organic, recycled)
- Need to design with the full lifecycle in mind
- Design for performance/fashion AND recyclability
- Increased communication and feedback loops
- Development of design guidelines to inform DfR

To support circularity, product design must integrate quality, durability, recyclability, as well as customer satisfaction. Design for recycling entails that products are ideally 100 % pure (not blended), contain only polymers, chemicals, additives, dyes, and finishes that do not contaminate the recycling system, and are easy to disassemble (e.g., removal of buttons, zippers). That said, these features are often what make garments (specifically outdoor apparel) durable and long-lasting. Improved data and decision tools would be useful to aid designers in prioritizing design characteristics. Similarly, design guidelines could help designers to incorporate DfR principles.

Increased communication between designers and the recovery industry is also necessary. This includes the need for feedback loops from recovery practitioners to designers with data pertaining to garment failure modes and recovery challenges and successes.

4.5.2 Alternative Business Models

Brands can also facilitate circularity by advancing new business models such as repair, resell, renting, or even the application of artificial intelligence (AI) and on-demand manufacturing to optimize production and avoid access. Eileen Fisher serves as an example of a brand that takes clothes back from customers (through mail or drop-off at warehouse) and sorts and cleans garments for direct resale, repair, or transformation into alternative textile products [67]. Patagonia provides a resale platform known as “Worn Wear” which allows customers to sell used gear. Alternatively, The Renewal Workshop works on behalf of brands to clean, sort, and repair damaged or returned items for resale either on brand-specific online platforms or shared marketplaces [68]. Ultimately, there is value in second-life applications for used textile products, and several ways brands can help keep their products in circulation while simultaneously supporting their bottom line.

Brand takeback and resale programs, together with the use of sustainable (e.g., recycled) textiles, could significantly influence consumer acceptance for reused/recycled products, a much-needed factor in transitioning to circularity. Takeback programs should be accessible to all customers and can include for example store drop-off or mail back. Brands can offer incentives for returning used garments, such as discounts, access to exclusive sets, or first opportunity at special products. With regards to retailing used or repaired items, terminology is key – terms such as 'pre-loved', 'pre-owned', 'pre-worn', 'vintage', 'retro', 'resewn', or 'recrafted' etc., may appeal to different customer-bases – and therefore understanding the customer is important. One challenge with takeback is ensuring that collected garments are appropriately processed through reuse, repair, and recycling channels.

4.6 End Market Development

Traditional recycling end markets include rag, shoddy, and mechanical fiber recycling while emerging recycling end markets include fiber-to-fiber (chemical) recycling. Traditional reuse markets are thrift, donation, and export while re-commerce and resale are emerging reuse markets. So, while there is a variety of end markets for textiles, they are at different stages of maturity and many of them are not domestic. As such, domestic market demand for circular materials needs to continue to grow. Below are several factors needed to support end market development identified in the workshop:

Needs for End Market Development

- Need downstream demand for feedstocks in combination with feedstock availability and quality
- Need brand uptake agreements that support a domestic recycler economy
- Need to rebuild domestic manufacturing
- Need to retrain consumers to appreciate the value in a product, away from reduced cost
- Need new business realities: Decrease in clothing purchasing, increase in sharing economy, e.g., swapping, leasing, renting

NEEDS

Reuse markets, such as resale and rental, offer significant value and promise. For example, the clothing rental sector is expected to reach $2.5 billion by 2023, while resale is expected to grow eleven times faster than the broader retail clothing sector by 2025 [58, 69]. But this growth necessitates increasing consumer awareness and acceptance of used textiles as well as systems and infrastructure to support the market. Additionally, brands and retailers must continue to commit to circular sources, and industry and brands need to participate in pilot projects, partnerships, and engagement with recyclers.

4.7 Standards and Certification Programs

Industry standards and certification programs can establish requirements and consistency for products, feedstocks, and processes. A selection of existing standards related to circular textiles is presented in Appendix C. Current standards generally support organic and sustainable production of natural fibers (e.g., cotton, wool, down), address social and environmental impacts of supply chains and manufacturing, and provide chain of custody verification tools of recycled content claims. Additional standards needs identified in the workshop include the following:

Standards Needed to Support Circular Textiles

- Product and performance standards: may include recycled content standards, minimum quality (e.g., laundry times), product certifications.
- Convenient collection standards
- Best practices for sustainable purchasing and maintenance of textiles
- Feedstock standards for chemical and mechanical recycling operations
- Guidelines to harmonize waste composition audits
- Testing standards for microplastic fiber pollution
- Environmental monitoring protocols to detect the successes and failures of societal changes

NEEDS

4.8 The Role of Policy/Regulation

The current linear model is highly incentivized for waste: it is less expensive to discard a textile product than it is to put it in a circular business model. Further, the current system taxes labor, which is generally the highest cost for a company, and not waste (i.e., taxes the desired input rather than undesired output). Currently, circularity is considered additive (e.g., takeback and resell is an added business strategy for brands) rather than a replacement to the existing model.

Many argue that a CE for textiles is not possible without policy and legislation to serve as a catalyst. Designed thoughtfully, policy and legislation can create a level playing field, unlock investment, incentivize textile recovery and infrastructure development, and ultimately encourage innovation and participation in recovery. Policy approaches need to be thoughtfully crafted to lessen creation with new resources, disincentivize waste, and instead drive efficiency and reuse of materials. That said, textiles policies need to avoid material monopolies, deterrence from reuse/repair, and unfair access [43]. Table 2 presents several policy approaches that can be implemented at the local, state, or federal level that can aide in facilitating a circular economy for textiles.

Table 2: Policy Approaches to Facilitate a Circular Economy for Textiles at the Local, State, and/or Federal Level (adapted from [17, 43, 70])

Policy Approach	Description
Partnerships:	With recovery stakeholders (incl. charities) and require reporting
Public Database:	Provide publicly accessible database of textile processors
Green purchasing:	Require public agencies to procure environmentally preferable products and include contracts with repair and recycling
Disclaimer laws:	Require disclaimers on products (e.g., recycled content)
Disposal bans & mandatory recycling:	Prohibit textiles from entering landfills/incineration; effective only when alternative collection and processing options are available and easily accessible
Extended Producer Responsibility (EPR):	Require brand owner to take financial and/or operational responsibility for EoL management of post-consumer textile waste with specified performance standards
Fees:	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)
PFAS and Microplastics:	Increased research on toxicity and source reduction
Development Incentives:	Encourage the domestic development of recovery infrastructure and supply chains through grants, low-interest loans, tax incentives, zoning allowances, etc.
Incentives for sustainable sourcing:	Reduce cost pressures and reward brands/retailers who implement sustainable sourcing, use sustainable materials, make fewer new products, manage repair programs, e.g., through favorable duty treatment, tax incentives, etc.
Product and performance standards:	May include recycled content standards, mandatory retailer takeback, product certifications, etc.
Remove subsides:	On virgin fossil fuels and cotton production
Labeling standards:	Include traceability of supply chain and provide data necessary for recovery/recycling
Preferential duty benefits:	Selective tariff rates to influence where products are made and with what materials

Outside of regulating landfills and waste-to-energy plants, the U.S. EPA does not currently have the regulatory authority to manage municipal solid waste (e.g., post-consumer material) as this is a state or local level responsibility. As a result, several states are currently introducing bills to manage textile waste, most focused on carpet stewardship programs (e.g., [71, 72, 73, 74, 75],) and one aiming to ban the disposal of textiles [76]. To date, however, California has the only fiber recovery law in the U.S.: a carpet stewardship program which passed in 2011 (see Appendix D for details). The disparate nature of State and Local initiatives may ultimately hinder the broad scale-up and distribution of recovery infrastructure. Rather, cohesive policy is needed that supports the timeline of scale-up and recovery capacities.

EPR is a comprehensive policy approach that extends a producer's financial and managerial responsibility for its products beyond the manufacturing stage – both upstream to product design and downstream to post-consumer reuse, recycling, or disposal [77]. In effect, this approach transitions away from taxpayers/governments funding recovery programs and internalizes these costs into the cost of manufacturing. To date, 33 U.S. states have passed 124 EPR laws covering 15 products, although to date no EPR laws cover textiles. Internationally, France currently has the only EPR law for textiles [78].

Recent European Union (EU) regulation includes the establishment of separate collection for textiles waste by January 1, 2025 [79]. Additionally, in 2022, the EU will introduce the Sustainable Textiles Strategy, laying the policy foundations aimed at making the EU textiles industry more sustainable. The strategy includes measures such as developing eco-design requirements, improving the business and regulatory environment for circular textiles in the EU, and boosting the sorting, reuse, and recycling of textiles with measures such as EPR [80]. These requirements will undoubtedly drive innovation and boost the competitiveness and resilience of the textiles industry in the EU and may influence the U.S. market as well.

4.9 Community Engagement, Education, & Outreach

Community engagement and education geared to all age ranges is critical to drive sustainable consumption and production of textiles and can take many forms. Below are several possible approaches to education and engagement activities identified in the workshop:

Engagement and Education Approaches to Support Textiles Circularity

EDUCATION

Industry Education

- Webinars and courses about transitioning from linear to circular business models
- Training programs to support repair, recycling workforce
- Certification programs in circular materials management

Academic Education

- Crafting classes/activities
- Lessons about material origin, characteristics, durability, and recyclability
- Link to textiles to climate change
- Lessons about consumer role in (un)sustainable consumption
- Lessons about recycling processes, role of design
- The social benefit of conscientious consumerism and donation

General Public Education/Services: Repair

- Do it yourself (DIY) education (e.g., fix-it classes)
- Repair Cafes
- Lending libraries of repair equipment (e.g., sewing machines)
- Knitting clubs, repair clubs

General Public Education/Services: Recycling

- Where and how to donate used textiles
- What textiles can and should be donated/recycled
- What happens to textiles once they are donated or recycled

Compelling outreach that drives engagement with consumers, brands, and communities is needed to drive textiles circularity. Repair skills should be introduced early in childhood education such as though crafting and home economics lessons. And sustainable consumption and production can be taught through cross-disciplinary activities throughout the education system. Outside of schools, DIY courses, clubs, and repair cafes can allow the general public to engage in circularity. Further, education campaigns can guide residents on where and how to donate used textiles, as well as what happens to textiles once they are donated or recycled. Controlled education and outreach campaigns can also help to address misconceptions about textile reuse and recycling, such as where donated clothing ends up or what can and should be donated. Such messaging needs to be clear, concise, and ongoing.

Education of workforces and training of experts in the field of CE is also critically needed. Educational program development should aim to strengthen and enhance the technical and practical skills of a workforce prepared to support the increased recovery and recycling of textile products. Academic programs could produce expertise tailored to the needs for circularity, including design strategies, technology innovation for collection, sortation, separation, and recycling, or business development to keep materials in the economy. Further, training programs should aim to promote the development of a skilled and distributed workforce focused on the growing field of circular materials.

4.10 Research Needs

Continued research is necessary to understand the current system and prioritize where and how advancements can be made. Specifically, economic assessment, waste composition studies, consumer behavior studies, and research and development (R&D) dedicated to fiber production and recovery systems are needed to facilitate a CE for textiles. Following are examples of information to be collected through research.

RESEARCH NEEDS

Economic Assessment

- Markets for collected materials
- Grades with highest value and easiest to collect
- Economic benefit for county/region to collect materials
- Feasibility (economically and practically) of textile MRFs
- Needed sorting capacity for a given region or waste-shed
- Local employment and economic impacts of the reuse/thrift industry
- Regions/states where organizations operate
- Cost of manual sorting and grading
- Distance textiles can be economically transported
- Equipment and technologies needed for accurate and cost-effective sorting
- Available market development support in a municipality or region

Waste Composition Studies

- Generator types: single-family vs. multi-family residential, retail, hospitality, healthcare, government (uniforms and prisons), post-industrial, thrift & donation
- Product types: clothing, household textiles, footwear, accessories, soft toys, etc.
- Fiber content: pure fiber vs. blend, prevalence of items that are multi-material or multi-layered
- Inclusion of finishes/chemicals
- Quality and condition

Consumer Behavior Studies

- Current consumption behaviors (e.g., how often, what, and from where textile products are purchased)
- Current usage behaviors (e.g., how often textiles are worn/used, how long are they kept)
- Current disposal behaviors (e.g., how often, how, and where textiles are discarded)
- Perspectives about reuse and thrift/charity (e.g., what, and how often people donate, how often people shop at charities/buy secondhand)
- Necessary motivators or drivers for behavior change

R&D for Production and Recovery

- Materials science advancements in textiles production for recovery (e.g., separation of blends, applications for degraded fibers, etc.)
- Rapid fiber identification and composition mechanisms (e.g., percentage of blends)
- Advancement of AI and robotics to identify, assess, and/or disassemble products
- Development of product and/or material traceability system (e.g., blockchain as distributed ledger for tracing material content and product life)
- Analytical methodologies for the assessment of recycled material composition
- Publicity of product materials/composition, while protecting Intellectual Property (IP)
- Analysis of purity tolerances for recycled feedstocks
- Elastane separation and recycling process development

Economic assessment is one such research endeavor needed to support domestic markets and align priorities for policy and infrastructure development. Specific research should be performed to assess the development of textile recovery and recycling infrastructure, including the potential for and role of regional textile sorting facilities (MRFs). Such facilities could aide in domestic processing of textiles and dramatically increase the volume of textiles sorted for reuse and recycling (and thus reducing both export and landfill/incineration), but it is yet unknown if they are economically and practically feasible. Assessment should include potential funding options, partners, operators, suitable end markets for sorted materials and grade specifications, potential commodity value relative to collection and processing expenses, as well as available for infrastructure development support by localities (e.g., low-interest loans, tax incentives, zoning allowances, etc.)

A need also exists for advanced and consistent waste composition audits to measure the volume of textiles that can be reused, repurposed, or recycled but are currently ending up in waste streams. Consumer behavior studies are necessary to collect qualitative data regarding behaviors and motivations around textile consumption, use, and disposal. This information can be used to direct information/outreach campaigns, design effective policy, and guide infrastructure development for collection.

Research and development must also be advanced on the technical aspects of sustainable textiles production and technological processes for textile sorting, separation, and recycling. In many cases, the transition from laboratory and bench-scale research to pilot projects and eventually commercialization is hindered by lack of investment. This is particularly the case for chemical recycling processes due to the low volume of materials collected for recycling which does not support significant investment. This situation is not justification for delayed research on recovery methods, but rather supports the need for government-funded R&D in the field. Government-funded R&D could enable private investment in sectors of the CE by providing the data and information necessary to alleviate market uncertainties and thus prompting the development and deployment of cost-efficient reuse and recycling processes.

5 Potential NIST Action Items

With sufficient resources, NIST could play an essential role in facilitating the transformation to a more circular textile economy. Based on the outcomes of the workshop, five key areas of NIST action items were identified: Data and databases, standards development, R&D, and education/outreach.

Convener

In general, NIST often can fosters collaboration towards common industry sector goals, such as circularity by serving as a convenor of industry, government, and non-profit organizations. Substantial efforts are already underway in multiple regions and sectors of the industry, and NIST could aide in ensuring these efforts are performed in collaboration and promote the exchange of knowledge and information. NIST continues to look for ways to bring stakeholders together to talk about approaches and strategies to support circularity.

Data and Databases

NIST could provide data repositories and registries following the FAIR data principles. All data infrastructures should be publicly accessible and interpretable by all stakeholders involved in the CE. Where data exists, NIST could aggregate or make it accessible through comprehensive data registries and repositories. NIST could also fill many of the data gaps identified in this workshop, including:

- Identification of fiber types and compositions, including possible reference data sets
- Public database of textile processors and collectors
- Feedstock availability and quality for recyclers
- Supply chain tracking/traceability

- Microplastics characteristics, emissions, and fate

Standards

NIST could support development of the standardization protocols and standards necessary to support consistency and reliability in the CE. Standards development requires verification methods which rely on extensive metrology and benchmarking, tasks NIST has vast experience performing. Examples of standards NIST could develop include the following:

- Product design standards
- Performance metrics for durable products
- Standard reference materials (SRMs) for the composition of recycled materials
- Best practices for sustainable purchasing and maintenance of textiles
- Feedstock standards for chemical and mechanical recycling operations
- Specifications for grades of reusable textiles for domestic end markets
- Guidelines for waste composition studies
- Testing standards for microplastic fiber pollution

R&D

NIST could support basic and applied research necessary to facilitate a CE. In particular, NIST could perform pre-competitive research that is too expensive or specialized for any one company to undertake, and, as such, can move the whole industry forward. Examples of R&D that NIST could perform, or support include:

- Economic assessment of domestic recovery and end markets
- Guidelines for purity tolerances for post-consumer recycling feedstocks
- Rapid fiber identification and composition assessment
- Publicity of product materials/composition, while protecting IP
- Identify, refine, and develop methodologies for the separation of blends and applications for degraded fibers
- Analytical methodologies for the assessment of recycled material composition
- Blockchain as distributed ledger for tracing material content
- Application of AI and robotics to identify, assess, and/or disassemble products
- Microplastic fiber detection and characterization
- Process development for elastane separation and recycling

Roadmap Development

A Circular Economy for Textiles Roadmap could provide a clear plan mapping out the timeline and path to transition to highly optimized sorting systems and materials circularity. Such a roadmap would identify opportunities across the value chain related to how waste can be minimized, and materials can be reused, repaired, or recycled. It can further identify new technologies, products, services, and industries needed for, or emerging from textiles circularity as well as stakeholder roles and necessary collaborations. The roadmap can also outline how textile waste will be tracked and measured, including how/where it is collected and how much of the collected volume is recycled versus discarded, and consider strategies to promote the reuse of the to-be discarded waste. The roadmap can outline the timeline of strategy implementation, including technology development and deployment, standards development, and policy design and enactment.

NIST could be a partner in supporting completion of a roadmap of this nature. For example, NIST's Office of Advanced Manufacturing (OAM) periodically releases funding opportunities for roadmap development, such as the Manufacturing USA Technology Roadmap Program [81]. This program in particular aims to establish new or strengthen existing (e.g., [82]) industry-driven consortia that address high-priority challenges and increase U.S. competitiveness and innovation in manufacturing. Roadmaps developed through programs such as this have the potential to influence significant future funding opportunities across the federal government.

Acknowledgements

We would like to share our appreciation for all the participants who not only contributed to the workshop discussion but also provided comments and feedback on this report. Additionally, we would like to thank the NIST Conference Services team for their assistance hosting the workshop.

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Appendix A: Workshop Agenda

NIST WORKSHOP ON FACILITATING A CIRCULAR ECONOMY FOR TEXTILES

Time (EDT)	Tuesday, Sept. 21	Wednesday, Sept. 22	Thursday, Sept. 23
10:00-10:45 am	Plenary 1: Current landscape, bottlenecks, and critical gaps	Plenary 2: Consumer challenges and opportunities	Plenary 3: Sustainable textile systems
10:45-12:15 pm	Session 1: Boundary-spanning tools to facilitate a CE for textiles	Session 3: Challenges to mechanical and chemical recycling of textiles	Session 5: Brand responsibility and best practices
12:15-12:45 pm	Break	Break	Break
12:45-2:00 pm	Session 2: Challenges with collection, reuse, and repair of textiles	Session 4: Environmental impacts of textiles	Session 6: Legal and regulatory barriers and opportunities
2:00-3:00 pm	Roundtable A: Data, standards, and terminology	Roundtable B: Reuse, repair, and recycling	Roundtable C: Policy approaches and needs

September 21-23, 2021 10:00 AM to 3:00 PM Eastern

Agenda at a glance

Appendix B. Workshop Speakers and Participants

SPEAKERS	
Name	**Organization**
Plenaries	
Marisa Adler	Resource Recycling Systems (RRS)
Marci Zaroff	ECOfashion Corp.
Kirsi Niinimäki	Aalto University
Session 1: Boundary-Spanning Tools to Facilitate a CE for Textiles	
Cyndi Rhoades	Worn Again Technologies
Shahana Althaf	Yale University
Traci Kinden	Revolve Waste
Tonny Colyn	Salvation Army Canada
Session 2: Challenges with Collection, Reuse, Repair of Textiles	
Jana Hawley	University of North Texas
Nicole Bassett	The Renewal Workshop
Jackie King	SMART (Secondary Materials and Recycled Textiles)
Scott Cynamon	Cyntex Co.
Session 3: Challenges to Mechanical and Chemical Recycling of Textiles	
Sonja Zak	Lenzing AG
Franco Rossi	Aquafil
Yong Li	Eastman Chemical Company
David Bender	Circular Polymers
Karla Magruder	Accelerating Circularity
Youjiang Wang	Georgia Institute of Technology
Session 4: Environmental Impact of Textiles	
Lars Mortensen	European Environment Agency
Kim Hiller	Kansas State University
Yuan Yao	Yale University
Jennifer Lynch	National Institute of Standards and Technology
Session 5: Brand Responsibility and Best Practices	

Rachel Kibbe	Circular Services Group
Natalie Banakis	Patagonia
Katja Beyer	Chemnitz University of Technology
Carmen Gama	Eileen Fisher
Julie Brown	EON
Session 6: Legal and Regulatory Barriers and Opportunities	
Eric Nelson	Circonomey Innovations
Scott Cassel	Product Stewardship Institute
Joanne Brasch	California Product Stewardship Council
Julie Hughes	US Fashion Industry Association

PARTICIPANTS

Name	Organization
Victor Adamian	INEOS
Marisa Adler	Resource Recycling Systems (RRS)
Shahana Althaf	Yale University
Meg Arnold	Los Angeles Cleantech Incubator (LACI)
Jess Atkinson	Product Stewardship Institute (PSI)
Christine Bakelaar	ECOfashion Corp.
Natalie Banakis	Patagonia
Nicole Bassett	The Renewal Workshop
Kate Beers	National Institute of Standards and Technology
P. Thathiana Benavides	Argonne National Laboratory
David Bender	Circular Polymers
Katja Beyer	Chemnitz University of Technology
Joanne Brasch	California Product Stewardship Council
Julie Brown	EON
Meriwether Bryant	US Environmental Protection Agency
Justine Burt	Manzanita Works

Scott Cassel	Product Stewardship Institute (PSI)
Tonny Colyn	The Salvation Army Canada & National Assoc Charitable Textile Recycling
Andrew E. Conn	National Institute of Standards and Technology
Rosemary Cubero	City of Los Angeles/ LA Sanitation
Rebecca Culler	Frederick County Government, Division of Solid Waste and Recycling
Anna Cummins	The 5 Gyres Institute
Scott Cynamon	Cyntex
Manish Dhiman	Unknown
John Dise	SproutGround
Lawrence Doppelt	US Environmental Protection Agency
Darlene Echeverria	North Carolina State University
Beth Eckl	Practice Greenhealth
Lisa Erdle	University of Toronto
Laura Espinal	National Institute of Standards and Technology
Rebekah Fadness	Natural Fiber Welding
Vincenzo Ferrero	National Institute of Standards and Technology
Spencer Fine	CalRecycle
Amanda Forster	National Institute of Standards and Technology
Sander Gaemers	Ineos
Carmen Gama	Eileen Fisher
Swarupa Ganguli	US Environmental Protection Agency
Shokoofeh Ghasemi	Natural Fiber Welding
Priscilla Halloran	US Environmental Protection Agency
Scott Hamlin	Looptworks
Natalie Hanson	US International Trade commission
Mary Harrelson	ECOfashion Corp.
Alice Hartley	Gap, Inc.
Jana Hawley	University of North Texas
Megan Helton	Eastman Chemical Company
Kim Hiller	Kansas State University

Elena Hogan	Ralph Lauren Corporation
Mark Hsu	LASAN
Julia Hughes	US Fashion Industry Association
Christine Marie Jasper	Ethical Patterns
Katie Jehenson	CreateMe
Iva Jestratijevic	University of North Texas
Orrin Jiang	Washington CORE
Nick Justice	Unknown
May Kassem	Scarabaeus Sacer
Rachel Kibbe	Circular Services Group
Taemin Kim	Argonne National Laboratory
Traci Kinden	Revolve Waste
Jackie King	Secondary Materials and Recycled Textiles (SMART)
Kat Knauer	National Renewable Energy Laboratory
Noah Last	National Institute of Standards and Technology
Karen K. Leonas	North Carolina State University/ Wilson College of Textiles
Yong Li	Eastman Chemical Company
Ron Li	CreateMe
Armando Lopez	National Metrology Center Mexico
Jennifer Lynch	National Institute of Standards and Technology
Gaston MacMillan	CreateMe
Karla Magruder	Accelerating Circularity
John D. Marts	National Institute of Standards and Technology
Nehika Mathur	National Institute of Standards and Technology
Alessio Miatto	Yale University
Kalman D. Migler	National Institute of Standards and Technology
Alexis Miller	Unknown
Liliana Morfin	Lenzing
Lars Mortensen	European Environment Agency
Eric Nelson	Circonomey Innovations
Shelly Nicholson	Dhana Inc.

Kirsi Niinimaki	Aalto University
Diana Ortiz-Montalvo	National Institute of Standards and Technology
Bob Peoples	Carpet America Recovery Effot (CARE)
Rachel Perlman	Independant consultant
Hope Pillsbury	US Environmental Protection Agency
Benjamin J. Place	National Institute of Standards and Technology
Rachel Raineri	North Carolina State University
Gwen Ramos	City of Los Angeles/ LA Sanitation
Raymond Randall	Waste Management
Leleh Rastegarzadeh	California State Water Board
Amy Rauen	Collective Intention
Barbara Reck	Yale University
Sara Reshamwala	ECOfashion Corp.
Maya Reslan	National Institute of Standards and Technology
Cyndi Rhoades	Worn Again Technologies
Shethir Riva	AMS
Alix Rodowa	National Institute of Standards and Technology
Franco Rossi	Aquafil USA
Kamalakanta Sahoo	USDA Forest Service Forest Products Laboratory
Rajlakshmi Sawant	Modern Meadow
Kristin Schillings	Green Zone Recycling
Kelsea A. Schumacher	National Institute of Standards and Technology
Lisa Sciannella	HELPSY
Jon Seppala	National Institute of Standards and Technology
Jeanine Sidran	StopWaste/ACWMA
Sharon Silbermann	Shamann Productions
Adrian Tan	King County
Zhe Tan	Modern Meadow
Tanya Torres	NOAA/NOS/OR&R
Nidia Trejo	Lawrence Livermore National Lab via North Wind
Rachel M. Trello	National Institute of Standards and Technology

Eric Wagner	Consultant
Micha Wallesen	Washington CORE
Youjiang Wang	Georgia Institute of Technology
Scott Welch	Loopt Foundation
Andre J. West	North Carolina State University Wilson College of Textile
Kate Wilkins	CalRecycle
Martijn Witteveen	Dibella
Katey Wolf	Cyntex
Hui Xu	Argonne National Lab
Yuan Yao	Yale University
Sonja Zak	Lenzing
Marci Zaroff	ECOfashion Corp.
Lena Ziegler	Looptworks

Appendix C. Existing Standards for Circular Textiles (Not Exhaustive)

Standard Name	Organization	Focus
Better Cotton Initiative	Better Cotton Initiative	Sustainable cotton production
Content Claim Standard	Textile Exchange	Chain of custody standard that provides companies with a tool to verify that one or more specific input materials are in a final product
Cradle to Cradle	Cradle to Cradle Products Innovation Institute	Sustainable and safe products
Fairtrade Textile Standard	Fairtrade	Social and environmental justice in supply chains
Global Organic Textile Standard	Global Standard GmbH	Production of all-natural fibers of organic status
Global Recycled Standard	Textile Exchange	Sets requirements for third-party certification of recycled input and chain of custody
Higg Index	Sustainable Apparel Coalition	Suite of sustainability self-assessment tools to assess the manufacturing, brand and product impacts of textile production
Organic Cotton Standard	Textile Exchange	Sets requirements for third-party certification of certified organic input and chain of custody
Recycled Claim Standard	Textile Exchange	Set requirements for third-party certification of recycled input and chain of custody
Responsible Alpaca Standard	Textile Exchange	Addresses the welfare of alpaca and the land they graze on
Responsible Down Standard	Textile Exchange	Aims to ensure that down and feathers come from animals that have not been subjected to any unnecessary harm
Responsible Mohair Standard	Textile Exchange	Addresses the welfare of goats and the land they graze on
Responsible Wool Standard	Textile Exchange	Addresses the welfare of sheep and the land they graze on

US Cotton Trust Protocol	US Cotton Trust Protocol	Sustainable cotton production

Appendix D. California's Carpet Stewardship Law

History:

CA AB 2398 passed in 2010 and was implemented in 2011 and has since been modified twice with new provisions. The bill represents the first carpet-specific product stewardship legislation ever passed and remains the only law in the world focused specifically on carpet. Clean-up legislation was passed in 2017 and 2019 to address program transparency and protect public fee money.

How the program works:

The program is funded by an assessment on new carpet sales paid by the consumers, which is currently $0.35/yd^2 or $0.04/ft^2 and scheduled to roll-out an eco-modulated fee system in April 2022. The budget is roughly $30M annually which goes to the Carpet America Recovery Effort (CARE), a third-party nonprofit carpet stewardship organization. Recyclers in the state are incentivized financially to grow, receiving per pound subsidies on recycled output, collections, and manufacturing. They are also eligible to receive capital grants for the expensive equipment required for processing.

Impacts:

Carpet recycling has significantly increased in California since 2011, especially when compared to the other 49 states (Figure C). In fact, very little collection or processing happens outside of the state [83]. At the close of 2020, a total of 168 full-time equivalent (FTE) jobs were attributed to the California Carpet Stewardship Program for collecting, hauling, and processing the covered materials [84].

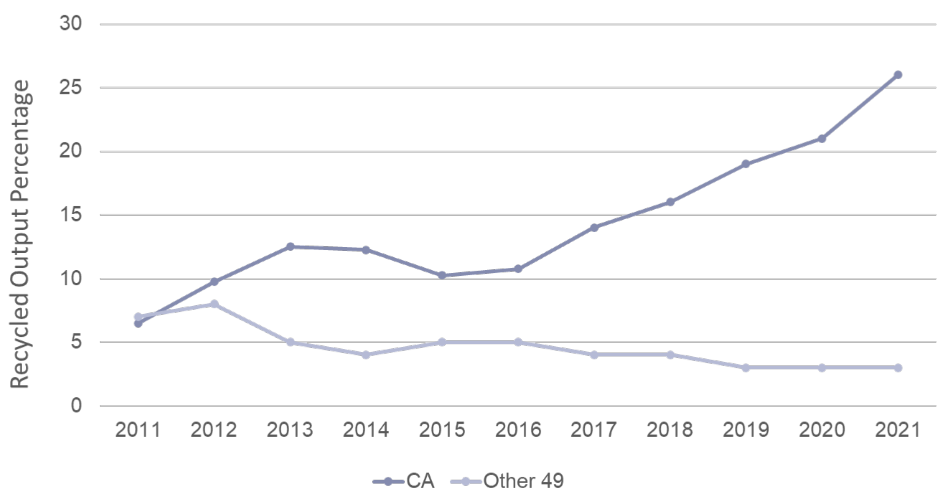

Figure C: Comparison of recycled carpet output between CA and other 49 US states [83]

Other States:

Other states have introduced carpet recycling bills, namely, to establish carpet stewardship programs, including New York (SB S5027A), Illinois (SB0345), Minnesota (SF 959), and Oregon (HB 3271). None have passed to date, although it appears some will be re-introduced in 2022 (e.g., [85]).

Opponents:

The major opponent to CA's carpet stewardship program, is the carpet manufacturing industry. New carpet sales in the state have declined year after year since 2013, a scenario the industry blames on the additional cost ($0.04/ft^2$). However, others argue that carpet sales have decreased across the country, not just in CA, due to shift in market share to alternative flooring materials [83].

Appendix E. Textiles Circular Economy Resources

Organization / Link	Resource
#sewtok	Textile upcycling videos
4Ocean	Retail company removing and recovering marine debris
Accelerating Circularity	Supporting the industry's transition by publishing reports on circularity, running trials, and developing tools.
Agraloop	Transforms leftover food crop into natural fiber
Ambercycle	Textile recycling company & operator
Bay State Textiles	Clothing Recycling for MA & CT
Block Texx	Regenerative (chemical) recycling for PET/cotton blends
British Columbia Product Stewardship Council (BCPSC)	Product Stewardship Organization
British Fashion Council's (BFC) Institute of Positive Fashion (IPF)	Circular Fashion Ecosystem (CFE): A Blueprint for the Future
Bureo	Recycling fishing nets into products
California Product Stewardship Council	California-based thought leader and expert on Product Stewardship and the Extended Producer Responsibility (EPR) movement
California Product Stewardship Council (CPSC)	Product Stewardship Organization
Carpet America Recovery Effort (CARE)	Non-profit organization working to advance carpet recycling
Carpet America Recovery Effort (CARE)	CARE California Carpet Stewardship Program: 2020 Report
Circ	Chemical recycler of textiles
Circular Polymers	Recycler of post-consumer carpet
Colorado Product Stewardship Council	Product Stewardship Organization
Connecticut Product Stewardship Council	Product Stewardship Organization
Council for Textile Recycling	Public awareness and engagement center for circular textiles
Cradle to Cradle	Innovation institute and certification program
Debrand	Clothing reverse logistics
Demeter	Owner of the "Biodynamic®" farm standard
Depop	Fashion marketplace app
Econyl	Regenerative Nylon
EON	Circular Product Data Protocol
EPR Club	Product Stewardship Organization
European Commission	Eurostat
European Recycling Industries' Confederation (EuRIC)	Handling & Sorting Specifications - For re-use and recycling of used textiles
European Recycling Industries' Confederation (EuRIC)	Best practice guide for textiles collectors and sorters
Evrnu	Recycler of pure cotton

EXPRA (Extended Producer Responsibility Alliance)	Product Stewardship Organization
FabScrap	Textile reuse and recycling service
Fair Trade Certified	Certification program for ethical production
Fashion Pass	Clothing Rental Subscription for Women
Fashion Revolution USA	Fashion activism movement
Fibershed	Non-profit organization developing equity-focused regional and land regenerating natural fiber and dye systems
Fibersort	Near Infrared Technology to categorize textiles
Finlayson	Recycling jeans into Terry towels
Flint Hills Farm to Fashion	Kansas State Research Group: Developing regional fiber, textile and clothing economy in the Great Plains
Florida: Informal Group Organized through NAHMMA Chapter	Product Stewardship Organization
GeoHay	Making erosion materials out of mixed fiber
Global Change Award - H&M	Change award to promote sustainable fashion
Global Fashion Exchange	Clothing Swap
Global Organic Textile Standard	Organic textile standard
Global Product Stewardship Council (Global PSC)	Product Stewardship Organization
GS1	Standards to create a common foundation for identifying, capturing, and sharing vital information about products, locations, assets and more
HELPSY	For-profit B Corp with an environmental mission to radically change the way people think about clothing recycling
HIGG	Sustainability Insights Platform
Ioncell	Closed loop chemical recycling
Jana Hawley, Kansas State University	Digging for Diamonds: A Conceptual Framework for Understanding Reclaimed Textile Products
Jana Hawley, Kansas State University	Textile recycling: A systems perspective
Kept sku	A shoppable recycling channel: curated mystery boxes of excess, returns, and slightly imperfect items
Lenzing	Post-consumer chemical recycling
Maine Product Stewardship Council	Product Stewardship Organization
Manhattan Solid Waste Advisory Board	Donate, Repair, Reuse Guide
Massachusetts Product Stewardship Council (MassPSC)	Product Stewardship Organization
Metawear	Turnkey sustainable apparel manufacturing
Midwest Product Stewardship Council (MPSC)	Product Stewardship Organization
Minnesota Product Stewardship Council	Product Stewardship Organization
National Association for Charitable Textile Recycling (NACTR)	Textile waste audit guideline
National Stewardship Action Council	Product Stewardship Organization

Nebraska Product Stewardship Initiative	Product Stewardship Organization
New York Product Stewardship Council	Product Stewardship Organization
New Zealand Product Stewardship Council	Product Stewardship Organization
NIST	Circular Economy Program
NIST	Circular Economy Registry
Northwest Product Stewardship Council	Product Stewardship Organization
Oeko-Tex Standard 100	Labels for textiles tested for harmful substances
Open Apparel Registry	Open Source Mapping Tool of Garment Facilities
Organic Trade Association	Promoting and protecting Organic with a unifying voice that serves and engages its diverse members from farm to marketplace
Parley for the Oceans	Space where creators, thinkers, and leaders come together to raise awareness for the oceans and collaborate on projects
Poshmark	Online consignment and thrift store
Product Stewardship Institute (PSI)	Product Stewardship Organization
Queen of Raw	Marketplace for unused fabrics
Recover Fiber	Mechanical recycler of textiles
Recurate	Full-service re-commerce partner
Recycling Council of British Columbia (RCBC)	Product Stewardship Organization
Redbag	Buy, sell, and exchange designer handbags, accessories, watches, and jewelry
Refibra	Recycler of pure cotton
Relooping Fashion	Cotton clothing recycler
Renewcell	Textile-to-textile recycling company based in Sweden
Rent the Runway	E-commerce platform for designer apparel rental and purchase
Repreve	Branded performance fiber made from recycled materials
RESET: Regenerate the Environment, Society, and Economy through Textiles	Farmer collective cultivating cotton using the principles of agroecology
Resource Recycling Systems (RRS)	"Textile Recovery in the U.S.: A Roadmap to Circularity" White paper
Reverse Resources	Software as a Service platform for global fashion brands and textile recyclers for steering and tracing textile waste from source to recycling
Revolve Waste	Specialists in mapping textile resources, matching waste to recycling technologies, and developing circular materials flows
Rhode Island Product Stewardship Council	Product Stewardship Organization
SimpleRecycling	Offering free curbside clothing collection and recycling
SMART (Secondary Materials and Recycled Textiles)	International association of wiping materials, used clothing, and fiber industries
SMART: Info on "Wiper Rule"	EPA Solvent Contaminated Industrial Wipes Rule (aka "Wiper Rule")

Stitch Fix	Online personal styling service
Suay Sew Shop	California-based sewing and production shop using post-consumer waste, deadstock and domestically, organically grown fibers
Sustainable Apparel Coalition	Higg Index: Suite of tools for the standardized measurement of value chain sustainability
Sustainable Apparel Coalition	The Higg Index
Texas Product Stewardship Council (TxPSC)	Product Stewardship Organization
TexRoad	Digital infrastructure for circular textiles
Textile Exchange	Recycled Claim Standard and Global Recycled Standard
Textile Exchange	Global nonprofit that creates leaders in the preferred fiber and materials industry
Textile Genesis	Traceability Platform
The Ocean Cleanup	Nonprofit engineering environmental organization based in the Netherlands
The RealReal	Online and brick-and-mortar marketplace for authenticated luxury consignment
The Renewal Workshop	Recovers discarded apparel for resell or recycling
ThredUp	Online consignment and thrift store
Tomra	Sensor-based recycling
TouchPoint	Offering sustainable workwear and closed-loop services for textiles
Tulerie	Peer to peer clothing rental community
Tyton	Regenerative (chemical) recycling for PET/cotton blends
Unspun	Robotics and digital apparel company
Upstream Policy Institute, Inc. (UPSTREAM)	Product Stewardship Organization
U.S. Department of Commerce, Office of Textiles and Apparel	Increasing the international competitiveness of the U.S. fiber, textile, apparel, footwear, and travel goods industries.
U.S. Environmental Protection Agency, Office of Resource Conservation and Recovery	Textiles: Material-Specific Data
Vermont Product Stewardship Council (VPSC)	Product Stewardship Organization
Vestiaire Collective	Luxury resale platform
Vigga	Children's wear leasing services from Denmark
Wardrobe	Apparel borrowing services
Wisconsin: Associated Recyclers of Wisconsin (AROW)	Product Stewardship Organization
Worn Again Technologies	Regenerative (chemical) recycling for PET/cotton blends
Worn Wear	Patagonia's resale platform