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Textiles in a circular economy: An assessment of the current landscape, challenges, and opportunities in the United States

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The production and consumption of textile products traditionally follows a largely linear (take, make, use, discard) economic model. Textiles are currently being produced in greater volumes than ever before, even after accounting for population growth, and unwanted products are discarded in mass quantities, most of which ends up in landfills or incinerated. This model causes serious social and environmental impacts and, thus, a transition to a more circular economic model – where materials and products are kept within the economy through reuse, repair, and recycling – is necessary. However, many challenges face a circular economy (CE) for textiles. Herein we discuss challenges and opportunities with the current textiles recovery system in the United States and outline activities and resources necessary to facilitate the transition to a CE in the U.S. Specifically, we describe the overarching need for collaboration, system harmonization, and data and information exchange. We further outline necessary actions in terms of standards development, labeling advancements, design characteristics, alternative business models for brands and retailers, end market development for recyclers, community engagement and educational programs, research and development, and the role of policy and regulation.

KEYWORDS

circular economy (CE), textiles, sustainability, recycling, circularity

Introduction

The traditional life of textile products has followed a largely linear path, where raw materials are extracted/harvested, manufactured, distributed, used, and then disposed, typically in either landfills or incinerators. Interest and momentum are growing for a transition to a circular economy (CE) to keep products and materials cycling within the economy and out of unwanted sinks (e.g., land, air, and water systems) (Ellen MacArthur Foundation, 2017; Piribauer and Bartl, 2019; Oregon State Legislature, 2021; European Commission, 2022). Unlike the linear economy, a circular economy aims to eliminate waste entirely by designing products that are durable, reusable, and repairable using materials that can be recovered and recycled at end-of-life (EoL) (NIST, 2022). As a result, public and private organizations at the national and global scale are urging increased circularity to address climate change, conserve limited natural resources, reduce pollution, and lessen supply chain disruptions (e.g., Ellen MacArthur Foundation, 2017; European Commission, 2018, 2022; United Nations, 2022).

The textiles' manufacturing industry is global and fragmented, and while collection for resale (e.g., thrift stores, donation bins) is practiced to some extent in the U.S., the majority of EoL textile products are discarded in landfills and burnt in incinerators (Adler, 2020; SMART, 2022). This represents a significant loss of material and economic value and causes acute social and environmental impacts. Progress is being made in the transition to a CE for textiles, but many challenges persist. Recent academic research has applied multi-modal methods to assess and prioritize challenges facing the circular textiles industry in Taiwan (Huang et al., 2021). Others have established a conceptual framework to tackle barriers to CE supply chains for textiles in select economies (Kazancoglu et al., 2020). Several other recent review articles (Jia et al., 2020; Bressanelli et al., 2022a) have applied thorough literature analysis, expert surveys, and convened panels of experts in an effort to identify the greatest challenges impacting circularity in the textiles industry, some at a regional level, and some more broadly.

The U.S. National Institute of Standards and Technology (NIST) has recently undertaken a research effort to identify the technical and economic barriers inhibiting a CE for textiles in the U.S., and methods of addressing those barriers domestically. The focus of this effort included extending beyond the literature to directly engage with stakeholders in the industry to identify these needs and potential next steps to address them. This paper begins with a background on textiles, their production and waste generation, and the social and environmental impacts associated with the current industry. We then discuss challenges and opportunities with the current recovery system, diving into the various practices (e.g., collection, sorting, grading, repair, and recycling) associated with textiles circularity as well as overarching aspects that influence circularity, for better or worse (e.g., economics and the direct relationship between plastics and textiles). NIST conducted a workshop to engage with this stakeholder community and better understand their needs (Schumacher and Forster, 2022). To the authors' knowledge this manuscript is the first comprehensive publication to evaluate the circularity of the textiles system in the U.S. based on insight from experts in the field to identify concrete steps that may facilitate a circular economy for textiles.

Textiles production and waste generation

Textiles introduction

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 then woven, knitted, matted, or otherwise bound together into fabrics (The Textile Museum, 2021). Fibers generally are categorized by their chemical origin, falling into two classifications: natural and manmade/manufactured/synthetic (Figure 1). Textiles can be 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* herein 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, and post-industrial textiles such as manufacturer clippings, overstock, deadstock, off-spec, and returns.

Growth of textiles production and fast fashion

Textile production has increased dramatically over the last two decades, reaching nearly 100 million metric tons (Mt) produced in 2020, nearly double that produced in 2000 and quadruple the production of 1970 (Niinimäki et al., 2020). While demand for cotton, wool, and cellulosics has remained fairly constant over the decades, demand for synthetics, especially polyester, has increased tremendously (Textile Exchange, 2021). It is estimated that today 60% of clothing and 70% of household textiles comprise synthetic fibers, and this trend is expected to increase into the future as consumers in emerging economies adopt Western lifestyles and attire (Niinimäki et al., 2020; Mortensen, 2021). Currently, 60% of global fiber produced is destined for the fashion industry, with the remainder used for interiors, industrial textiles, geotextiles, agrotextiles, and hygienic textiles, among other uses (Niinimäki et al., 2020).

The textile manufacturing sector is a complex industry due to its fragmented and heterogeneous nature that is dominated by small and medium enterprises (SMEs) (Hasanbeigi and Price, 2012). In the current linear model (Figure 2), the value chain of textiles is characterized by vertical disintegration and global dispersion of successive processes that span several industries including agriculture (natural fibers) and petrochemicals (synthetic fibers) as well

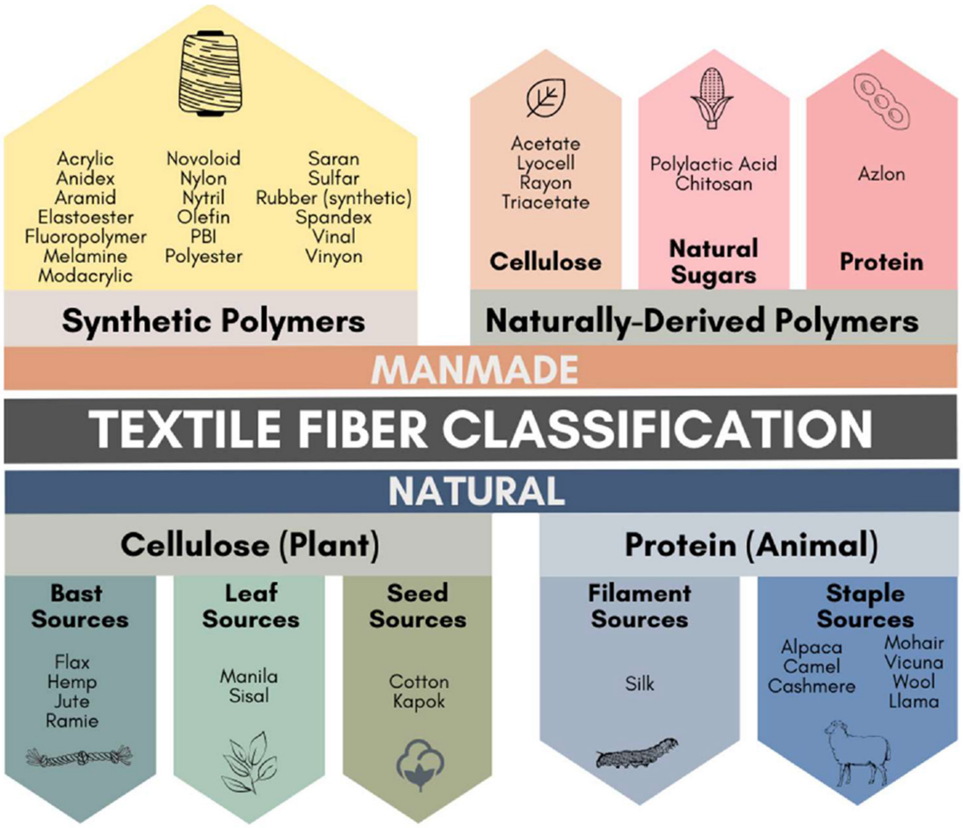

FIGURE 1
Classification by fiber type [as defined in Morton and Hearle (2001); Code of Federal Regulations (2022)].

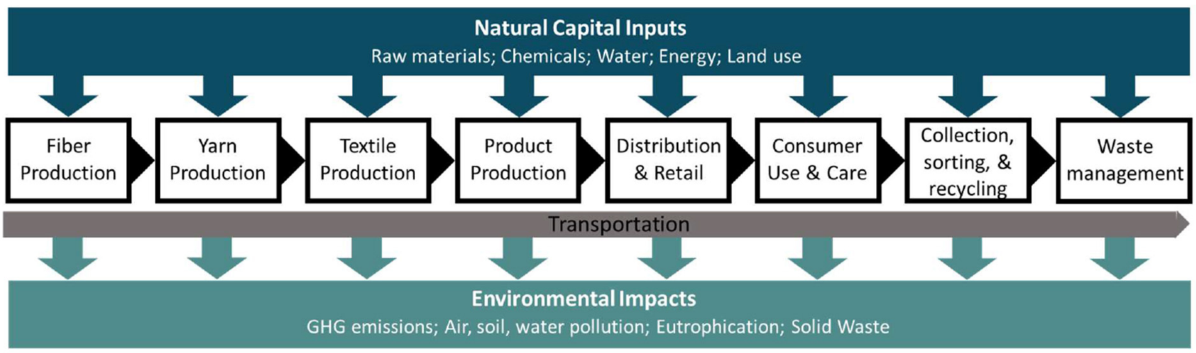

FIGURE 2
Current linear supply chain of textile products with associated natural capital inputs and environmental impacts [adapted from Niinimäki et al. (2020); European Environment Agency (2021)].

as manufacturing, distribution logistics, and retail (Niinimäki et al., 2020).

Growing production of textiles has aligned with a global shift of textile and garment production from developed 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 worth of textiles and $158.4 billion worth of apparel (Lu, 2021). Other major textile and garment producing countries include India, Turkey, South Korea, Bangladesh, Pakistan, and Vietnam (Bevilacqua et al., 2014; Niinimäki et al., 2020). Currently, more than 90% of apparel sold in the U.S. is imported from other countries (Yao, 2021). 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 geographical region with unique labor, economic, and environmental policies (Niinimäki et al., 2020). The textile and clothing industry is a major contributor to economies around the world and is estimated to be worth over $3 trillion and employs 300 million people, many of them women (Hiller, 2021; UN Alliance for Sustainable Fashion, 2021).

Fast fashion

The tremendous growth in textiles production, particularly since the mid-1990s, has been largely driven by 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 (Niinimäki, 2021). The term *fast fashion* 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: (1) rate of production, (2) number of fashion cycles, delivery, consumers' decision to purchase, and (3) rate at which garments are worn and disposed (Crumbie, 2021).

Social media has also been a driver of fast fashion, as higher visibility has increased the rate at which trends cycle. From a business model perspective, fast fashion has been exceptionally successful. However, it has caused negative social impacts on the workforce, and has resulted in a situation where cheap product prices lead to 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 durable or suitable for resale, repair, or repurposing into alternative textile products (e.g., wiping rags) (Niinimäki et al., 2020).

Textile waste generation

Textile waste sources include clothing and apparel, home and hospitality textiles, contract textiles, uniforms and workwear, and upholstery fabrics as well as manufacturer or retailer overstock, deadstock, off-spec, damages, and returns (Adler, 2021). Distinctions are made between *pre-consumer* (often referred to as post-industrial) waste, which is generated during the manufacturing process (i.e., before it reaches the consumer), and *post-consumer waste*, which is generated by the consumer after use (Federal Trade Commission, 2012). The former tends to be the cleanest and easiest stream to identify material compositions, while the latter represents the highest volume stream that includes blends of all fiber types and often contain contaminants (Wang, 2010; Johnson et al., 2020).

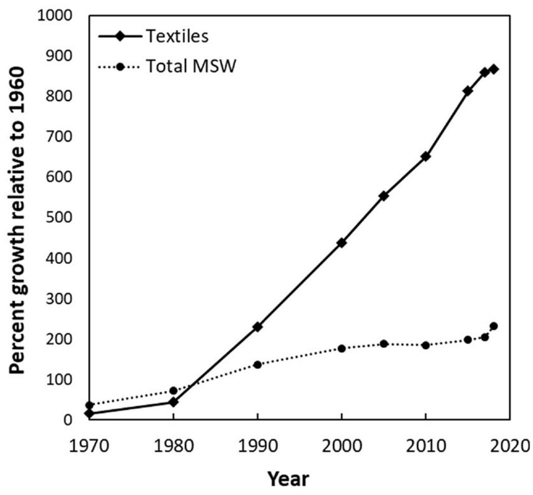

FIGURE 3
Percent change since 1960 of textile waste and total municipal solid waste (MSW) generation in the U.S., based on EPA data (US EPA, 2020; Code of Federal Regulations, 2022).

The rate of both pre- and post-consumer textile waste generation has increased significantly over the last several decades. Figure 3 presents the percent change since 1960 of post-consumer textile waste generation and total municipal solid waste (MSW) generation, per U.S. EPA data (US EPA, 2020). Textile waste generation increased 868 % during the reported timeframe while total MSW increased 232%. On a per capita basis, textile waste grew 55% between 2000 and 2018, indicating that the increased textile waste generation is not only due to population growth but also increased affluence (Adler, 2021). Each American discarded an average of 47 kg (104 lbs) of textiles in 2018. By comparison, the annual per capita discard rates in Finland and Sweden are 17 kg per capita and 24 kg per capita, respectively (Niinimäki, 2021). In 2018, textiles comprised 5.83% of the total municipal solid waste (MSW) stream generated in the U.S. (roughly 15.5 million metric tons) (US EPA, 2021a). It must be noted, however, that the U.S. EPA does not track or measure the volumes of textiles donated to non-profits or charities for reuse, which potentially comprises a large, unrepresented segment of the total volume of discarded textiles. Additionally, insufficient data exists to confidently measure pre-consumer 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 produced are discarded as waste during garment production (Magruder, 2022).

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 (King,

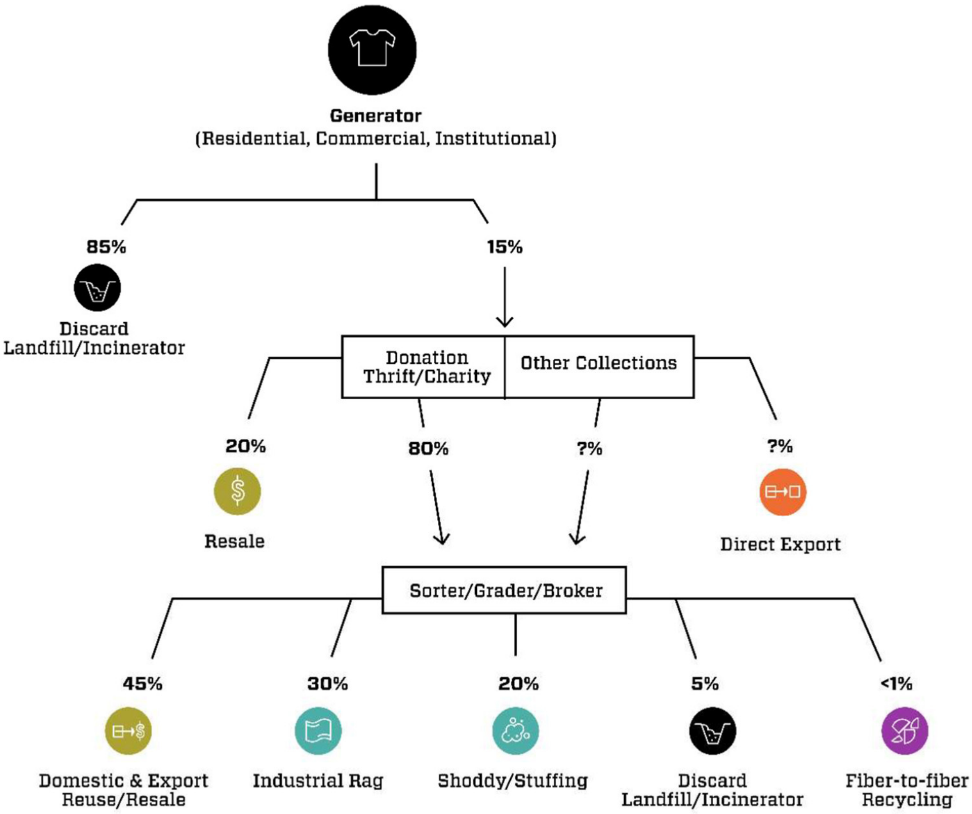

FIGURE 4
Current fate of used textiles in the United States. Question marks indicate flows for which reliable data are unavailable. Shoddy is made from shredded fibers and used for insulation and stuffing. Based on data from Adler (2021), US EPA (2021b), Magruder (2022).

2021; US EPA, 2021b). The volume recovered are collected either through donation to thrift stores and charities or collected through curbside collection programs and retail store takebacks (Figure 4) (Adler, 2020). It is estimated that thrift stores sell approximately 20% of textile donations, while the remainder are sold to sorters-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, down cycled to rags or stuffing, or sent for disposal (Adler, 2021; King, 2021). Industry experts claim that a significant amount of textiles are not sorted or graded before being exported and sold internationally (Magruder, 2022). Currently, less than 1% of textiles collected go to fiber-to-fiber recycling (Adler, 2021).

The cost of managing textile waste in the U.S. is significant. In 2020, it was estimated that textile collection and disposal cost Americans over $4 billion based on average disposal fees and collection costs (Adler, 2021). This cost will likely increase as transportation costs rise and available landfill capacity is reduced.

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 the benefits and detriments of importing used textiles are a subject of significant debate (Adler, 2021). Several countries in Eastern Africa have collectively banned the import of used textiles to protect their own domestic textile industries (United Nations, 2018).

Social and environmental impacts of the textiles industry

The textile industry is rife with negative social and environmental impacts due to the high usage of energy, water, and chemicals; the leakage of pollutants to environmental sinks; and the lack of sound and enforced environmental and social regulations in nations where production and manufacturing currently takes place. Figure 2 displays the resource inputs and resulting emissions along the textiles supply chain. Natural fibers, especially cotton, require large amounts of land, water, and agrochemicals for production. By comparison, synthetic fibers such as polyester and nylon rely heavily on petroleum feedstocks and therefore have high climate change impacts, but have low demand for land and mineral resources, and low toxicity during production. Ultimately, all textile materials have environmental impacts and shifting away from one to another may only serve to shift the environmental burden; therefore, efforts should focus on reducing the impacts of all fiber types.

The textile industry consists of many production and manufacturing facilities that together consume a significant amount of energy (Niinimäki et al., 2020). 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. Further, the global distribution of the textiles supply chain requires substantial transportation, which itself is a significant source of carbon emissions (European Environment Agency, 2021). Therefore, reducing GHG emissions associated with textiles production is necessary to address climate change.

Additionally, the textile industry is a major water consumer and source of water pollution. Quantifying the global water consumption used by the industry is challenging, and estimates range from 20 trillion liters (L) to 215 trillion L (World Bank, 2019; Niinimäki et al., 2020; Hiller, 2021; UN Alliance for Sustainable Fashion, 2021). Nearly all phases of the supply chain utilize water in some capacity, and water demand of textiles use, particularly for clothing, is high due to laundering. Furthermore, some areas 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 (Niinimäki et al., 2020; Hiller, 2021). The amount of water used in the textiles industry is expected to increase, which combined with population growth, will further stress water availability.

Chemicals are used or applied in nearly every stage of the textile supply chain. While agrochemicals are used on natural fiber crops, synthetic fiber production is a complex industrial chemical process with many petrochemical inputs. Textile manufacturing processes such as spinning and weaving utilize lubricants, accelerators, and solvents and wet processing of fabrics use chemicals such as bleaches, dyes, water, and stain repellents, among others (Niinimäki et al., 2020). Some of these chemicals can be harmful to the environment, factory workers and local communities, and consumers. For example, per- and polyfluoroalkyl substances (PFAS) are widely used synthetic chemicals that make clothing, carpets, and other products to impart water or stain repellent properties yet are of concern because of their persistence in the environment, solubility in groundwater, and potential adverse health effects (Peaslee et al., 2020; US EPA, 2021c).

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 U.S. and Europe, is then often used on agricultural soils, thus directly releasing the MPF to the environment (Cai et al., 2020). Furthermore, as discussed above, many low-income countries do not have modern wastewater treatment facilities and, thus, untreated wastewater is often directly discharged to waterways (WWAP, 2017). 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 EoL (i.e., in landfills) (Henry et al., 2019; Lynch, 2021). Discarded fishing nets, which are made of synthetic fibers, are also expected to be a significant source of MPF in the oceans (Lynch, 2021).

While any country producing textiles and textile products experiences negative social impacts, the globalization of the textile and fashion industry has resulted in the uneven distribution of environmental consequences. Low-income countries are 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.

Working conditions and labor rights should also be included in a discussion about the social impacts of the textiles industry. Undeniably, the textiles industry is a major source of employment, particularly for women. However, producing nations often lack occupational health and safety regulations, minimum wage requirements, or child labor restrictions, making labor justice an issue. The collapse of the Rana Plaza building in Dhaka, Bangladesh that housed five garment factories resulted in the death of over 1,100 people. The event has become a symbol of the working conditions of garment manufacturers and spurred movements to improve labor standards, although many still face resistance (Bair et al., 2020).

Transitioning to a CE for textiles has the potential to address many of these impacts and impart social and environmental benefits. Extending the life of products and recycling at EoL reduces the resource demands and emissions and pollution associated with the production of new garments. At present these environmental benefits are difficult to quantify, as they are process and location dependent and necessitate sufficient and reliable data and lifecycle assessments. Additional work is needed to measure these benefits. Textile circularity also has social benefits particularly through the donation of used products to charities for resale. The donation and resale ecosystem provides reliable jobs (often to marginalized populations), supports charities' fundraising efforts and social missions, and enables such organizations to extend the life and value of textiles (Schumacher and Forster, 2022). Additionally, textile repair and recycling industries have the potential to provide many job opportunities domestically and abroad.

Challenges and opportunities with the current textiles recovery 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. Furthermore, the complex market relationship between the plastics and textile industries, particularly with respect to the demand for recycled polyethylene terephthalate (PET), is also discussed.

Collection, sortation, and grading

Current textile collection generally includes thrift stores and charities, drop-off centers, curbside collection programs, donation bins, and retail store takeback programs. However, availability of these programs differs greatly across the U.S. As mentioned previously, only 15% of textile waste is currently recovered in the U.S., with 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. Further, products not sold through resale are sorted and graded for cascading uses and end markets (such as wiping materials, shoddy, fiber recycling). Specific challenges and opportunities facing textiles collection, sorting, and grading are identified in Table 1.

Widespread access to consistent collection services is essential to support downstream markets for used textiles. Textiles cannot be readily added to existing recycling services due to contamination and because municipal recycling facilities are not typically equipped to separate out textiles. Textiles could potentially be collected separately as part of waste/recycling collection services (e.g., in a separate container), but this comes with increased cost and logistics (Brasch, 2021). It is argued that if the downstream processes 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 damaging for local programs (Brasch, 2021).

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 million to $25 million to construct a recycling facility without knowing it can collect 34,000 to 45,000 metric tons (75 million to 100 million pounds) of textiles. Increasing collection to warrant this investment requires a combination of brands and retailer takeback programs, charity, for profit, and municipal collection programs as well as legislation to stimulate the investment needed to transition from a linear to circular economy.

TABLE 1 Challenges and opportunities for textiles collection (Schumacher and Forster, 2022).

Collection

Challenge	Opportunity
No established infrastructure for convenient, consistent, widespread, and reliable collection	Need significant evolutionary change, not incremental improvement
Current system is fragmented and *ad hoc*	Expanding collection on the scale necessary requires involvement and cooperation from brands and retailers as well as legislation
No harmonized textile collection rules or standards: materials must be clean, dry, and have no odor or hazardous chemicals to maintain value	Need harmonized collection rules with an emphasis on preserving the quality without contamination
High transportation costs	Consumers need to recognize the value of used textiles and know options and best practices for collection

Sorting/Grading

Challenge	Opportunity
Currently relies on manual labor, which is expensive	Development of high-speed automated sorting systems
Manual sorting cannot identify fiber composition	Advancements in sorting technologies, identification of fiber composition, and digital identification on products
Existing technologies are incapable of screening for current styles and trends or identifying rips, stains, or wear	Advancements in artificial intelligence (AI) algorithms to identify and automatically screen textile inputs
No harmonized sorting standards or criteria	Standards and best practices for sorting criteria
Lack of dedicated textile sorting facilities	Establishment of dedicated domestic sorting facilities

Currently, approximately 20% of collected textiles are reused through domestic resale (Figure 4) and some is directly exported and sold internationally (Adler, 2021; Magruder, 2022). Textiles not sent for resale are sorted and graded for alternative uses and markets. This involves the identification and categorization of textiles based on quality, condition, and format for sale in downstream markets (Adler, 2021). 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 (King, 2021). 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 (Barker, 2021). 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 (e.g., 80 to 95% purity) (Schumacher and Forster, 2022). As a result, many identification technologies on the market still require some level of human labor.

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 spectroscopy, artificial intelligence, and robotics; the former to identify fiber types and provide percentages of polymer/material compositions, and the latter two to separate the textiles based on desired categories (e.g., fiber composition, color, etc.). Efforts are underway in this regard (Fibersort, 2021) and necessitate the simultaneous expansion in collection of 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 (Adler, 2021).

Digital identifiers (IDs) such as Quick Response (QR) codes or Radio Frequency Identification (RFID) tags on textile products have the potential to increase the speed and efficiency of textile sorting. Rapid attribute identification such as fiber composition, chemical additives, etc., would greatly enhance the sorting-grading process. This topic is discussed in further detail in the Section Labeling.

Reuse and repair

Reuse of used textile products is the highest value approach when compared to alternative pathways (e.g., repurposing or recycling) and offers the lowest impact from an environmental standpoint (King, 2021). However, several challenges currently face reuse and repair industries, which are outlined in Table 2.

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

TABLE 2 Challenges and opportunities for textiles reuse and repair (Schumacher and Forster, 2022).

Challenge	Opportunity
Lagging consumer and industry acceptance that reuse is highest and best use for the environment	Education regarding garment care, reuse, and repair Education to support increased popularity and awareness of the benefits of reused/repaired products
General public lacks knowledge, tools, interest, or time to repair garments	Workshops or educational resources that help the general public learn basic garment repair skills
Disenfranchised repair industry	Programs aimed at assisting those employed in the repair industry
Materials must be clean and dry and have no odor or hazardous chemicals	Consumer education on best practices for donating and purchasing used products
People throw unwanted materials away and do not understand reuse capabilities	Build industry acceptance and support for resell and repair industries
Fast fashion clothing quality is inferior, not suitable for resell or conversion and appropriate only for lower uses, e.g., wiping rags	Consumer education on the true impact of fast fashion and lower quality goods and standards for quality and durability of textiles

The repair sector is integral to the circularity of textiles, forming partnerships and collaborations may take additional effort. Furthermore, large-scale, franchised garment 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 the relatively 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). Some brands have recently launched a repair service for consumers to send in damaged garments for repair and have reported significant consumer participation with this model (Feitelberg, 2018).

Recycling

Recycling is the next approach to retain value in textile products after reuse and repair. In general, textile recycling involves reprocessing post-industrial or post-consumer textiles into new products, but several classifications of textile recycling routes exist that require defining. The term *recycling* refers to the conversion of textile waste into something approximating the same value (e.g., recovery of fibers back into fibers), but is often also used as the catch-all for all forms of recovery pathways. *Upcycling* refers to turning discarded textile material into something of higher value (e.g., making new garments or products with materials from waste textiles). *Downcycling* is the turning of waste textile material into something of lower value such as rags. In *closed-loop recycling*, the material from a product is recycled and used in a similar or identical product, whereas in *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/or chemical processes that turn textile fabrics back into their fiber components to then be remanufactured into fabrics. Mechanical recycling processes generally include shredding waste textiles into small fractions, carding 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 (Johnson et al., 2020). Post-consumer waste results in lower-quality recycled fiber due to degradation during wear, therefore, only pre-consumer waste is typically recycled mechanically (Johnson et al., 2020).

Chemical recycling refers to the process of using chemical methods to disassemble textiles back to their basic chemical components. Most chemical recycling technologies are in the start-up research and development phase (between technology readiness levels 3 to 7) with only a few operating at scale (e.g., Aquafil Global, 2022; Lenzing, 2022). Chemical recycling approaches for synthetic, polymer-based textiles, typically include depolymerization to reclaim the monomer or oligomer constituents which can then be repolymerized and re-spun into new, virgin-like fibers (Wang, 2010). Natural or cellulosic fiber 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 (Johnson et al., 2020). 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 (MBA) will be required to trace recycled content through the process (Beers et al., 2022).

Table 3 presents challenges and opportunities facing the mechanical and chemical recycling of textiles. Recycling routes often consist of a combination of mechanical and chemical processes. For example, garments are first subjected to mechanical pretreatment to remove items such as zippers and buttons, then ground or shredded and, in some cases (e.g., carpet recycling), separation and debonding of components using mechanical methods (e.g., loop-clipping, density separation, centrifugation) is needed (Wang, 2010). In this regard, chemical recycling still requires pre-processing for most raw materials to meet input specifications and material handling requirements, which generally include mechanical processes.

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 or more fibers) 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 (Wang, 2022). 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 (Bender, 2021). Color-independent 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 have expressed a preference for comfort and stretch in their clothing, thus increasingly products 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 out and recycle elastane.

Currently, post-industrial (or pre-consumer) streams are the most successful for mechanical 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 that 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.

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, greater than bottle-to-bottle recycling. This is largely due to the more forgiving fiber

TABLE 3 Challenges and opportunities for textiles recycling (Schumacher and Forster, 2022).

Challenge	Chemical recycling	Mechanical recycling	Opportunity
Recycling economics require subsidization	•	•	Establishment of post-consumer textile supply chain and new economic prospects
No dedicated funding for scaling of recycling technologies	•	•	Development of domestic recycling options
Removal of dyes, additives, finishes	•	•	Advancements in separation of components and removal of buttons, zippers, etc.
Does not work well for blends	•	•	Advancements in separation of blended fibers
Degradation of fibers during processing		•	Advancements in recycling methodologies
Post-consumer textiles result in lower quality recycled fiber		•	Advancements in spun yarn technology to take advantage of shorter fiber lengths
High temperature, pressure, time, and cost requirements	•		Advancement in chemical recycling processes
Use or production of hazardous chemicals	•		Evaluation of alternative/greener chemicals for recycling
Requires pure, reliable, high-volume feedstock	•		Development of clear guidelines and input feedstock metrics
No processes for select, common fiber types	•		Development of methods to separate and process non-cellulosic/polyester content
Unknown energy consumption and overall environmental impacts	•		Quantification of environmental impact for chemical recycling

market and favorable cost structure compared to food-grade end markets (Adler, 2020). 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 would like that to increase to 45% by 2025 (Textile Exchange, 2022). However, as more food and beverage brands commit to 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 holistically to ensure adequate supply for all end uses and selection of the most efficient circular pathway for all materials.

Economics and globalization

Circularity for textiles 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 due to fast fashion. Similarly, the cost to collect and recycle textiles exceeds the price that end users are willing to pay for the product. Often, consumers are unwilling to pay "the circular premium", that is, the difference in price for a circular product (e.g., made from bio-based or recycled materials) than a traditionally manufactured product (D'Adamo and Lupi, 2021). Even if the U.S. were to expand collection systems, processing systems, and market demand, the economics do not currently support the business model (Bender, 2022). 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 might allow for a funding mechanism that supports circular business models through options such as eco-modulated fees, which are varying levels of fees on virgin raw materials and products that do not meet different thresholds of minimum recycled content criteria, that could drive design for recyclability. Consumer-driven initiatives, such as sustainable fashion driven by pop culture and social media could also influence the economics of textiles circularity.

The globalization of the textiles industry has resulted in the shift of garment production from developed countries in the West to developing countries, primarily in southeast Asia. While this shift has complicated supply chain logistics and transparency therein, it may also be viewed as an opportunity to revitalize former textile industrial districts in the West to expand CE practices. As experienced in the industrial district of Prato, Italy, historically a center for textile production of international relevance, has become recognized for its reorganization and revitalization with a focus on circular textiles, primarily the recovery and recycling of woolen products (Bressanelli et al., 2022a,b). Similar opportunities for enhanced circularity have also been identified other geographic regions (Kazancoglu et al., 2020; Huang et al., 2021). In this sense, the traditional labor market, supply chain structure and relationships, and political environment can be utilized and adapted to support the transition of industrial districts to a CE.

The challenges described above closely align with those identified in several recent research reviews. Bressanelli et al. (2022a) discerned design, legislation, and labor competences as key challenges preventing a CE for the textile industry in Prato, Italy. Kazancoglu et al. (2020) recognized the primary challenges facing circularity were management and decision-making (the business decision to pursue circularity), high labor intensity (e.g., for collection, sorting, and repair of textiles), design challenges, materials (the inclusion of non-recyclable materials, chemicals, and additives in textiles), rules and regulation, knowledge and awareness of circularity, integration and collaboration, cost, and technical infrastructure. Jia et al. (2020) described organization barriers, meaning those related to a particular company's policies, such as internal support for circularity, metrics for performance, access to resources such as training for employees, and adequate strategic planning. Next, they discussed financial barriers, given that cost is a major obstacle to adopting new practices, and finally they named policy barriers, such as a lack of regulations and laws surrounding sustainable practices that extend beyond waste management and consider the full value chain for textiles. Similar barriers were also explored by Huang et al. (2021) who found governmental and regulatory issues, economic and financial issues, technological issues, societal issues, organizational and managerial issues, and infrastructural, supply chain, and market issues, many of which were also identified by the other reviews and discussed herein. This indicates that there is general consensus amongst the community regarding the biggest challenges facing a CE for textiles and the next section will discuss some methods to address them.

Steps to a circular economy for textiles

Addressing the challenges and fostering the opportunities identified above necessitates several actions. Collaboration across the textiles value chain can support system harmonization and the collection and exchange of data and information, which are all necessary for circularity. The following section explains each of these steps in greater detail. Note that all the steps discussed below are deemed necessary to realize a circular economy for textiles and thus are not presented in any prioritized order.

Collaboration

Transitioning to a circular economy for textiles requires an uncommon amount of cross-sectoral collaboration. Increased communications between stakeholders throughout the value chain and reverse logistics are necessary to understanding the many different dimensions of the issue and recognizing and serving the diverse perspectives and needs of various stakeholders. Innovative strategic partnerships including public-private partnerships can be 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 that are participatory and inclusive. Collaborations must include the stakeholders depicted in Figure 5.

Several challenges face this collaboration, particularly for select stakeholder groups. Some stakeholders are unable to participate in external events such as virtual meetings or workshops 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 to connect with these stakeholders. For example, doing personal outreach, lessening restrictions, or providing access and translation services.

Harmonizing communications and systems

There is a significant need to harmonize many aspects of the textiles system including identifying and agreeing upon aspects such as a common language, definitions, classifications, industry tools, and standards. For example, the very definition of textiles, as well as what products are included is not well established. 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 (OECD, 2020). Similarly, agreement is needed on concepts such as biodegradable and bio-based polymers. Agreement is also needed regarding whether contamination includes chemicals introduced by design, stains and residue resulting from product use, or both. Classifications for waste audit studies must also be harmonized to enable comparisons and compilation.

Standards related to a circular economy for textiles are emerging at various levels around the world (e.g., Global Standard GmbH, 2021; ISO, 2022; Textile Exchange, 2022). Harmonization of these standards at the international level is needed to promote interoperability and facilitate trade for businesses with circular modes of operations (OECD, 2020).

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

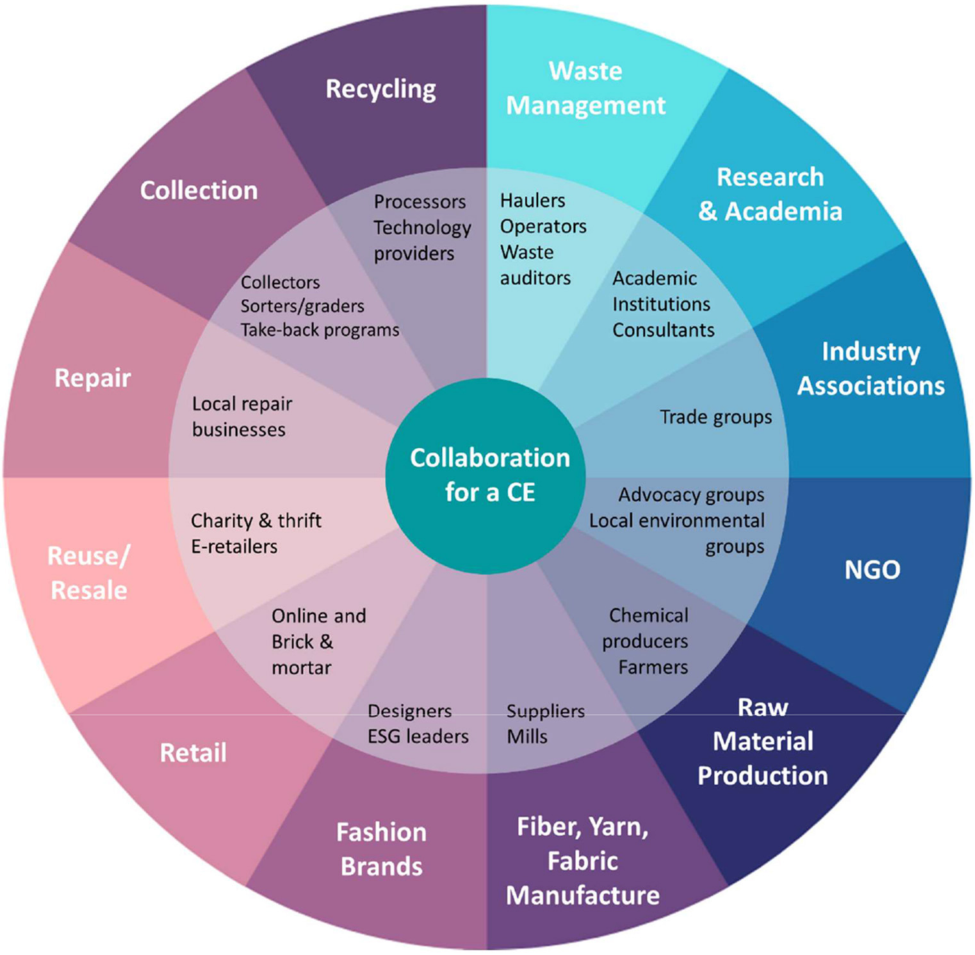

FIGURE 5
Connections and collaborations needed between stakeholders to facilitate a CE for textiles.

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 more consistency 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.

FAIR data and information exchange

Significant data gaps currently inhibit the advancement of many CE efforts. Without quality and available data, it is not possible to reduce the industry's environmental footprint, design effective policy, or drive social change.

Acquiring or collecting 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. Further, 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 4 identifies some of the specific data needed to facilitate a CE.

A need exists for a unified infrastructure 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

TABLE 4 Data needs to facilitate a CE for textiles.

Level	Data needs
Material	- 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	- 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	- 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	- 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

Principles of Findability, Accessibility, Interoperability, and Reusability to ensure effective data discovery and application (Wilkinson et al., 2016). 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 (Zaroff, 2021). 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 between 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.

Labeling

Much of the data necessary to drive circularity could come in the form of improved labeling on textile products. In the U.S., 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 U.S. be labeled with the following information: fiber content, country of origin, manufacturer or dealer identity, and the care instructions (FTC, 2021, 2000; Office of Textiles and Apparel, 2021). Only fibers that comprise 5% or more of a product need to be identified ($<$ 5% should be disclosed as "other fibers") and non-fibrous materials such as plastic, glass, wood, paint, metal, or leather, do not have to be included on the label (FTC, 2014). While states and localities are preempted from implementing tag and label laws, they can require disclaimers for things like recycled content and toxic substances (Benson and Reczek, 2016).

Table 5 outlines challenges facing labeling for circularity and opportunities for improvement. 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 (Circle Economy, 2020). Additionally, current labeling is designed for the consumer, not circular partners, and are often removed prior to reaching post-consumer stakeholders.

Alternative labeling strategies are necessary to support and communicate textile traceability throughout the lifecycle of products. Such a strategy could include, for examples, digital product identification (often called a digital passport) in which a garment is equipped with a permanent digital identifier such as a QR code, 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, style, etc.), and production information (fiber origin and composition,

TABLE 5 Challenges and opportunities for labeling of textile products for circularity.

Challenge	Opportunity
Fiber composition on labels is often inaccurate	Enhanced transparency of materials and chemicals in products
Labels are designed for consumer, not circular partners	Advancements in digital product identification/product traceability
Labels are often removed	Advancements in permanent label technologies
Only fibers that comprise 5% or more of a product need to be identified	Revised standards for product labeling
Non-fibrous materials not required to be identified	Revise guidelines to include identification of non-fibrous materials

chemicals/additives/dyes, certifications). Naturally, such digital identification requires an online database to host the data. Nascent efforts of this nature are already underway (EON, 2021; TextileGenesis, 2021), however, they have been criticized for their cost and network structure as 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. In addition, standards and policy development is needed to ensure accuracy and verifiability of the identifier information through conformity assessment.

The role of fashion brands

Fashion and textile brands have a significant role in facilitating a CE for textiles. While many brands are taking steps to increase the circularity of their products through design for circularity, use of recycled materials, and zero waste production [see Moorhouse and Moorhouse (2017) for examples], these practices are not the mainstream and thus significant room for improvement remains. 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 and support their bottom line.

Design

Fashion brand designers have a significant influence on the circularity of textile products, including upstream innovations and fiber sourcing, manufacturing processes and quality, as well as product durability and recyclability. However, in general, current design practices fail to consider the full lifecycle of products. Table 6 presents several circular design challenges and opportunities.

TABLE 6 Challenges and opportunities for circular design.

Challenge	Opportunity
Contradiction between design for durability and design for recycling (DfR)	Improved design guidelines for performance/fashion AND recyclability
Current design does not consider the full lifecycle of product	Guidelines to consider designing with the full lifecycle in mind
Inclusion of EoL procedures into design	Increase demand for sustainable fiber types (e.g., organic, recycled) and pure fiber compositions (not blends)
No existing mechanisms to facilitate communication between designers and the recovery industry to understand full life cycle of product	Increased mechanisms for communication and feedback loops across the life cycle chain
The production and use of popular textile materials are a major source of environmental pollution and GHG emissions	Innovative material design that is regenerative, sustainable, non-toxic/polluting, and recyclable

To support circularity, product design must balance the needs of quality, durability, and recyclability, with customer demand and cost. Design-for-recycling (DfR) 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. Currently, the knowledge of sorters, graders, dismantlers, and recyclers is not codified to be used by designers for the re-design of products. As such, a need exists for practical guidelines to formalize information sharing between EoL service providers and designers. This necessitates agreed upon terminology, metrics, evaluations, and information sharing mechanisms.

Additionally, the design of textile materials themselves needs to be more sustainable and circular. As mentioned previously, modern textile materials are increasingly synthetic in nature, which causes significant environmental impact during production and use and can be difficult to recycle at EoL. The use of biomaterials and bioengineered polymers specifically is one area that has seen increased interest to address some of these challenges (e.g., Schiros et al., 2021), but materials engineers and designers must consider the lifecycle impacts of materials including compatibility with recycling infrastructure.

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 excess. Some brands have initiated garment take-back programs (through mail-in or drop-off programs) in which they may sort and clean garments for direct resale, repair, or transformation into alternative textile products (e.g., Gama, 2021; Patagonia, 2022). Alternatively, some organizations (e.g., The Renewal Workshop, 2022) work on behalf of brands to clean, sort, and repair damaged or returned items for resale either on brand-specific online platforms or shared marketplaces. Ultimately, there is value in reuse 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 store drop-off or mail back. Brands can offer incentives for returning used garments, such as discounts, access to exclusive sets, or priority for the launch of special products. One challenge with takeback is ensuring that collected garments are appropriately processed through reuse, repair, and recycling channels.

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 end markets are thrift, donation, and export while re-commerce and resale are emerging reuse end markets. So, while there is a variety of end markets for textiles, they are at different stages of maturity. Further, most of these markets are distributed globally and the transport costs can be prohibitive. Thus, efforts are needed to identify and advance more opportunities for local markets.

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 (ThredUp, 2021; Zaroff, 2021). 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.

TABLE 7 Standards needs to facilitate a CE for textiles.

Life cycle phase	Standards needs
Design	- Product and Performance: e.g., recycled content standards, minimum quality or performance (e.g., fabric strength, resistance to abrasion, resistance to wear, and laundering), product certifications
Consumption and use	- Best practices for sustainable purchasing and maintenance (such as laundering practices to reduce or capture microfibers) of textiles
EoL	- Convenient collection standards - Feedstock standards for chemical and mechanical recycling operations - Guidelines to harmonize waste composition audits
Environmental monitoring	- Testing standards for microfiber pollution in waterways - Test methods for identification of microfiber-borne pollution, such as dyes or additives in water supplies - Environmental monitoring protocols to detect the successes and failures of societal changes

Standards and certification programs

Industry standards, specifications, and certification programs can establish requirements and consistency for products, feedstocks, and processes. 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 needed are outlined in Table 7.

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 redirect it toward 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, promote investment, incentivize textile recovery and infrastructure development, and ultimately encourage innovation and participation in recovery. Policy approaches need to be carefully 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 (Brasch, 2021). Table 8 presents several policy approaches that can be implemented at the local, state, and/or federal level that can aide in facilitating a circular economy for textiles.

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 responsibility is left to the state or municipality. As a result, several states are currently introducing bills to manage textile waste, most focused on carpet stewardship programs (e.g., Illinois General Assembly, 2021; Minnesota Legislature, 2021; Minnesota House of Representatives, 2021; Oregon State Legislature, 2021; The New York State Senate, 2021) and one state aiming to ban the disposal of textiles (MassDEP, 2021). To date, however, California has the only fiber recovery law in the U.S.: a carpet stewardship program which passed in 2011. 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 (Cassel, 2021). 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, however no EPR laws cover textiles. Internationally, France currently has the only EPR law for textiles (Légifrance, 2007).

Recent European Union (EU) regulation includes the establishment of separate collection for textiles waste by January 1, 2025 (European Commission, 2018). 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 (Šajn, 2021). 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.

TABLE 8 Policy approaches to facilitate a circular economy for textiles at the local, state, and/or federal level [adapted from Adler (2021), Brasch (2021), Hughes (2021)].

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 and 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 subsidies	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

Community engagement, education, and 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. Table 9 provides several possible approaches to education and engagement activities that can help facilitate a CE.

TABLE 9 Engagement and education approaches to support textiles circularity.

Audience	Education needs
Industry	- 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	- Lessons about material origin, characteristics, durability, and recyclability - Link textiles to climate change - Lessons about consumer role in (un)sustainable consumption - Lessons about recycling processes, role of design - Social benefit of conscientious consumerism and donation
General Public - Repair	- Do it yourself (DIY) education (e.g., repair, simple tailoring classes) - Repair Cafes - Lending libraries of repair equipment (e.g., sewing machines) - Knitting clubs, repair clubs
General Public - 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 - Support for clothing exchanges or swaps to promote reuse

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 through crafting and home economics lessons. Sustainable consumption and production can be taught through cross-disciplinary activities throughout the education system. DIY courses, clubs, and repair cafes can allow the general public to engage in circularity. Further, consumer 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 what happens to donated clothes 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

TABLE 10 Research areas and associated data/information to be collected.

Research area	Date/information needed
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 audits	- Generator types: single-family vs. multi-family residential, retail, hospitality, healthcare, government (uniforms and prisons), post-industrial, thrift and 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
Technical R and D	- 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

innovation for collection, sorting, 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.

Research needs

Continued research is necessary to understand the current system and prioritize where and how advancements can be made. As displayed in Table 10, needed fields of research span from broader economic assessments and system-wide waste generation and social behavior studies to technical research and development.

Economic assessment is also necessary to evaluate the development of textile recovery and recycling infrastructure, including the feasibility 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 reduce both export and landfill/incineration. But it is yet unknown if they are economically and practically feasible. Assessment should include partners, operators, suitable end markets for sorted materials, grade specifications, potential commodity value relative to collection and processing expenses, as well as potential public and private funding support for infrastructure development (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. Table 10 provides data that should be included in textile waste audits.

Consumer behavior studies are also 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 research and development (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.

Conclusions

A transition to a CE for textiles will support economic growth, provide reliable jobs, as well as reduce the environmental impact of textiles and associated products. However, many challenges persist that must be addressed to facilitate textiles circularity in the United States. We discussed many of the technological, economic, and social barriers to a CE for textiles and identified specific data, tools, standards, R&D, and educational approaches to address them. This works reveals the need for harmonization of terminology, classifications, industry tools, and standards to unify approaches, increase interoperability of tools and resources, and promote broad adoption of CE strategies. Further, none of the opportunities identified can be pursued in isolation. Many factors, including economic, social, and environmental influence the motivation to shift toward a CE, and therefore moving toward circularity necessitates broad, multidisciplinary, multi-stakeholder collaboration. Through this cooperation, we can reach an optimized CE that depends on reciprocity, trust, transparency, and cooperation between all players.

Author contributions

KS wrote the first draft. AF revised and edited the draft. KS and AF were involved in the writing of this paper. Both authors approved the final version of the paper.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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