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Fundamental Challenges and Opportunities for Textile Circularity

Kedron Thomas [1,*], Hira Durrani [2], Julia Brady [1], Kendall Ludwig [3], Michelle Yatvitskiy [3], Abigail R. Clarke-Sather [2], Huantian Cao [3] and Kelly Cobb [3]

[1] Department of Anthropology, University of Delaware, Newark, DE 19716, USA; julbrady@udel.edu
[2] Department of Mechanical and Industrial Engineering, University of Minnesota Duluth, Duluth, MN 55812, USA; durra027@d.umn.edu (H.D.); abbie@d.umn.edu (A.R.C.-S.)
[3] Department of Fashion and Apparel Studies, University of Delaware, Newark, DE 19716, USA; kludwig@udel.edu (K.L.); mayatv@udel.edu (M.Y.); hcao@udel.edu (H.C.); kcobb@udel.edu (K.C.)
* Correspondence: kedron@udel.edu

Abstract: The negative environmental impacts of the current linear system of textile and apparel production are well-documented and require urgent action. The sector lacks an effective recycling system, resulting in massive waste and environmental pollution. This paper presents the results of qualitative research involving textile and apparel industry stakeholders, including representatives from brands and retailers, waste collectors, recyclers, non-profit organizations, academic institutions, and government agencies. Our research focused on stakeholder perceptions of the significance and importance of textile circularity, the challenges that exist for transitioning the textile and apparel industry from a linear system to a circular economy (CE), and resources that exist to support this transition. The results of this study call attention to the following urgent requirements: a consistent definition of CE to promote transparency and accountability and prevent greenwashing; improved systems for materials identification, sorting, and pre-processing of post-consumer textile waste to enable recycling; innovations in mechanical recycling technologies to maintain the value of recycled materials; and new, materials-driven approaches to design and manufacturing that are responsive to feedstock variability and diverse consumer needs. The research findings also suggest the need for flexible, regional CEs that are rooted in community partnerships.

Keywords: circular economy; sustainability; post-consumer waste; apparel; mechanical recycling

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1. Introduction

The textile and apparel industry is a massive, global economic sector, encompassing multiple stages of sourcing and manufacturing from fiber and yarn production to dyeing, printing, cutting, sewing, and quality control [1]. The industry largely follows a "take-make-waste" model, in which materials are used for a limited time before being discarded. This linear approach has negative environmental and economic impacts as it involves resource depletion and generates large amounts of waste [2]. Globally, at least 88.9 million tonnes of textile waste are produced every year, the vast majority of which ends up in landfills or incinerators [3]. Textile waste and clothing underutilization results in USD 500 billion in estimated lost value annually [4]. In spite of growing public concern, the industry shows no signs of slowing production. On the contrary, global per-capita textile production increased from 5.9 kg in 1975 to 13 kg in 2018 [5]. Consumers now purchase an estimated 61.7 million tonnes of apparel annually, and this number is projected to reach 101.6 million tonnes by 2030 [5].

The need for systemic change is urgent. The Intergovernmental Panel on Climate Change insists that societies in the Global North must fundamentally transform the way clothing is produced and consumed within the next decade [6]. The term "circular economy" (CE) has been used widely by sustainability scholars and business professionals to denote

an industrial system in which the life cycle of a product and its constituent materials are extended beyond the context of initial intended use [7]. Scholars and designers advocate for a circular economic model for fashion that consistently maintains the utility and value of fibers and other materials involved in clothing production and consumption [8]. This can occur through the reuse of textiles and apparel, the repair of clothing items, or the recycling of discarded textiles. These processes have the potential to maintain or restore the functionality of the product over multiple life cycles.

A recent meta-analysis suggests that a major impediment to advancing CE in many sectors is the lack of information sharing across stakeholders [9]. Information sharing is considered an important driver of circularity because "sufficient access to information about the product and operation of other actors is necessary to keep products and materials in the loop" [9]. The textile and apparel industry has been characterized by a lack of transparency and information exchange across organizations and supply chains [10,11], making the transition to circularity a difficult prospect.

The purpose of this research was to gather and analyze data from a diverse set of stakeholders about the main challenges and opportunities they perceive related to textile circularity, with a focus on textile recycling. This research was conducted as part of a larger project, funded by the National Science Foundation (NSF) Convergence Accelerator program, with the aim of designing and building CEs for textile recycling in two US regions. Given the lack of information sharing across the industry, the research team sought to fill important gaps in scholarship and corporate reporting on the technical, infrastructural, and social barriers that organizations face when attempting to recycle discarded textiles or incorporate recycled materials into their product lines.

The qualitative research carried out by team members resulted in novel findings regarding the major obstacles that stakeholders perceive to the development and implementation of CEs; the meanings and importance of circularity for textile and apparel industry stakeholders; and the opportunities stakeholders perceive for advancing textile circularity. Notably, this research points to three specific interventions that are needed to bring about systemic change: a need for technologies and processes that maintain the value of recycled materials; a need for processes that reduce costs and increase efficiency of preparing post-consumer textile waste for recycling; and a need to build the technical, organizational, and policy infrastructures to support circular flows of products and materials. As for opportunities and resources that can support a circular transition for the textile and apparel industry, stakeholders emphasized the vast quantities of post-consumer waste that are available for recycling, increased private and public investment in CE, and important policy changes that are under consideration in the US and other nations.

This research provides the opportunity to share aggregated and anonymized information about industry needs and practices that otherwise might not be shared within the textile and apparel industry. Future research and collaboration are needed to tackle the challenges and take advantage of the opportunities that are detailed below. This research further suggests a need for routine data collection and information sharing across the growing number of individuals and organizations who are invested in CE for textiles and apparel.

2. Literature Review

2.1. Environmental Impacts of the Textile and Apparel Industry

Textile production requires considerable natural resources and results in significant environmental pollution. For example, approximately 7000 L of water are currently used to produce one kilogram of conventional cotton [12]. A total of 20% of industrial water pollution worldwide is the result of the dyeing and treatment of textiles, and estimates suggest that the textile and apparel industry is responsible for 8–10% of global CO_2 emissions [4,13]. Notably, 70% of the textile and apparel industry's carbon emissions stem from upstream activities, particularly energy-intensive processes involved in raw material production, preparation, and processing. The remaining 30% arise from downstream activities such as

transportation, packaging, and retail operations. CO_2 emissions from textile manufacturing alone are expected to increase by 60% by 2030 [14]. If these trends persist, the fashion industry could consume over 26% of the carbon budget permissible under a 2 °C global warming limit by 2050 [15].

Resource depletion, environmental pollution, and a growing textile waste crisis are being driven by increasing clothing production levels worldwide. This trend has been exacerbated over the last 20 years by the rise of "fast fashion", where new clothing styles are introduced at decreasing intervals [5]. The surge in production has been coupled with a nearly 40% decline in the average number of times that an individual wears an item of clothing [16]. In 2018, the U.S. generated approximately 15.4 million tonnes of textile waste, which represented 7.7% of all landfilled municipal solid waste [17]. Landfill disposal not only contributes to pollution but also represents lost opportunities for resource recovery.

2.2. Circular Economy Concept and Practice

At present, there is no standardized or large-scale system in place to capture and recover resources at the end of a garment's life cycle, when the consumer is no longer wearing an item of clothing [18]. CE focuses on creating closed-loop systems that minimize waste and promote the continuous reuse of resources. According to the Ellen MacArthur Foundation [15], CE principles emphasize efficient resource use and waste elimination throughout product life cycles with the goal of keeping materials in circulation as long as possible. Key implementation strategies include reduce, reuse, repair, and recycling. Reuse extends product life by finding new applications. In the apparel sector, re-commerce (buying and selling second-hand apparel) currently comprises about 7% of the market and is projected to grow by more than 10% annually, driven by Gen Z and Millennials [15]. Repair strategies prioritize durability and modular designs to facilitate easy fixes and foster a culture of maintenance that is essential for CE. Textile recycling and the substitution of new fibers with recycled fibers can reduce environmental impacts in several ways, depending on the waste stream utilized and new materials that are avoided. Previous studies indicate that by replacing 30% of new cotton fibers with mechanically recycled cotton fibers within existing global supply networks, the textile and apparel industry could achieve reductions of at least 2.2% of greenhouse gas emissions, 0.6% of water use, 1.4% of total air pollution, and 3.1% of land use [19]. In general, textiles that are mechanically recycled are estimated to utilize no more than 20% of energy use relative to manufacturing new fibers [20]. The implementation of a comprehensive CE system, including reuse, repair, and recycling, offers substantial environmental and economic benefits, with potential savings estimated at approximately 143 million tonnes of greenhouse gas emissions by 2030 [21,22].

2.3. Obstacles to Textile-to-Textile Recycling

Some infrastructure is already in place to facilitate reduce, reuse, and repair strategies among textile and apparel producers and consumers. Second-hand clothing collectors and online resale platforms, for example, are seeing increased utilization year over year [23]. Textile recycling, however, lags far behind. In 2018, textile recycling rates were alarmingly low, with only 14.7% of textiles (about 2.5 million tonnes) recycled, and recycling rates for clothing and footwear were even lower at around 13% [17]. Chemical recycling and enzyme hydrolysis of textiles have attracted considerable attention from media and investors in recent years. Compared to mechanical recycling, however, these processes generally have higher energy, water, and chemical input needs, require more time, and are limited to specific materials [2,20,24]. Chemical recycling of polyester is estimated to use more energy than mechanical recycling but no more than 12% of what is needed to manufacture new polyester fibers. Enzymatic textile recycling processes may fail economically during scale up due to too low concentrations of the desired output created after fermentation reactions, with further concerns among some parties related to heavy reliance on genetically modified organisms [20].

Mechanical textile recycling has its own challenges, however. Currently available shredding technologies result in downcycling rather than recycling, meaning that the resulting products have less economic value than the original apparel product. Downcycling also limits opportunities for multiple recycling and use cycles because of reduced fiber length and quality [25,26]. Based on trials conducted using commercially available textile shredders, researchers estimate that polyester can be recycled seven to nine times and cotton can be recycled four to six times before these materials are shortened and degraded in ways that make further recycling impossible [27]. A 2006 study found that 95 percent of the mechanically recycled textile waste that was tested was suitable only for nonwoven applications because the recycled fibers were too short to spin into yarns [28]. A more recent study demonstrated that 50 to 60% of recycled materials were wasted when researchers attempted to spin recycled fibers into yarns [29]. Recent work also reveals concerns with post-consumer fibers versus pre-consumer fibers, since wear and laundering can shorten the length of fibers and degrade the molecular components of textiles [30].

Previous studies indicate that mechanically recycling post-consumer textiles poses different challenges than the recycling of pre-consumer textiles. The process of identifying and sorting mixed post-consumer materials and separating blended fabrics into single fiber types requires too much time and labor to make post-consumer recycling a cost-effective enterprise [31–35]. Furthermore, mechanical recycling cannot remove dyes or toxic additives used in textile production, and these compounds can be released during recycling, causing harm to human health and ecological systems [5]. On the business side, the presence of harmful chemicals on recycled fibers generates risks related to not passing regulatory requirements [36]. In sum, existing research indicates that the cost currently associated with collection, transportation, and sorting of post-consumer textiles is "not outweighed by its subsequent value through recycling", although this situation could change if new techniques and technologies were developed to allow for faster processing and to make a wider array of materials recyclable [6].

The existing literature on textile-to-textile recycling is helpful for identifying many of the technical barriers to circularity in this sector. Additional research was needed, however, to understand how stakeholders perceived these challenges, what additional (technical and non-technical) obstacles they might perceive to the successful development and implementation of textile recycling systems, and what resources exist for overcoming these challenges.

3. Materials and Methods

The authors are involved in the ReSpool project, a multi-year partnership with industry leaders, government agencies, and nonprofit entities that aims to build circular, regional textile ecosystems in order to move the textile and apparel industry from a linear to a circular model [37]. ReSpool has achieved several milestones, including the successful development of the Fiber Shredder [38], a patent pending technology for fabric-to-fiber recycling promoted by Waypoint Forward LLC, and the innovation of a set of proprietary processes for creating woven and non-woven textiles and textile products from recycled fibers [39,40]. We have also solidified long-term partnerships in two test regions (Minnesota's North Shore and the Delaware Valley) with academic institutions, textile manufacturers, apparel and home goods brands, waste management companies, government agencies, and nonprofit partners including Goodwill of Delaware and Delaware County (DDC) and True North Goodwill, located in Duluth, Minnesota. The two Goodwill organizations are affiliates of Goodwill International, a leader in post-consumer clothing collection and resale.

In 2023 and 2024, major funding for ReSpool was provided by the NSF Convergence Accelerator program. In accordance with the program's framework and curriculum [41], the ReSpool team prioritized user-inspired and applied design thinking (IDEO) principles [42] with the goal of tailoring research aims and activities to the needs of community partners and accelerating the translation of our scientific research into practice. The first step was to gather information from community partners and recognized experts in CE and textile

sustainability. Between February and November 2023, a team of 10 ReSpool researchers conducted semi-structured interviews with 41 of these stakeholders, either in person or over Zoom. The study population was selected through a method of purposeful sampling, seeking actors with specific knowledge, experiences, or characteristics most relevant to the study aims [43]. Interviewees were professionals working in the fields of waste collection, recycling, fashion design, fashion sustainability, fashion retail, home goods design and retail, textile manufacturing, materials development, government policy, and economic development (see Table 1). Most interviews (n = 28) were conducted by two ReSpool researchers working in tandem who each contributed different perspectives when asking questions and engaging the participants in conversation.

Table 1. Summary of interviewee information.

Professional Sector	No. of Interviewees	Sample Job Titles	No. of Interviewees Attending Workshop
textile waste management or recycler	7	president, founder, recycling manager, director of government affairs	
textile or product manufacturer	2	president/CEO, plant manager	
national brand or retailer	4	VP of sustainability, sustainability coordinator, senior director of sustainability and human rights	
small brand/retailer or entrepreneur	14	owner/CEO, founder/CEO	10
investor	2	project director, executive VP	
government or policy maker	3	senator, materials research engineer, recycling specialist	
consulting	3	sustainability lead, senior consultant, founder/CEO	
economic development	2	director of innovation, science and technology advocacy consultant	
trade association	1	executive director	
academia	3	associate professor, academic researcher, textile designer	1

We utilized these interviews to test assumptions about challenges to and possibilities for textile circularity that were rooted in our reading of the existing literature, gather data about additional obstacles to developing and implementing textile recycling systems, and learn about the resources available at various scales for advancing CEs for textiles and apparel. The research instrument thus addressed three overarching questions:

1. Is textile circularity important at this time, and, if so, why?
2. What are the major obstacles to achieving a circular textile system?
3. What technologies, processes, and connections already exist that could help to advance a circular textile system?

The research instrument also included questions about the meanings that interviewees attach to the terms "sustainability" and "circularity" and interviewees' expectations for the future of material circularity in the textile and apparel sector. Each interview was recorded, transcribed, and then coded for relevant and recurring themes. Our analysis looked for commonalities and differences across participants' responses.

In addition to semi-structured interviews, 15 stakeholders attended a participatory knowledge exchange workshop facilitated by a ReSpool researcher. The researcher, who is also a textile designer, asked the stakeholders to interact with and comment on recycled fiber and fabric prototypes that resulted from the ReSpool team's lab-scale mechanical textile

recycling and manufacturing processes. Among the 15 workshop participants, 11 of them had participated in the semi-structured interviews (see Table 1). The other four participants included three entrepreneurs and one academic researcher. The purpose of the workshop was to collect feedback from yarn and fabric producers, home goods and apparel brands, and textile researchers on the properties of the mechanically recycled textile materials and the potential for their integration into new or existing manufacturing processes and product lines. The workshop also involved informal interviews about challenges to and opportunities for textile circularity. Immediately following the workshop, participants were asked to record their reflections on potential uses of recycled textile materials and possibilities for textile circularity and then submit these notes to the workshop facilitator via email. Notes from the workshop and the participants' emailed reflections were coded for relevant and recurring themes and then compared with responses from the interviews to identify commonalities and differences across the data sets.

Finally, the researchers carried out several site visits that involved tours, meetings, observations, and informal interviews with employees at each site. These included visits to three Goodwill organizations in the US and Canada (involving tours of a retail store, sorting facility, and warehouse operated by each organization); an academic research center focused on fashion design and sustainability; a textile recycling operation; a textile resale business; an industrial sewing innovation and education center; a textile manufacturing business; two sustainable apparel and home goods companies; and a regional ecosystem incubator that promotes sustainable development policies and practices for US communities. The purpose of the site visits was to document existing practices related to textile circularity and learn about ongoing challenges in the development of circular systems for textiles and apparel. During each site visit, members of the research team collected data in the form of field notes. Members of the research team coded the field notes for relevant and recurring themes and then analyzed the data collected across the interviews, workshop, and site visits for commonly reported insights and perspectives as well as contrasting meanings, experiences, and knowledge.

Study protocols were reviewed and deemed exempt by the appropriate Institutional Review Board. All subjects interviewed and/or observed for this study gave their informed consent for inclusion before they participated in the research project. Participants consented to be interviewed for the study on the grounds that personal data and identifiers would not be published or otherwise made available to anyone other than the research personnel. Data collected via each of the three methods described above are stored as digital files on secure, password-protected servers.

4. Results

This research generated original findings in three areas: (1) meanings and importance of circularity for textile and apparel industry stakeholders; (2) major obstacles to achieving circular textile systems, as perceived by stakeholders involved in the development and implementation of CEs; and (3) potential solutions that can be achieved through innovations in partnerships, technology, and manufacturing processes.

4.1. Textile Circularity: Meanings and Importance

Stakeholders interviewed for this study expressed marked enthusiasm about advancing circularity for textiles and apparel. Brand and retail employees and industry consultants described a noteworthy transition taking place within their organizations and among their clients. This transition involves a shift from viewing discarded textiles and apparel as "waste" to viewing these materials as a valuable "resource", as participants put it. Several brand executives and industry consultants indicated that their businesses are poised to invest in a circular textile transition. As one industry consultant stated, "The [fashion] brands are very interested in accelerating a transition to a circular economy. And they are interested in showing that their products are being handled responsibly, but also that they are going to be able to have access to either the reuse fraction so they can resell it, or the re-

cycled content that they want to incorporate into their supply chains". Executives reported that large firms are incorporating goals for resale and the use of recycled content into their environmental impact and sustainability agendas. A set of brands and retailers are also investing in take-back programs to provide consumers with a direct path for returning used garments for resale, recycling, or upcycling when they are no longer worn. The owner of a collection service for apparel and footwear expressed optimism about consumers' desires to participate in textile circularity. "The community actually shows up", this stakeholder stated. She explained that, in her experience, consumers eagerly participate in textile reuse and recycling if collection is convenient for them.

Though all stakeholders endorsed the idea of circularity, they tended to provide vague definitions of the term when asked. These definitions commonly centered on a transformative process through which some type of output resulted from a product that had previously been in circulation. A few stakeholders were more specific. One interviewee suggested that materials must remain in the industry in which they were initially used in order for the resulting product to be considered circular. Another stakeholder working in government similarly defined circularity as "taking resources and putting them back into the original use intended from that resource". This participant associated circularity with recycling but noted that recycling does not always result in "true circularity" since recycling processes can yield many different types of products. Other stakeholders prioritized reuse through repeated cycles of donation and/or resale in their definitions of circularity. A few of the stakeholders interviewed for this study expressed concern that there is not a clear and agreed-upon definition of circularity in the textile and apparel industry. They lamented that their organizations or others could participate in "greenwashing" if well-defined standards and mechanisms of accountability are not put in place.

A key theme that emerged from the interviews, workshop, and site visits was the need to design for circularity. When asked to define circularity, stakeholders from a range of organizations—recyclers, government agencies, and apparel brands—focused on design in their responses. Some stated that designing products out of high-quality materials that lend themselves to reuse is the only way to achieve circularity. An employee who works in upper management at a major retailer indicated that designing for circularity is a central component in her company's plans for transitioning from a linear model to a circular one. The founder of a recycling technology company advocated product design for disassembly and "using materials that can be recovered and recycled at the end-of-life stage".

When asked what circularity means to them, some interviewees stated that full circularity is impossible. Managers in the recycling sector, in particular, were quick to point out that there will always be some measure of waste, even within a circular system. They also indicated that it is impossible for goods to be made of 100% recycled materials. People working in recycling offered up these caveats in ways that seemed rehearsed to ReSpool team members, as if this was not the first time they had clarified the limitations of what their businesses can deliver.

4.2. Major Obstacles

4.2.1. Downcycling and the Problem of Limited Value

Stakeholders working in collection, recycling, and waste management who were interviewed for this study reported that their textile recycling experience has centered on markets for rags, wipes, and shoddy (shredded fabric pieces and short fibers) used mainly for insulation. These are downcycling markets for end-of-life apparel. Interviewees consistently emphasized the need for recycling processes that maintain the length of fibers and economic value of materials. They also emphasized the need for recycling processes that allow for multiple cycles of reuse and recycling. The manufacturers, brands, and retailers interviewed for this study all explained these needs as keys to making CE a viable and sustainable business model.

A set of stakeholders from the mid-Atlantic region reported that markets for textile recycling "dried up" in the 2000s for economic reasons. They referred specifically to the

market for rags and the market for shredded polyethylene terephthalate (PET) bottles for recycling polyester fiber, and they cited low prices and a lack of regular buyers as two key factors leading to the decline. Stakeholders in Minnesota emphasized that a top priority is the production of high-quality recycled products that can be warrantied in the same way as existing product lines that are manufactured with new materials.

4.2.2. Characteristics of Post-Consumer Waste

The qualitative research conducted for this study indicates that although a set of recycling options exist for pre-consumer industrial textile waste such as remnants, imperfect garments, and overruns, post-consumer apparel has been largely viewed as a problem too big to tackle. In interviews, the workshop, and during site visits, stakeholders emphasized the need for recycling options for growing quantities of post-consumer textiles and apparel (especially discarded fast fashion items). Stakeholders described several characteristics of post-consumer textiles and apparel that make these materials especially challenging to recycle, including the inconsistency of feedstocks; the perceived high cost of materials identification, sorting, and pre-processing; and the presence of contaminants in post-consumer apparel.

The inconsistency of post-consumer textiles and apparel is perceived as a major challenge to circularity. Stakeholders talked about the challenge for yarn mills and textile manufacturers to handle recycled feedstocks derived from post-consumer materials, since these facilities are accustomed to processing materials of guaranteed fiber content that are in steady supply. Collectors pointed out that the composition of post-consumer materials varies by location, season, and other factors. A range of stakeholders agreed that without the consistent availability of well-characterized and standardized feedstocks, it will be difficult for mills, manufacturers, product developers, designers, buyers, and others working within textile and apparel supply chains to plan and manage their operations in the ways that they are accustomed.

Closely related to lack of consistency in post-consumer feedstock is the lack of efficient and effective technologies and processes for materials identification and sorting. Manufacturers and recyclers noted that the fiber composition of post-consumer materials is frequently unknown, and textile products are often composed of multiple layers of distinct fiber composition. Stakeholders pointed to the lack of industrial-scale technologies for identifying and sorting materials and the lack of technologies capable of separating blended fabrics into single fiber types as major challenges. Participants in this study reported that they have attempted to address this challenge in various ways. For example, businesses that work mainly with pre-consumer apparel or who handle garments collected through brand- or retailer-specific take-back programs rely on bills of materials or product labels to aid in the accurate identification of fiber content whenever possible. Some stakeholders voiced interest in the possibility of working directly with major brands to aid with accurate identification of post-consumer materials but acknowledged that the degree of coordination this would require across many different companies would pose a considerable challenge.

One stakeholder who prepares pre-consumer apparel (including overruns and imperfect goods) for resale and downcycling indicated that they rely mainly on volunteer labor for identification, sorting, and pre-processing at the company's locations. Volunteers sort the materials according to garment type and remove buttons, zippers, and other non-textile components (with scissors) from garments that will be downcycled into shoddy. This process is labor intensive and can be hazardous. Another business owner indicated that employees at his company currently sort production waste manually by material, a process that he implemented in the hopes that textile-to-textile recycling technologies will be available in the near future (the sorted materials are currently sold for downcycling). He also described the challenges associated with identifying and sorting out blended fabrics that include Spandex or elastane, since the textile recycler he contracts with for downcycling cannot shred any Spandex content without damage to the shredding machine. Other stakeholders reported using near infrared (NIR) scanning technologies and optical

sensors to identify fiber content. They perceived significant promise related to evolving technologies but expressed concerns about the accuracy of the scanners that are currently available, the need for industry-wide standards, and the need for reference materials that can be used to improve accuracy and reliability. One stakeholder indicated that current scanning technology is sufficient to support downcycling but questioned whether the results are accurate enough to meet the feedstock specifications of brands and manufacturers if large-scale textile-to-textile recycling is to happen successfully.

Another important characteristic of post-consumer waste that stakeholders pointed to as a significant challenge is contamination in the form of colorants, dyes, finishes, and other additives. At present, there are no scaled processes in place for identifying chemicals that may be present in post-consumer materials. Stakeholders expressed worry that textile recycling might add to health and ecological problems rather than alleviate them. They talked about the possibility for mechanical recycling to release toxic chemicals such as polyfluoroalkyl substances (PFAS) and microplastics into the environment.

4.2.3. Infrastructure

A final challenge commonly mentioned by stakeholders is that the development of circular textile systems is impeded by the way business is currently conducted across the textile, apparel, and recycling industries. As the owner of one small brand noted, "the system is not really built for" circularity. Stakeholder concerns went beyond the lack of specific technologies needed for accomplishing recycling goals. They expressed frustrations with how the fashion industry and adjacent industries currently operate, viewing the normal functioning of these industries as inhibiting the CE transition.

Stakeholders in waste management, recycling, and post-consumer collection expressed frustration with the lack of transparency and potentially "unethical" practices that they associate with textile recycling. One stakeholder lamented that textile recyclers are not required to disclose the potential environmental impacts associated with shredding textiles to produce shoddy (e.g., chemical release and microplastic contamination). Other stakeholders expressed concerns about the lack of transparency in the export industry for post-consumer apparel. Many of the people interviewed for this study posed questions about how much clothing ends up in landfills after being collected for purposes of resale and recycling. Current estimates suggest that 40% of post-consumer apparel exported to the major resale markets in Accra, Ghana, is considered waste and discarded upon arrival [44,45].

Interview participants also pointed to incentive structures in the fashion industry that work against the successful achievement of CE goals. "We're still very much driven by sales and margins", stated one person working in upper management at a major fashion retailer. She explained that companies do not typically measure employee performance based on sustainability or circularity goals, which makes these goals a lower priority for people across the industry. Other stakeholders commented that their companies are unlikely to take risks that might result in losses. People working for brands, retailers, and consultancies emphasized that product changes must be "cost neutral" in most cases in order to be approved by upper management. These findings suggest that companies may view circularity as a minor adjustment to current practices and products rather than as a major overhaul of how the textile and apparel industry functions.

Given the challenges related to post-consumer textile recycling described above, stakeholders indicated that large companies are unlikely to make meaningful investments in this area until the technologies and systems are proven, and costs align with the industry's current financial models. Several interview participants and stakeholders we spoke with during site visits advocated for joint efforts among multiple brands and retailers as a way to share costs and minimize individual risk. These findings indicate that the question of who should bear the cost of circularity research, testing, and implementation is unclear to industry stakeholders. They may be unwilling to take on the financial burden of the CE transition, given a lack of incentives for any one enterprise to do so.

Our research also revealed that the disconnect between brands and retailers, on the one hand, and materials suppliers and manufacturers, on the other hand, is perceived by stakeholders as an obstacle to circularity. Several stakeholders observed that their companies' reliance on intermediaries to source primary inputs (fibers, yarns, and non-textile components, for example) means that they have little control over how the supply chain for those materials is organized. They expressed frustration that this arrangement makes it difficult for them to seek out recycled materials or advocate for the incorporation of recycled materials into product lines. They also acknowledged that their materials specifications for new apparel change frequently and that suppliers might have difficulty sourcing recycled materials that could meet these specifications. The inconsistency of post-consumer feedstocks makes it even more difficult to source recycled inputs at desired quantities and on time, according to these stakeholders.

Other stakeholders—primarily in the areas of collection, sorting, and recycling—commented that the overall decrease in the quality of new apparel makes textile recycling harder than ever before. They pointed to fast fashion as the major driver of decreasing quality, noting that garments are being designed and manufactured with lower quality materials, and that brands intend for these garments to have relatively short life cycles. "Garbage in, garbage out", stated one stakeholder who owns a textile collection and recycling business in the Delaware region. This person explained that fast fashion items are of such low quality at the start of their life that it is not worthwhile to recover them for reuse or recycling. A different stakeholder involved in post-consumer waste collection commented that issues of quality and consistency are irrelevant because of the lack of basic infrastructure to support mechanical recycling.

4.3. Potential Solutions and Opportunities

Despite enormous challenges, the stakeholders interviewed for this study emphasized that the sheer quantity of available post-consumer materials makes them interesting as a future feedstock for the textile and apparel industries. The stakeholders referred to post-consumer materials as a potentially valuable resource if necessary improvements in technology, processing, and infrastructure were realized. The negative social and environmental impacts of landfilling, incinerating, and exporting these materials to Global South countries is also of increasing concern to brands and retailers. Together with impending legislative changes in the European Union and United States that are likely to restrict and/or raise the cost of textile disposal, a number of stakeholders expressed urgency around the development of sustainable recycling solutions for post-consumer materials.

The challenges that stakeholders noted represent opportunities for technology and process innovation, partnership-building, and the development of appropriate infrastructures to support post-consumer textile recycling. Two stakeholders mentioned that there has been considerable public and private investment in chemical recycling of textiles, and they expressed frustration with the fact that mechanical recycling has not received the same attention. Stakeholders also commented on the fact that more options exist for the recycling of pre-consumer textile waste than post-consumer materials. They encouraged the ReSpool team to focus its efforts on the mechanical recycling of post-consumer materials in order to meet pressing needs.

One stakeholder indicated that the US, in particular, is facing uncertainty regarding how best to finance a transition to circularity and develop the infrastructure needed for textile recycling. Stakeholders were enthusiastic about the possibilities enabled by federal grant programs that promote research and development in areas of sustainability and circularity (including the NSF Convergence Accelerator program). A stakeholder who works as an industry consultant noted that public and private grants to support academic research and technology transfer will be an important driver of change. She explained that grant funding removes cost barriers in the initial stages of innovation, lowers barriers to entry, and creates more favorable conditions for private investment at later stages.

A final opportunity that our team identified based on the stakeholder interviews and site visits is the development of circular systems that operate on regional scales. Collectors, recyclers, and the owners of small- and medium-sized brands and retailers all expressed strong agreement with the idea that textile circularity should happen region-by-region rather than at national or global scales. These stakeholders provided several reasons to support their claims. First, they pointed to the reduced costs and carbon emissions associated with transporting feedstock and fibers within regional boundaries as compared with cross-country or international shipping. Second, they noted that the characteristics of post-consumer waste vary on a region-by-region basis, which means that processing, milling, and manufacturing need to be tailored to regional feedstocks to achieve efficiencies. Finally, stakeholders noted that there is regional variability in consumer needs, such that design and product development with recycled materials should ideally be tailored to meet those specific needs (rather than risk contributing to the twinned problems of overproduction and production waste that currently characterize the textile and apparel industries).

Government and industry stakeholders alike indicated that textile recycling is a vital need for their regions. Officials in Delaware, for example, pointed to the small state's limited landfill capacity and the steep costs associated with exporting waste across state lines. Delaware officials also commented on the state's strong support for small- and medium-sized business development, especially in "green" manufacturing sectors. Government stakeholders whom the ReSpool team interviewed indicated that state officials are unlikely to develop public textile collection programs since consumers are already accustomed to utilizing private (nonprofit and for-profit) drop-off options. Officials expressed positive support for policies that would ban the landfilling of textiles by commercial operations and consumers, but had serious concerns about how such programs could be implemented without first building the infrastructure needed to facilitate textile recycling. In several interviews, stakeholders mentioned extended producer responsibility (EPR) policies such as California's SB 707 (signed into law on 28 September 2024) as a possible solution to textile waste, but, again, they worried that the necessary infrastructure is not yet in place to make EPR a viable option.

5. Discussion

5.1. Developing a Common Language for CE

The concept of circularity is ubiquitous, and policies to incentivize or mandate more circular systems are currently under consideration in the European Union and several US states [16]. Our research revealed high levels of enthusiasm among stakeholders regarding the possibility of textile circularity, although the meaning of terms such as "circularity" and "circular economy" varied widely among participants. As Vulsteke et al. point out, the "lack of consistent definitions and standards in CE policy frameworks" can be a significant barrier to successful implementation of the CE model [46]. Competing or contradictory definitions of circularity may lead to confusion within organizations or prove a stumbling block to coordination across organizations. The lack of consistent definitions can also lead to greenwashing in the fashion industry, as brands and retailers may make claims regarding circularity that are contested or altogether unsubstantiated.

Several organizations have recently published CE guides that define circularity for the textile and apparel industry and provide recommendations for how organizations can put CE into practice. These include the Ellen MacArthur Foundation's 2017 report, "A New Textiles Economy: Redesigning Fashion's Future", the white paper on "Textile Recovery in the US" published by Resource Recycling Systems, and Accelerating Circularity's "Spent Textile Hierarchy" graphic and "Modeling and Linking Report" [4,36,47,48]. Definitions of CE that appear in these resources and in the scholarly literature call attention to reduce, reuse, repair, and recycle as important parts of CE [12], but the stakeholders interviewed as part of our research tended to emphasize only one of these processes in their definitions. Design and materials selection were described by stakeholders as crucial decision-making

points in CE. However, it is noteworthy that design and materials selection were often talked about as if the same people would be making these decisions, which is not necessarily the case in the apparel industry [49]. We recommend that organizations who commit to participating in the CE transition adopt and promote a consistent and commonly agreed-upon definition of circularity for internal and external communications. Clear and transparent standards and mechanisms of accountability that have been vetted by external stakeholders are also crucial for ensuring that the CE transition is successful.

Various stakeholders said to us that "full circularity is impossible". We take this statement as an important corrective to the overpromises that some industries are making about what CE can accomplish, especially the idea that CE can lead to a zero-waste or waste-free system of production and consumption. CE is sometimes presented by companies and governments as a silver bullet for waste, corporate social responsibility, environmental sustainability, and climate goals [50]. We advocate for greater scrutiny of claims that CE alone can solve such "wicked" problems [51], especially when CE is discussed without critical attention to growth models that continue to drive economic decision-making in global markets.

5.2. Addressing Post-Consumer Waste

Our research confirmed that innovations such as the Fiber Shredder and the novel manufacturing processes developed by ReSpool are needed in mechanical textile recycling to move from downcycling to a process that maintains the quality and value of inputs. Our findings also indicate that technological innovation and manufacturing advances are not sufficient for transitioning the industry to a circular model. Multiple processes need to be developed and implemented in the areas of materials identification, sorting, and pre-processing to facilitate efficient and effective apparel recycling. Post-consumer apparel poses a particular set of challenges in these areas given its enormous quantities, inconsistent supply, mixed materials, variable quality, and potential contamination.

There are promising research projects underway that could result in more efficient and accurate approaches to the identification, sorting, and pre-processing of post-consumer apparel. Recent trials conducted by the non-profit organization Fashion for Good in collaboration with the consultancy Resource Recycling Systems (RRS) and by the non-profit organization Accelerating Circularity demonstrate the utility of near-infrared and optical scanning for identifying fiber content and color, while several other studies suggest that the integration of machine learning can further improve outcomes [35,52,53]. Findings thus far from a major research project led by faculty at Rochester Institute of Technology [54] suggest that a combination of several scanners can also improve accuracy.

The potential for chemical contaminants and microplastics to be released into the environment through mechanical recycling is an especially vexing concern we share with the stakeholders who participated in this research. Without major technical innovations, it is unlikely that contaminants can be quickly and effectively identified and removed from discarded garments. Legislative efforts underway in multiple US states and the European Union to ban PFAS chemicals (a diverse class of chemicals that include compounds known to be harmful to human health) from consumer applications could eventually reduce this problem, at least as it concerns new garments [55,56].

5.3. Building Regional Infrastructures for Circularity

A circular infrastructure for the textile and apparel industry does not yet exist. Our findings indicate that a successful transition to circularity will require the development and implementation of new economic models and systems that prioritize CE principles of reduce, reuse, repair, and recycle. The push for extended producer responsibility in the textile and apparel industry could drive investment and development of some of the infrastructure needed for CE, since EPR requires producers to share responsibility for end-of-life product management [57]. Based on stakeholder input, we have also identified a need to rethink how success is defined within the textile and apparel industry and to break down

current divisions of labor that prevent people working in sourcing, materials development, design, product development, manufacturing, and other parts of the value chain from coordinating their efforts to advance environmental sustainability and circularity goals.

New approaches to design and manufacturing are needed to advance CE. Standard practice in the textile and apparel industry presumes the ready availability of large-scale quantities of standardized materials. Our research participants noted that the inconsistent supply, mixed materials, and variable quality of post-consumer waste seriously limits possibilities for incorporating recycled, post-consumer feedstock into new and existing product lines. This finding, however, also reveals an opportunity to reframe variability as a positive attribute of feedstocks and to promote flexibility as a core value in textile and apparel design and manufacturing. Material-driven design (MDD) offers one way of conceptualizing and putting into practice this shift. MDD privileges hands-on interaction with fibers and other materials as a means to uncover what the material can create. This contrasts sharply with traditional approaches to design and product development in which the vision for the end product drives the design process [58]. MDD treats diversity and inconsistency in material inputs as positive attributes that open up new, creative possibilities for the textile and apparel industry. Such an approach fits well with CE models, since MDD also encourages designers and product developers to take into account the end of life of materials at the beginning of the design process [59]. This goes beyond other "design for circularity" approaches that start from the premise that materials will be selected from among a range of readily available options [60]. Building on MDD, our team has initiated the development of design and product development approaches that are "waste-led" [61,62]. The ReSpool team's efforts in this area parallel other projects such as the READY project, including the microfactory at Via University College, in Denmark [63], which makes use of recycled materials based on their unique properties to create new textile products.

The need that some research participants expressed for regional infrastructures for textile circularity highlights the importance of geography, scale, and community partnerships for a successful CE transition. The development of production and consumption systems that are geographically circumscribed to be small-scale and community-based is a central tenet of sustainable apparel design research [64,65]. Existing research also suggests that sustainability initiatives involving community-based forms of empowerment and collaboration can impart shared senses of collective responsibility that drive ongoing change [66]. The textile waste-sheds [67] of different communities yield different materials for recycling [68], which can, in turn, feed into the development of tailored product lines that meet specific customer needs. These needs are likely to shift over time given the changing climate and changing economic situations confronted by diverse communities, making flexible responsiveness to regional needs an important principle in sustainable design [2]. Our findings from the stakeholder interviews, workshop, and site visits suggest that a regional approach to building circular infrastructures and forging community partnerships is likely to generate strong buy-in and environmental sustainability gains.

6. Conclusions

This research investigated stakeholder perceptions of the importance of textile circularity and identified the challenges and opportunities to realize regional CE for textiles in the US. This research had several notable limitations. First, the time constraints of completing stakeholder interviews, data analysis, and preliminary reporting within six months impacted subject recruitment. Although the research team recruited additional subjects following the initial research period, a larger number of research subjects and a broader sample of participants with more diverse job titles and work experiences would strengthen the research. Second, this research relies on the reported perceptions of the research participants and does not include extended observations of the participants' actual practices or experiences, nor did this research involve the review of any quantitative data regarding the decision-making or operations of the organizations that the participants represent. This

may have resulted in certain biases in the data collection, since interview participants could have answered questions in line with what they assumed the interviewers wanted to hear or learn from the research. To reduce the likelihood of bias in our results and reporting, the research team asked questions in multiple ways and compared the responses that were collected from each participant against their other answers as well as against the answers from other participants who work in the same type of organization and/or work role. Whenever possible, answers to interview questions and information collected during the workshop and site visits were also compared with publicly available reporting from the research participants' organizations.

All of the stakeholders who participated in this research endorsed circularity in textiles and apparel. However, they provided disparate definitions of "circularity" or "circular economy". A variety of stakeholders such as recyclers, government agencies, and apparel brands also emphasized the importance of product design in circularity.

The major challenges for textile and apparel circularity include the quality reduction from mechanical recycling (downcycling); the inconsistency of post-consumer textiles and apparel; the lack of effective technologies for post-consumer materials identification and sorting; the contamination of dyes, finishes, and other additives; and the lack of information sharing and coordination across the textile, apparel, and recycling industries. There is disconnection between brands/retailers and materials suppliers/manufacturers. A circular infrastructure for the textile and apparel industry does not exist.

These challenges to textile circularity bring opportunities in the areas of technology and process innovation, partnership-building, and infrastructure development. Innovations are needed to move mechanical recycling from downcycling to quality and value maintenance; to identify, sort, and pre-process post-consumer apparel efficiently and accurately; and to identify and remove chemical contaminants (dyes, finishes, other additives) from end-of-use garments. New approaches to textile and apparel design and manufacturing, such as material-driven design, are also needed to advance textile circularity. The stakeholders who participated in this research expressed strong agreement that the development of textile circularity should operate on regional scales rather than at national or global scales. To build regional infrastructures for circularity, the successful development and implementation of new economic models and systems that prioritize CE principles of reduce, reuse, repair, and recycle are required.

7. Patents

A provisional patent was written and submitted for the Fiber Shredder, #63/503,209 (date: 27 June 2023). A provisional patent was written and submitted for Novel Processes to Remanufacture End-of-Use Textiles into Second Generation Textiles, #63/512,155 (date: 6 July 2023).

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investigator in such a manner that the identity of the human subjects cannot be readily ascertained, either directly or through identifiers linked to the subjects.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author due to privacy restrictions. The study participants consented to participation on conditions of anonymity and the protection of personal data. Data provided on request from the corresponding author will be de-identified and anonymized.

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