DRIVERS AND CHALLENGES FOR THE EXPANSION OF RENEWABLE RESOURCE FEEDSTOCKS: THE SUSTAINABLE APPAREL SECTOR

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Drivers and Challenges for the Expansion of Renewable Resource Feedstocks: The Sustainable Apparel Sector

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Executive Summary
Companies are increasingly exploring renewable resource feedstocks as inputs into consumer products in an effort to shift away from non-renewable feedstocks and support internal sustainability goals. However, a significant gap exists in understanding the opportunities and barriers in the expansion of these renewable resource feedstocks, specifically within the apparel sector. In this study, the authors conducted a global stakeholder analysis to explore perceptions of renewable resource feedstocks within the apparel value chain and provide an overview of the renewable resource feedstock landscape. For the purposes of this study, renewable resource feedstocks (RRFs) were defined as: a feedstock created from a resource that can be replenished by ecological cycles within a time period relevant to human planning.

A global survey was administered to professionals within the apparel value chain from December 2016 to January 2017. The survey was built in Qualtrics and consisted of 28 questions, 4 of which were tailored to specific steps within the value chain. The survey was administered through email to approximately 849 individuals, some of which were from the same company, but within different departments. The survey participants included raw material developers, yarn spinners, fabric mills, apparel manufacturers, apparel brands, retailers, and NGOs intimately engaged with the sector. A literature review of consumer and scientific perceptions, as well as RRF leaders, was conducted as part of the stakeholder analysis to supplement the survey results. A total of 162 individuals completed the survey, representing a 19% response rate. However, each question was answered by a varying number of respondents. Although the survey did not track the specific geography of the respondents, through communication with respondents, it was understood that the results were multinational and some responses were collectively developed by companies.

The greatest drivers in RRF utilization were customer demand from brands and retailers, industry sustainability trends, sourcing availability, and cost of inputs. The major barriers to RRF utilization were cost of inputs, sourcing availability of feedstocks, performance, and required change in technology and processing time. Information gaps identified by respondents included RRF environmental impacts, food competition, RRF traceability, and RRF procurement. The main operational difficulties included cost and resource availability. In terms of RRF
performance, the performance of RRFs was rated by 80% of respondents as comparable to or better than synthetic options. Many of the respondents that rated the performance as merely fair or poor indicated that they believed the performance will increase in the future to levels acceptable by their company. While RRF was the terminology used for this study, the results indicated a lack of homogeneity in the term RRF and with what materials are considered “sustainable.”

Scientific perceptions reinforced industry perceptions regarding difficulties in achieving commercial viability and uncertainty with food competition in the agricultural sector, as well as environmental benefits of the feedstocks. Literature review on consumer perceptions showed that consumers demonstrated a lack of awareness in both the breadth of the apparel value chain and the sustainability issues within it. Consumer purchasing patterns do not necessarily match consumer stated willingness to pay more for sustainable goods and consumer attraction to brands with environmentally friendly options. Additionally, consumers’ purchasing patterns are highly influenced by attitudes towards goods and their peers.

Overall, our analysis revealed a lack of knowledge about RRFs, including their traceability, environmental impacts, and associated costs within the value chain. Future research should focus on overcoming financial, logistical, and informational difficulties, as well as exploring consumer influence in using RRFs. Additionally, the terminology and definition surrounding these feedstocks lacks standardization, which the apparel industry should work to overcome.
Introduction

Industries and governments around the globe have increasingly sought to improve the sustainability of consumer products (1). Various policies, as well as sector and science initiatives, are aiding in this effort. This includes the growing utilization of Life Cycle Assessment (LCA) modeling (2), eco-labeling (3), industry consortia (4), and government policies (5). As a means to reduce environmental burdens associated with the utilization of non-renewable feedstocks, such as oil-derived feedstocks, many organizations are increasingly exploring a transition to renewable resource feedstocks (RRF), primarily biobased.

While alternative biobased fuels including ethanol and biodiesel have had a strong penetration in the U.S. and European marketplaces predominantly due to government mandates, there has also been growth of consumer products that incorporate biobased feedstocks. One well known example has been Coca-Cola’s® (Atlanta, Georgia) “PlantBottle™”, which launched in 2009 and is created by converting naturally occurring sugars in plant material into 30% plant-based Polyethylene Terephthalate (PET) plastic. Coca-Cola estimates that it has distributed over 35 million PlantBottles to date (6).

The apparel sector has been a leader in product sustainability, in part due to the collaborative industry-led Sustainable Apparel Coalition (SAC) and its development of the LCA based Higg Index. The index drives product sustainability by providing designers with the ability to quantify the environmental and social benefits associated with their value chains, including the utilization of RRFs.

Leading apparel brands, such as Patagonia (Ventura, California), have recently invested in smaller biochemical companies in an effort to achieve additional sustainable fibers (7). These brands are also implementing stricter sourcing policies, increased transparency, and standards of sustainability (8). Meanwhile, leading chemical companies are producing innovative feedstocks to replace nylon for knit and woven fabrics, such as DuPont™ (Wilmington, Delaware) with Sorona® and INVISTA (Wichita, Kansas) with LYCRA® (9,10).

In addition to industry-led initiatives, the U.S. government during the Obama administration
(2008-2016) instituted a 95% acquisition goal of identified biobased product categories (97 categories as of 2016) by federal agencies through Executive Order 13154. The federal government also established the USDA BioPreferred® Program which oversees the USDA Certified Biobased Product label. In part, the federal government is helping grow the bioproducts sectors due to the perceived economic and environmental benefits to the American public. For instance, the bioproducts industry (excluding bioenergy) contributed 4.22 million jobs in the United States in 2014 and $393 billion to the U.S. economy (11). This represented an increase from 4.02 million jobs and $369 billion value-added contribution in 2013 (12). Additionally, prior research has shown that the utilization of bioproducts resulted in a displacement of 6.8 million barrels of oil and reduction of 10 million metric tons of CO2-eq for the same 2014 reporting year (11).

Although policy makers have begun to track the economic and environmental implications of this growing sector, a gap exists in understanding what opportunities and barriers exist for the continued expansion of RRFs, specifically in apparel. The authors conducted a global survey of apparel and textile industry professionals to address these perceptions and provide an overview of the RRF landscape.

Materials & Methods
The Duke Center for Sustainability and Commerce (Durham, North Carolina) administered a global, online survey from December 2016 to January 2017 to understand how various players in the apparel industry perceive the opportunities and barriers in RRF adoption. The survey was built in Qualtrics, an online survey platform, and consisted of 28 questions, 4 of which were tailored to specific participants in the apparel supply chain. The survey was submitted to Duke’s Institutional Review Board (IRB) for approval before being distributed to the survey recipients. The survey was administered through email to approximately 849 individuals, some of which were from the same company but within different departments. The survey participants included raw material developers, yarn spinners, fabric mills, apparel manufacturers, apparel brands, retailers, and NGOs intimately engaged with the sector. The results were analyzed from January 2017 to February 2017. Phone interviews with self-selected survey participants were also conducted at this time. In addition to this stakeholder analysis, an industry and literature review
was conducted to understand consumer and scientific perceptions of RRFs, as well as the current portfolio of RRFs available.

**Results & Discussion**
A total of 162 individuals completed the survey, representing a 19% response rate. However, each question was answered by a varying number of respondents. The survey did not track the specific geography of the respondents, although through communication with respondents it was understood that the results were multinational and some responses were collectively developed by companies. The respondent breakdown consisted of 29 raw material developers, 7 yarn spinners, 8 fabric mills, 40 manufacturers, 98 apparel brands, and 43 retailers. Respondents were offered the option of answering the survey from multiple perspectives within the apparel value chain, with 37 respondents identifying with more than one part.

**RRF Definition**
Before beginning the survey, respondents were provided with a definition of RRF: A feedstock created from a resource that can be replenished by ecological cycles within a time period relevant to human planning. Renewable resources do not include fossil fuels. Examples of RRFs include corn, potatoes, beans, sugar cane, wood, plants, and vegetation residues, among others. For the purposes of this survey, we are excluding cotton. Inputs refined from these feedstocks include starch, cellulose, glucose, lignin, carbohydrates, oils, and plant fibers. Cotton which is clearly a RRF was excluded in this survey to more effectively capture the perceptions of less utilized RRFs and man-manipulated biopolymers.

The majority of survey respondents (80%) agreed with the definition provided in the survey or had similar definitions. However, there was disagreement with the details of the definition. The most cited difference was the inclusion of organic or sustainable cotton, post-consumer recycled PET, and textile waste. Many respondents felt that material that is recycled or reused is more sustainable than standard options, thus the term RRF and its definition should be expanded to include these material types. Several respondents claimed that wood was not considered renewable by their organizations, as sustainable sourcing and deforestation are prominent issues. Some respondents were more rigid with their definitions and pointed out that the only plants that
should be included in RRFs are those that are byproducts of the food industry or naturally occur in nature without human intervention. In contrast, there were respondents who had a less narrow definition of RRF, stating that RRFs are options that are “green and environmentally friendly.” While many respondents only pointed out the differences between the survey definition and their own organizational definitions, there were respondents who did not understand the term “RRF” itself. Several respondents believed that the words “renewable resource” and “feedstock” did not fit the apparel sector, and were more related to energy and livestock. They instead used terms such as raw materials, sustainable materials, renewable fibers, environmentally preferred fibers, and sustainable fibers.

**RRF Adoption**

The majority of respondents (72%) stated they utilized some type of RRF within in the last 12 months. Although, 64% reported that RRFs comprised 15% or less of their portfolio, Ten respondents reported that 16-30% of their company’s portfolio contained RRFs, with eight respondents reporting more than 30%.

An essential question rests on why brands and manufacturers are incorporating RRFs in their portfolios as compared to synthetic options. An overarching set of reasoning was indicated by the survey respondents, summarized as: 1) Possible environmental impact reduction over the fiber’s lifecycle, 2) Decreased reliance on nonrenewable resources, 3) Positive addition to a company’s sustainability goals or offerings of environmentally-friendly products, and, 4) Consumer and employee demand for more sustainable fibers.

According to the 2015 Nielsen Global Sustainability Report, 66% of global consumers are willing to pay more for a sustainable product (13). Both the Millennial and Generation Z (under 20 years of age) consumer groups, who will soon control the majority of the market, are pursuing brands that integrate environmental stewardship into their business and products (13). One study found that 84% of consumers seek out responsible products, which is important in the renewable feedstock context given that 56% of consumers think they know what “renewable resource” means (14). However, these findings conflict with brand perception of consumers, as survey respondents stated that consumers are not willing to pay premiums on apparel made from RRFs.
In fact, this is a reason listed as preventing the use of many renewable feedstocks, depending on the company’s market segment. Alternatively, a few brands indicated that internal employees, rather than consumers, were a driving force for using sustainable materials, both through making sourcing decisions and discovering new fiber offerings.

The environmental implications of using RRFs in apparel can be modeled through environmental Life Cycle Assessment (LCA), which quantifies the potential impacts a product has on the environment in categories such as ozone depletion, climate change, acidification, eutrophication, smog formation, human health impacts, and ecotoxicity (15). In this study, 67% of survey respondents reported using LCA modeling at their company, yet only half of these respondents have modeled their RRF products specifically. This result stood out as multiple respondents were skeptical of the environmental benefits of RRFs. Specifically, the top concerns indicated were whether food would be displaced thereby increasing total land-use, whether more water and energy were required than for synthetic options, and whether the fibers were biodegradable or recyclable at end-of-life. An LCA study by Shen, Worrell, and Patel (2010) compared Lenzing Modal®, Tencel® (Austria), Lenzing Viscose® (Asia), Lenzing Viscose® (Austria), Tencel® (Austria in 2012), conventional cotton (China and United States), PET (Western Europe), and polypropylene or PP (Western Europe). The study found that Modal, Tencel, and Viscose (Austria) had better environmental performance overall than PP, PET, or cotton (16). Sorona was compared to nylon in an LCA study by DuPont. The study found that Sorona production uses 30% less nonrenewable energy and reduces greenhouse gas emissions by 63%, compared to nylon production (17). Lenzing reports that Lenzing fibers produce 1.3 million tons less carbon dioxide each year, compared to an equivalent volume of polyester fibers. Lenzing also reports that Lenzing Modal and Lenzing Viscose (Austria) fibers are carbon neutral (18,19).

Land-use requirements for feedstocks are difficult to quantify, especially with factors such as the various types of feedstocks available, land competition, changing climatic conditions, and uncertain demand projections. UNEP’s IRP reports that global cropland expansion for biomaterial supply from 2005 to 2050 is estimated at a total of 4 to 115 million hectares (20, 21). Agricultural land already covers approximately 30% to 38% of global land area, and expansion/shifting of land brings issues such as land degradation, nutrient pollution, and
biodiversity loss (20, 22). However, land-use and crop concerns are not associated with all renewable feedstocks, dependent on the feedstock being utilized. Companies are already taking action to address these concerns. For example, Ralph Lauren® (New York, New York) recently committed to new sourcing standards for their cellulosic-based products (including viscose and rayon) to ensure these fibers are not connected with deforestation (23).

Other tools exist for assessing environmental sustainability in apparel, such as the SAC’s Higg Index. The Higg Index provides performance scores that are data-driven and allows for benchmarking compared to others in the textile industry (24). Approximately 80% of survey respondents indicated that they used the Higg Index. Additionally, the SAC released the MSI in 2016, which allows companies to perform a side-by-side sustainability comparison of materials (24). Respondents indicated use of the MSI to decide what materials were considered sustainable at their company. The Textile Exchange’s Material Snapshots and Summaries and Preferred Fibers were also utilized to investigate the sustainability of materials (25).

**Utilization Drivers**

An important takeaway from the survey was the identification of drivers that would increase the utilization of RRFs. When asked if they would be increasing their production or sale of RRF over the next three years, 55% of respondents stated that they would be increasing their production and the remainder indicated they would be staying consistent with their current usage. The respondents that stated they would be increasing RRF were asked to rate a range of factors based on their influence in driving the increase. Figure 1 shows each variable and the percentage of respondents that ranked it as a ‘medium to high influence’ or ‘little to no influence’. Based on Figure 1, 80% of respondents ranked ‘internal sustainability goals’ as having ‘medium to high influence’ in driving their RRF production. These perceptions are in line with statistics put out by the U.S. Green Building Council, which found that over 50% of Fortune 500 companies have internal sustainability practices (26). Similarly, according to the 2015 Sector Benchmark Report by the Textile Exchange, which surveyed 57 leading companies from 14 countries, 81% of companies have a sustainability strategy that addresses fibers and raw material use and 57% of companies have set goals to incorporate sustainable, recycled, or organic material into their business (27).
Customer demand from brands and/or retailers was indicated as the next highest driver in the ‘medium to high influence’ category at 77%. Industry sustainability trends and sourcing availability were chosen as a ‘medium to high influence’ by a lower percentage of the respondents at 68% and 63%, respectively. The greatest driver that had ‘little to no influence’ on respondents’ increased production/sale of RRF were ‘domestic or international regulations’ (79%). This low priority rank falls in line with the current regulatory environment, which does not contain specifically set standards for renewable resource materials or fiber requirements in the textile sector. While the textile manufacturing sector addresses topics such as chemicals used in the dying process, social labor standards, and labelling disclosures, it does not specifically mention minimum renewable resource fibers (28,29,30). Furthermore, while governments have been targeting carbon emission reduction through policies, such as renewable fuel standards (31), renewable portfolio standards (32), and carbon markets (33), there are no specific regulations on the amount of renewable material that should be utilized in the textile sector.

Individual consumer demand, cost, and competition were perceived by approximately the same percentage of respondents to have a ‘medium to high influence’ and ‘little to no influence’. Other drivers not included in the survey that respondent's documented as having a ‘medium to high influence’, included environmental impact reduction and the ability for downstream customers, such as brands or retailers, to pay a higher price for the RRF materials.
All respondents were then asked to rate the importance of key drivers in increasing future RRF utilization, as shown in Figure 2. 54% of respondents cited customer demand as the most important factor, followed closely by cost (49%), fabric performance (47%), and sourcing availability (44%). Many brands and retailers are sourcing from suppliers that meet their own internal sustainability standards, such as NIKE’s (Washington County, Oregon) Sustainable Manufacturing & Sourcing Index and Walmart’s (Bentonville, Arkansas) Sustainability Index. Other brands and retailers use rating tool standards, like the aforementioned Higg Index, to push suppliers to change their sourcing and production practices in order to meet customer demands (34, 35, 25). Competition, internal sustainability goals, and industry trends for sustainability metrics or labelling requirements were seen as moderately important drivers for increased RRF utilization. Individual consumer demand and domestic/international regulations were seen as the
least important drivers.

**Figure 2.** Drivers for Increased Utilization of RRF (Part 2)

**Barriers to Utilization**

Respondents were asked to rate the barriers in increasing RRFs at their organization (Figure 3). The cost of inputs was rated as an extremely important barrier by 66% of the respondents. When asked to elaborate on the cost barrier, respondents pointed to a variety of reasons. These included financial barriers to invest, the reluctance for downstream brand, retailers, and individual consumers to pay for the added costs of producing RRF compared to synthetics, and the risk of sourcing a material available from minimal suppliers. A few cited the global “fast-fashion” trend...
as the major driver for ensuring minimal costs. The fast fashion trend is the phenomenon of producing cheap clothes, through low quality inputs and mass scale production, to satisfy the demand for clothing with a high consumer turnover rate (36). Furthermore, the lack of RRFs at a commercially viable price was cited as a major deterrent to increasing utilization. This perception complements findings from the Milken Institute, with support from the U.S. Department of Agriculture, which identified the greatest financial barriers to biobased products to be: 1) long gestation periods, 2) competition from petrochemical producers, and, 3) expensive capital requirements to scale up production from the laboratory (37). In order to lower input costs, improvements in logistics for RRF, innovative production routes with high yields, new microbial enzymes, and successful downstream processing will need to be developed at a large scale (38).

**Figure 3. Barriers to RRF Utilization**
Availability of inputs was a barrier selected by 60% of the respondents as an extremely important barrier. Closely following barriers included performance of RRF at 56% and change in manufacturing technology needed at 43%. RRF processing times and a general lack of knowledge were selected as moderately important barriers by 56% and 46% of respondents, respectively.

Regarding availability of inputs, respondents cited the lack of availability of raw materials for large-scale commercialization as well as location of supply as major issues. In terms of performance, respondents pointed out that the manufacturing and dying process of synthetics can be improved to reduce environmental impact without sacrificing fabric quality more easily than they could be in RFF processes. Additionally, respondents indicated that technology/process changes needed to increase RRF materials would require a change in current plant configuration and capacity, scalable technology, adjustment of chemical synthesis processes, and planning time frame to allow for new vendor vetting and contract developments. Respondents indicated that building large-scale plants can be difficult with unclear estimations of supply and demand for RRF as well as unfamiliarity with associated technology.

The general lack of knowledge cited by respondents stemmed from various factors. Respondents were unsure of the traceability of RRF supply chains, and subsequently, how substantial the environmental benefits of RRF were compared to synthetics or other fibers. Another common uncertainty was the connection of RRFs to the food industry. This uncertainty stemmed from the perspective that RRFs may take away valuable land, water, and resources that can be used in agricultural production. A smaller barrier was a lack of interest in RRF among fabric suppliers and final consumers, and internal prioritization towards lowering Scope 2 emissions through renewable energy rather than through renewable feedstocks.

**Performance**

The performance of material is an essential attribute, especially for consumers making a purchasing decision. Despite the recent “fast fashion” trend, a survey completed by Cotton Incorporated (Cary, North Carolina) in 2013 found that 80% of consumers would not buy a piece of clothing if the quality degraded after several wears, and 70% of consumers state they would
not purchase clothing if it held odor, pilled, or shrank (39, 40). This is important, especially since product value to the consumer is linked to the success of the product for the brand (41).
Performance was defined in this analysis as the functionality of a material relating to stain and fade resistance, durability, care attributes, etc.

This survey asked how companies perceived the performance of renewable feedstock apparel on a scale of “poor” to “excellent” (Figure 4). Approximately 41% of respondents indicated that the performance was perceived as “average” and 39% believed performance to be “good” or “excellent.” Several respondents stated that the performance was the same as synthetic options and was not an issue in using RRFs. However, 20% of respondents reported performance to be merely “fair” or “poor.” These respondents were then asked if they believed the performance would increase in the future to levels acceptable by their company. The response was partially divided, with 61% indicating that the performance would increase to acceptable standards and 39% indicating that they did not think feedstocks would reach desired performance levels.

![Figure 4. Stated Performance of RRF](image)
Many companies manufacturing RRFs analyze their performance. For example, NatureWorks LLC. (Minnetonka, Minnesota) provides performance data on washing, drying, wicking, odor, pilling, and more on its plant-based fiber Ingeo™ (42). DuPont provides similar performance information on its Sorona polymer, including properties such as wrinkle-resistance, packability, comfort, and colorfastness (43). Research on RRFs and their performance attributes should be conducted to comprehensively understand their performance, specifically for apparel applications and in the viewpoint of the consumer. Broader comparative studies of performance have already been completed on biopolymers and cellulosic fibers, such as the work of Van de Velde and Kiekens (2002), Niaounakis (2015), Flaris and Singh (2009), and Shen, et al. (2010) (44,45,46,16).

**Operational Difficulties**

Survey respondents were asked about the operational difficulties in using RRFs (Figure 5). Operational difficulties in this analysis were the upstream (of the consumer) challenges in processing, obtainment, and, manufacturing. These difficulties included challenges with cost, resource availability, performance during processing, manufacturing technology needs, and time. Approximately 27% of respondents indicated that cost was the most significant operational difficulty. A few companies pointed out that this would be alleviated if consumers shifted their mindset on what clothing truly costs, as well as if sustainable materials could be used in a wider variety of goods and not just “specialty” items. Resource availability was chosen by 21% of respondents as a significant operational difficulty. One brand pointed out that it encountered challenges in both fiber access and quantity of supply.
As a few companies noted, the operational difficulties companies face may partially originate from RRFs being nascent in the market. As with any new product, there is a learning curve over time until the manufacturing methods, costs, and technology involved are comparable to mainstream options. The survey results indicate that more research should be completed on the manufacturing technology and sourcing options available for RRFs.

**Industry Leaders**

The need for more sustainable apparel has driven innovations in textile creation. A basic search of renewable textiles reveals fabrics made from a variety of materials such as recycled plastic bottles, shoes, seaweed, and pineapple leaves (47,48). Survey respondents were asked to identify whom they believed are industry leaders for RRFs, for both brands and manufacturers. There were a total of 18 brand leaders and 22 manufacturers stated. Table 1 shows several of these leaders.
<table>
<thead>
<tr>
<th>Brand/Manufacturer</th>
<th>RRFs</th>
<th>Details</th>
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<tbody>
<tr>
<td><strong>Patagonia</strong></td>
<td>Various RRFs and sustainable materials</td>
<td>Patagonia is considered by many respondents to be a leader in renewable textile use. Twelve of our survey respondents mentioned Patagonia as a leader in this field. They incorporate a large portfolio of RRF technologies into their apparel. These include plant-based products like hemp and organic cotton, recycled materials including nylon, down, plastic polyester, and wool, and more technologically sophisticated products like Tencel® Lyocell and Yulex®, both of which are plant-based fibers (49).</td>
</tr>
<tr>
<td><strong>Elieen Fisher</strong></td>
<td>Various RRFs and sustainable materials</td>
<td>Eileen Fisher was mentioned by three respondents in our survey. They are gradually replacing Rayon with Tencel® (50), use recycled cashmere and cotton scraps from production, use recycled nylon (from fishing nets), and polyester made from recycled bottles, clothing and other post-consumer waste. (51)</td>
</tr>
<tr>
<td><strong>Levi’s®</strong></td>
<td>Various RRFs and sustainable materials</td>
<td>Levi’s®, famous for their “Waste&lt;Less” collection which integrates 20% post consumer waste (largely plastic bottles) into their apparel, was mentioned three times by survey respondents (52).</td>
</tr>
<tr>
<td><strong>H&amp;M</strong></td>
<td>Various RRFs and sustainable materials</td>
<td>H&amp;M was mentioned by six respondents as a leader. H&amp;M encourages consumers to recycle used clothing and has facilitated the process for them, recycling more than 12,000 tonnes of garments collected at their stores in 2015. The company blends in about 20% of recycled fibers into their clothing (53). They also use recycled polyester made from PET bottles (53).</td>
</tr>
<tr>
<td><strong>Inditex</strong></td>
<td>Various RRFs and sustainable materials</td>
<td>Inditex, the fashion retail group behind eight brands including Zara, was mentioned by three respondents and uses Tencel® Lyocell, recycled polyester and cotton, and organic cotton in its products (54).</td>
</tr>
<tr>
<td><strong>DuPont™</strong></td>
<td>Sorona®</td>
<td>DuPont™ Sorona® has emerged as a leading RRF. The Sorona® polymer contains 37% renewable plant-based ingredients, made from corn starch. It is a flexible fiber that combines nylon and polyester-type performance for usage in denim and athletic apparel (43).</td>
</tr>
<tr>
<td><strong>Lenzing</strong></td>
<td>Tencel®</td>
<td>Among resource providers, Lenzing, which produces Tencel®, was recognized as a leader. Tencel® is incorporated into many of the leading brands above. Tencel® is a lyocell fiber originating from the pulp of trees and then dissolved in a non-toxic solvent which is then recycled in a closed-loop cycle. It can be used in place of textiles such as rayon, which also originates from wood pulp, but often uses toxic chemicals like formaldehyde for processing. Tencel® is known for its durability and strength as a fiber (55).</td>
</tr>
<tr>
<td><strong>Lenzing</strong></td>
<td>Modal®</td>
<td>Lenzing Modal® is produced from beechwood tree fiber sourced from Austria. Its main attribute is its softness. Lenzing Modal® is fully integrated on site in Austria, leading to reduced energy impacts and the recovery of leftover wood (56).</td>
</tr>
<tr>
<td><strong>NatureWorks LLC.</strong></td>
<td>Ingeo™</td>
<td>NatureWorks LLC. Ingeo™ is a biopolymer created from sugars from corn, known for its versatility and performance. NatureWorks LLC states that in the future sources can be agricultural waste and non-food plants. Ingeo™ also can be purchased with a choice of certification options related to genetic modification (57).</td>
</tr>
</tbody>
</table>
**Overview of Consumers**

Consumers play a critical role in sustainability efforts within the apparel sector. Consumers’ willingness to pay for products, knowledge of sustainability practices, and attitudes towards sustainable options influence whether or not an apparel company will benefit from its sustainability efforts in the market. In turn, these consumer factors are essential to investigate for the increased utilization of RRFs.

**Sustainability in the Apparel Industry**

A study by Hill and Hyun-Hwa (2012) on generation Y consumers (18-35 years of age) investigated consumer perception of sustainability in the apparel sector. The study found that three dominant themes arise in consumer’s definition of sustainability in apparel, including extended product life, resource conservation/preservation, and environmental considerations (58). 28% of survey respondents in the study believed they had knowledge of environmental impacts in apparel, with top impact issues stated as synthetic fibers and use of natural resources, cited by 11% and 9% of consumers, respectively (58). Additionally, a main sustainable practice in apparel was thought to be use of natural or environmentally friendly fibers (58).

There are also doubts about sustainability in the apparel value chain. One theme that appeared in literature was the conflicting interest between apparel and sustainability; that the two were inherently at odds with each other. The “fast fashion” trend, concerns with quality and durability, preconceived notions of luxury versus sustainability, and convenience of products play a role in this (59, 60). Even if a consumer looks for sustainable apparel, the quick turnover of fashion trends may lead to the frequent disposal of the apparel, contributing to increased waste (61). A survey on sustainability and fashion found that only 14% of consumers state they always think about sustainability/ethics when purchasing products and quality is a higher priority when buying clothing. Although, the consideration of renewable fibers was indicated by several individuals as well (61).

Relationships exist between attitudes towards environmental products and personal environmental impact with the actual purchase of a sustainable product. When looking at perceived environmental knowledge, attitude towards purchasing, and environmental concern,
attitude has the most influence on future intention to buy sustainable apparel (62). In general, the more positive the attitude and the higher the awareness a consumer has on their personal environmental footprint, the greater the likelihood of purchasing a sustainable product (62). However, many individuals feel that their apparel consumption does not have an impact on the environment and know little about the upstream textile production processes (62).

**Lack of Knowledge**

A consumer concern in sustainability and apparel is the lack of knowledge in environmental impact (58). Consumers are in a “pre-awareness” phase with sustainability in apparel, especially as compared to other sectors such as food, primarily due to lack of personal connection and transparency in supply chains (63). Utilizing social influences, enhancing positive emotions for sustainable apparel, and being transparent with both the successes and failures of apparel impacts will aid in informing consumers (63,64). Interestingly, research has shown that once a consumer decides to remain ignorant in obtaining or disseminating information on a good, the consumer is less likely to change their purchasing habits in the future (64). This ignorance, referred to as “willful ignorance,” arises out of avoidance of feeling a negative emotion that would be associated with the purchase of a product that may go against what the consumer cares about, such as environmentally-friendly or ethical attributes (65, 64). In contrast, if social norms are positive and point to society purchasing environmentally-friendly apparel, a consumer is more likely to purchase the apparel product himself (62).

This lack of knowledge doesn’t necessarily mean a consumer will not purchase a sustainable product (66). Labeling is an influential part of buying sustainable apparel, as 57% of consumers are educated about a product's sustainability attributes through its product label while only 22% actively seek information on the product brand’s website (59). But some consumers are uncertain in the validity of green claims on the label, and rely on the sustainability efforts of the brand itself in guiding their trust in the product (67). Labels don’t always provide all the information needed to make a purchasing decision, so brands need to focus on providing *enough information* and the *right information* to influence the purchase (63). This is where sustainability indexes, such as the Higg Index, can play a role in consumers’ perceptions of sustainable performance in apparel brands and increase label clarity (68). Studies have found that 60% of generation Y
consumers show favorability to brands they regard as involved with sustainability and consumers today are more attune with a company’s responsibility efforts (58,62).

More on Purchasing Patterns
Product cost plays an influencing role in the purchase of products. This is especially true in apparel, as often the consumer’s perception of what a piece of clothing should cost is often vastly different than what that piece of clothing truly costs, as explained by one surveyed apparel brand. Consumer indication of willingness to pay for sustainable products, as described early in this report with the Nielson Survey results, has increased in the past years. Millennials are more attuned to sustainable products and state a high willingness to pay for them (69). Conversely, apparel companies do not see this willingness translate into purchasing in many cases. The attitude behavior gap describes consumers’ positive attitude towards sustainable goods but the lack of tangible action in purchasing the goods due to personal motivation and benefits, public influence, or the like (70,71). Other studies site that consumers are demanding more sustainable, transparent products and this demand will continue to grow (72). Once consumers shift their mindset and accept sustainable materials, including the recognition of their benefits, the apparel chain believes opportunities exist (73).

Scientific Perceptions
A literature review of scientific journals was conducted to understand the scientific perceptions surrounding RRFs. The term ‘biopolymers’ is used in this section because the scientific community was more likely to use the terms ‘biobased plastic’ ‘biobased polymer’ and ‘biopolymer’ instead of RRF. Additionally, more research was available regarding man-manipulated chemical feedstock derived from biological monomers. The sustainability of biopolymers is still an ongoing debate in scientific literature depending on the raw material feedstock, agricultural practices, energy consumption during bioplastic conversion, and cradle to grave LCA (74). This section outlines a few major perceptions uncovered.

Benefits
Energy and Greenhouse Gas Reduction
A primary benefit of biopolymers as compared to petroleum-based polymers are the reductions
in energy and carbon emissions. According to Massachusetts Institute of Technology’s Materials Systems Laboratory, polyester production produced about 706 billion kilograms of greenhouse gas and is expected to increase to 1.5 trillion kg CO2e by 2030 (75). According to the U.S. Department of Energy (76), substituting a biopolymer, such as polylactide (PLA), for petroleum-based fibers can reduce fossil energy use by about 62%. According to a study found in the Journal of Cleaner production that evaluated lifecycle sustainability of biopolymers, Polytrimethylene-terephthalate (PTT) requires 26-50% less energy and emits 44% less greenhouse gas while another common biobased polymer, polylactic acid (PLA), uses 30-50% less energy and produces 50-70% less greenhouse gas emissions than conventional polymers (77).

**Chemical Structure**

To be able to supplant conventionally produced synthetic fibers, biopolymers must possess similar properties or performance of the fibers it aims to replace. Current technology can produce bio-based monomers or recycled polymers that mimic the performance of conventionally produced synthetic fibers (78). There are currently two dominant approaches to producing biopolymers- bioreplacement polymers and bioadvantaged polymers. Bioreplacement polymers are formed from monomers derived from bio-based sources that are chemically identical to the petrochemical counterpart (79). Through catalysis and synthetic biological tools, feedstock such as starches, sugars, and lignin can be broken down into simple molecules also found in oil. Because the produced monomers are identical to the petroleum-based monomers used for synthetic fiber production, companies that are using such polymers will not have to relearn how to integrate these monomers into the final products during the later stages of the supply chain (79).

**Rural Economic Development**

According to a report from the Milken Institute, the rural United States is a leading exporter of agricultural goods. Increased demand for biopolymers can increase demand for cash crops, cellulosic fiber, and biochemical production and processing jobs, thereby stimulating the rural United States economy (80).
**Challenges**

Barriers to large-scale adoption of biopolymers based on literature review showed uncertainties in environmental impacts, food competition, overcoming financing and scalability barriers, and waste management.

**Food Competition**

Food competition is more prone to arise in developing countries, where farmers may choose to grow more valuable biofeedstock for biopolymer production rather than cheaper food for human consumption (78). This was seen during the “Mexican Tortilla Crisis” in 2007 after the U.S. had committed to increasing production of bioethanol from corn. Financial speculation caused the price of corn to inflate in Mexico, making the staple largely unaffordable to the masses (78). In contrast, food competition may also be viewed as a problem of the future as biofeedstock replace a larger portion of petroleum-based products, and not one that is evident from current biopolymer production volumes (81). Scientific literature is still debating the food versus material conflict without a concrete conclusion and more research is needed to understand this debate (81). As shown from the results of the survey, however, this topic is still a major perception in the apparel sector.

**Agricultural Impacts**

Environmental uncertainties, especially related to climate change mitigation, are unclear. While reducing fossil fuel burning will ultimately reduce carbon emissions, increased production of RRF can affect natural carbon sequestration by transforming rainforests and naturally occurring grasslands into farmland (78). With land use conversion and increased pesticide usage comes biodiversity loss (78). Increased usage of fertilizers to grow biofeedstock can contribute to greater emissions of nitrous oxide. Further scientific research and analysis is needed to develop an overarching, single methodology to evaluate emissions and biodiversity impacts from land-use conversion and RRF production (82).

The principles laid out by the Sustainable Biomaterials Collaborative call into question genetically-modified organisms, petroleum-based copolymers during production, hazardous additives or untested nanomaterials, and inefficient use of water and energy, as not
environmentally sustainable. (77). Occupational-safety hazards are also cited as concerns due to exposure to pesticides, terephthalic acid, dimethyl terephthalate, and methanol and the explosive hazards posed by pulverized starch (77). To bypass this barrier, it is recommended to derive RRFs from agricultural and industrial byproducts, such as corn stover and lingo-cellulosics, that will reduce land use for polymer production, and also address the food competition barrier mentioned above (78,77). Also, utilizing sustainable agriculture or certification methods is another way to overcome the environmental concerns associated with RRF production (77).

Life-Cycle Uncertainties
Consumer product developers’ hesitation about adopting biopolymers can stem from environmental impact uncertainties regarding biopolymer lifecycle and the complexity of assessing and interpreting the impacts from input to waste stream as compared to petroleum-based polymers (81). Such uncertainties can create a perceived greenwashing and marketing risk from touting environmental and sustainability benefits that companies may not be confident about (81). This perception can be strengthened by the misconception that biopolymers are automatically biodegradable, which is not always the case, especially if deposited into a landfill (78). Biodegradable biopolymers can also produce exclusively carbon dioxide and water as they degrade over a long period of time and can disintegrate into small micro-and nanoparticles, which pose inhalation risks to human health (78).

Commercial Viability
Similar to the perceptions upheld as a barrier in this study’s survey, literature review also supported commercial viability to be a significant barrier. A major contributor to this barrier is the cost of bioconversions to transform the feedstock into a monomer (82). An important contributor to the success of biopolymers is to improve the efficiency and productivity of bioconversions, such as fermentation processes, to increase the variety of monomers that can be produced at an industrial level (82). As mentioned previously, bioreplacement polymers result in the production of monomers that are similar to their petroleum-based counterpart but lack commercial viability because of a few major challenges- increasing the specificity of the target compound, managing the toxicity of product, and cost-effectively recovering the product at an appropriate purity level (79). Additionally, the petroleum industry has a major advantage in that
they can amass value through specialty value-adding products; 90% of the value of the petroleum industry comes from specialty products that account for only 10% of the volume (79).

Long gestation periods and scalability are other barriers hampering commercial viability. The long gestation periods for biochemicals, about 5 to 10 years, poses a risk to investors who are typically looking for shorter investment periods, leaving many biotechnology companies stranded in the ‘valley of death’ (80). While the petroleum industry has the time advantage of over 100 years to produce strong economies of scale, supply chains, and fully amortized refineries, the biopolymer industry faces large challenges in achieving those three complex tasks while attracting investors and buyers with lower than average costs (74,80). Finally, chemical feedstock, as a cheap commodity, lacks commercial attractiveness to investors. These different issues disincentivize investors from investing in young biobased companies, thereby contributing to lack of large-scale commercially available biobased chemical feedstock acknowledged in the survey.

**Definitional Challenges**

In accordance with our survey results, scientific literature review indicated a lack of a consensus definition for biopolymers (77). The Business-NGO Working Group for Safer Chemicals and Sustainable Materials defined bio-based plastic as plastics that have 100% of their carbon derived from renewable agriculture and forestry resource. In contrast, the U.S. Department of Agriculture accepts that a bio-based plastic does not have to be 100% derived from renewable resources but should have a significant portion of its carbon derived from renewable resources. Most biopolymers on the market contain a mix of bio-based and petroleum-based derivatives (77). This variation in definitions could contribute to the lack of understanding or uncertainties regarding the environmental impact of renewably sourced materials in the industry today.

**Recommendations**

Based on findings from the stakeholder survey and literature review, there are four, key recommendations we propose for the apparel industry. Exploring these recommendations would allow stakeholders to better understand the RRF landscape and possibly increase their utilization throughout the value chain.
**Recommendation #1: RRF Term Development**

One of the most prominent analysis findings was that the term “renewable resource feedstock” is not widely recognized or used within the apparel industry. Survey respondents were confused by the term, preferred other terms in its place, defined the term differently, and held various opinions on the scope of the definition. With this level of ambiguity, it would be difficult to increase the utilization of RRFs or effectively demonstrate their placement in the market.

Industry should decide on a concrete definition of RRF. This should include what feedstocks are accepted as RRFs, the minimum percentage of RRF that a material must contain to be considered an RRF product, and standards on land practices for forest/agriculturally derived feedstocks (i.e. certifications and best land practices). One point to consider is the use of recycled or reused material for apparel. Stakeholders indicated that recycled PET and materials such as fishing nets should be considered feedstocks, especially since they are more “sustainable” than other options.

If industry consensus cannot be reached on the definition and its scope, it will be increasingly difficult to use RRF as an umbrella term. Companies will stick to their own subjective and individualized terms and definitions.

**Recommendation #2: Reduce uncertainties surrounding environmental impacts**

Our second recommendation is for the industry to attempt to reduce misperceptions surrounding the environmental impacts of RRFs. As many respondents indicated, they were concerned about the potential impacts with regards to land use, GMOs, and life cycle emissions and impacts from fertilizer and pesticides used to grow the feedstocks. Life cycle assessment is guided by International Standards Organization (ISO) standard 14040, which describes the principles and framework for these assessments. Specifically, these guidelines guide the way organizations carry out these assessments. ISO also provides guidelines for Environmental Product Declarations (EPD) which is an “independently verified and registered document that communicates transparent and comparable information about the life-cycle environmental impacts of products” (83). EPDs are used by companies to assess the environmental impacts of products, which are reviewed by a third-party reviewer, providing a level of legitimacy.
Despite this, distrust persists when a company shares the environmental benefits of its products. Our primary recommendation is for the industry to move toward a standardized methodology or means of comparison for materials. Both the Higg Material Sustainability Index and the Textile Exchange Preferred Fibers guide are moving the industry in this direction. Because of their nature as industry organizations, these tools may be perceived by customers and consumers as trustworthy and will allow them to easily compare between materials based on their environmental attributes.

While a standardized methodology for life cycle assessment is one solution, certification strategies may also move the industry toward increased customer/consumer acceptance of RRFs. Certifications exist in a variety of industries to produce assurance that raw materials were sourced in an environmentally or socially preferable way. The industry could certify the raw materials that go into RRFs (sugar cane, corn, forestry products, etc.) to demonstrate the environmental benefits (whether showing that deforestation or land use degradation did not occur, or that the product was grown in a sustainable way). By communicating this attributes via a product tag, the consumer can make a better decision at the point of purchase without having to conduct extensive external research.

**Recommendation #3:**
As indicated from both industry and scientific perceptions, commercial viability must be explored further to improve the feedstock supply and the financing of the technology and infrastructure required to produce biobased chemical feedstocks. Specifically, improvements in large-scale commercialization of the feedstock, enhancements in traceability of the feedstock across the supply chain, and an increase in the number of suppliers will help to increase the security of the supply base.

As mentioned before, bio-processing technology and infrastructure is expensive, time consuming, and lacks profitability due to the fact that chemical feedstocks are cheap commodities and competition exists with the mature petrochemical industry. These reasons disincentivize investors from investing in young biobased companies, which contributes to the
small supplier base and prevents biobased feedstock developers from achieving scalability. To combat these issues, green banks should offer standardized bonds to finance loans that are backed in part by the government and traditional investors (“Financial Innovations Lab”, 2013). Furthermore, partnerships between large chemical companies and young biobased companies could allow for idea sharing, cost sharing, and technology and infrastructure sharing.

Advances in biotechnology could help overcome commercial viability barriers by emphasizing stand-out performance and cost of RRF (84). For instance, bioadvantaged polymers are produced from biological monomers, some of which have no petrochemical counterpart, such as unmodified vegetable oils, proteins, cellulose, and starch chitosan (79). Such monomers hold an advantage in capturing a market through their physically and chemically distinct properties and potential for innovative applications. These monomers are also advantageous in that they do not have to be broken down into simple molecules before polymerization, which can be a costly step (79).

**Recommendation #4: Improve Marketing**

Our final recommendation is for the apparel industry to further market the environmental and performance attributes of these products, as well as to engage in consumer behavior change to influence consumer’s purchasing decision.

As demonstrated in our study, the industry regards performance as one of the most important reasons to choose or not choose a specific fiber. Many of these fibers perform similarly, if not superiorly, to traditional synthetic fibers, with some having unique attributes that make them stand out in the industry. Companies need to market the performance of these products first and then market the environmental attributes as an added benefit. Consumers are willing to pay more for a product that performs better, yet the reputation of environmental products as having inferior performance persists.

Moreover, the uncertainty surrounding the environmental impacts of RRFs was identified as a use barrier. Companies utilizing RRFs need to increasingly work to reduce this uncertainty. As mentioned above, the Higg MSI and the Textile Exchange Preferred Fibers definitions are
moving the industry in this direction. The initial goal of the Sustainable Apparel Coalition and the Higg Index was to eventually produce a consumer-facing label that easily communicates the environmental and social impacts of the article of clothing on its tag. Our consumer research revealed the consumers are more likely to be persuaded by an attribute listed on a tag as opposed to researching information on a website.

Conclusion & Future Discussion
While the apparel supply chain is increasingly utilizing RRFs due to pressures such as consumer demand and sustainability goals, our study revealed barriers to implementation and knowledge gaps. Predominate barriers include cost, technology, and sourcing difficulties. A significant issue is with the terminology used for sustainable materials. In order for the industry to further adopt RRFs, an agreed-upon definition of the term or change in the term entirely will be needed. Moreover, continued collaboration across the apparel supply chain, as well as technology advancements, are crucial components in RRF adoption. Based on the survey’s results, a strong need exists for further research of RRFs, their environmental impacts, and the major barriers in their adoption.
References


