An Analysis on the Environmental Impact of the Fashion Industry

by

Alejandra M. Navarro

Submitted to the
Department of Mechanical Engineering
In Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science in Mechanical Engineering

at the

Massachusetts Institute of Technology

June 2021

Signature of Author: ____
Department of Mechanical Engineering
May 2021

Certified by: ____
Svetlana Boriskina
Research Scientist of Mechanical Engineering
Thesis Supervisor

Accepted by: ____
Kenneth Kamrin
Associate Professor of Mechanical Engineering
Undergraduate Officer

An Analysis on the Environmental
Impact of the Fashion Industry

by

Alejandra M. Navarro

Submitted to the Department of Mechanical Engineering
on May 2021 in Partial Fulfillment of the
Requirements for the Degree of

Bachelor of Science in Mechanical Engineering

Abstract

The fashion industry is a large global sector. Cultivation, manufacturing, and distribution is spread out throughout the world with travel connecting all these pieces to deliver garments. With clothing accounting for 7% of the world's exports, demand is high, and the sector is evidently growing. This projected growth, however, is not able to be sustained for much longer.

This thesis explores the current state of the industry, expanding on different metrics to grasp its impact on the environment. The lifecycle of textiles is used to get a holistic picture of the fashion world. With pressure on companies and individuals to change and adopt to needed sustainability efforts, there are already movements occurring to encourage a green industry. These are seen through alternative textiles, new technologies, and sustainable marketing. Studies reveal that consumers' shopping behaviors do not always agree with their belief that current environmental status is a concern, which could pose new threat. With promising solutions emerging, the time to act and mobilize action to reshape the fashion industry is now.

Thesis Supervisor: Svetlana Boriskina
Title: Research Scientist of Mechanical Engineering

TABLE OF CONTENTS

LIST OF FIGURES

1. Introduction

The fashion industry is a global producer of nearly 100 billion garments annually [1]. The overconsumption of clothes results in a short use period which is evident by 80% of textiles ending up in landfills or incinerated—rather than recycled—within a few years after production [2]. An estimated 10% of global greenhouse gas emissions come from this industry alone, beating aviation and shipping combined. Additionally, textile production contributes to 20% of global water pollution [3].

Evidently, the industry is a large-scale contributor to the current state of the environment and climate change. The focus of this thesis is to examine this industry sources of high impact and what steps it is taking towards a more sustainable future.

2. Background

The environmental impacts of the textile industry are mostly concentrated in the following five areas: water scarcity, eutrophication, chemicals, climate change, and abiotic resource depletion. In order to quantify these impacts and compare different fabrics and garments to each other, a coalition of industrial players developed a cradle-to-gate lifecycle analysis tool, which assigns a non-dimensional environmental impact to a material, known as the Higg Materials Sustainability Index. Water scarcity is measured by water use, subsequent effect on water availability, and direct impacts on the water resource and its users from emissions to air, soil and water. These impacts can take form of eutrophication and water acidification [4]. Eutrophication the result of wastewater providing excessive enrichment to soil. This results in excessive agal growth that depletes the water of oxygen. The most common cause is nitrogen and phosphorous in fertilizers, which become deposited into water during the cultivation state of a material [5]. There are over 15,000 chemicals in use in the textile industry, which include dyes, pigments, and auxiliary chemicals[6]. They are heavily used during the wet pre-treatment and dyeing of material. The chemicals, and their emissions can be toxic and also be released into wastewater, posing a threat to marine environments. Climate change can be defined as the resulting change in global temperature from greenhouse gas emissions. The recent rate of rising global temperature is expected to bring drastic consequences such as climatic disturbance, desertification, and rising sea levels [7]. Climate change is measured in kilograms of CO2 equivalent. In Figure 2.1, global carbon dioxide levels have been increasing rapidly within the past century and are project to rise even more.

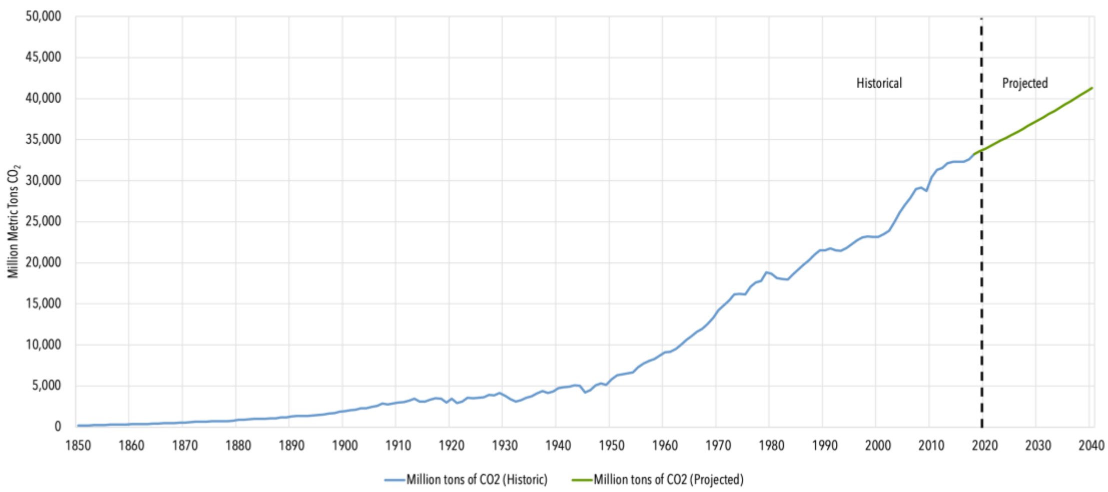

Figure 2.1 Global carbon dioxide emissions [8]

A more detailed analysis in Figure 2.2 reveals that China is drastically outputting more carbon dioxide than other countries. With more than 25% of textile production being done in China, as well as it being a manufacturing hotspot, this is not surprising. Moreover, China is projected to significantly output even more carbon emissions, while other countries are expected to be somewhat constant with current emissions.

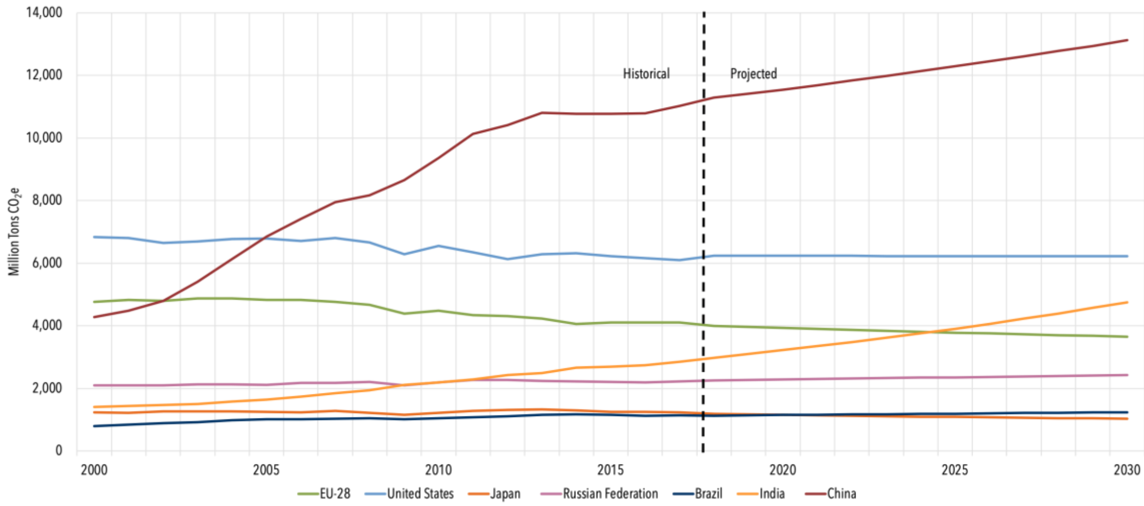

Figure 2.2 Carbon dioxide emissions of major economies [8]

Abiotic resource depletion refers to the use of fossil fuels, minerals, and metals. Fossil fuels have been a current problem regarding their depletion as well as their greenhouse gas emissions. Their consumption is seen through electricity, water heating, synthetic material production, agricultural machinery fueling, and other integrated forms throughout the industry [9]. The current energy production in the United States is seen in Figure 2.3, revealing the overwhelming dependence on fossil fuels. Nuclear and renewable sources of energy are rising slowly, but fossil fuels still drastically dominate the energy sector.

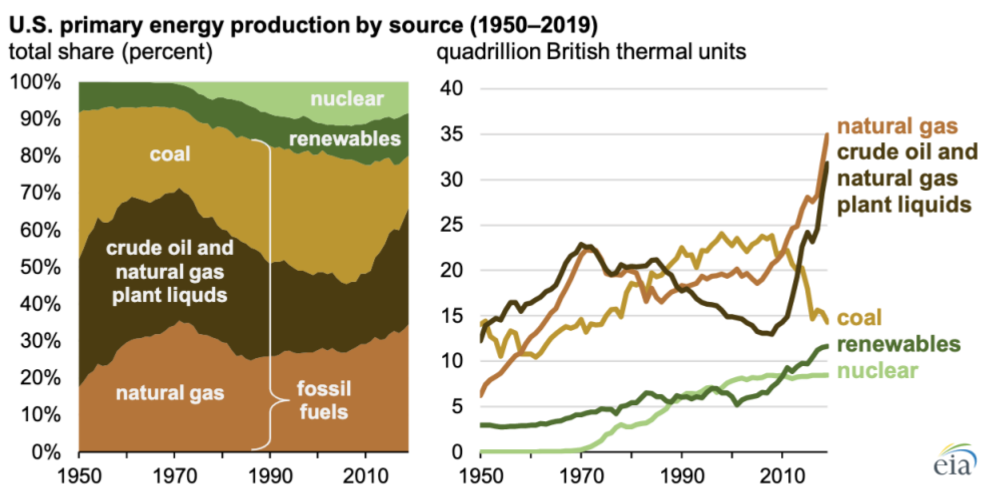

Figure 2.3 United States energy production [10]

These five categories of impact and determining sustainability of a material are relevant throughout all parts of a fabric's lifecycle that is explored in the next chapter.

3. Fabric Lifecycle

3.1 Raw Extraction

Cotton is the most popular fabric in the world, with an estimated 75% of clothing having some amount of cotton in it [11]. With 2% of total agricultural land used for cotton, it's large cultivation also requires lots of resources. This fiber is responsible for 24% of global pesticides use and is estimated to require anywhere from 7,000 to 29,000 liters of water per kilogram of cotton fiber [12]. The water use in cotton is extensive during cultivating stage and is at least 20 times higher than in the rest of its lifecycle. Organic cotton is grown without synthetic fertilizers or pesticides, and has a reduced toxic impact of 90% when compared to conventional cotton [13]. However, production of organic cotton is currently less than 1% of total cotton production, revealing a difficulty in switching over that might be related to higher costs. Hemp is being currently explored as an alternative to cotton as it requires little irrigation and less pesticides. It additionally has the added value of being stronger as well as being more resistant to abrasion, mildew, shrinkage, and fading [14]. Figure 3.1.1 compares these two fabrics on their impact. Cotton requires almost thirteen times more water than hemp with most of the water use coming from water extraction. There are evident trade-offs as hemp as more than three times an impact on eutrophication.

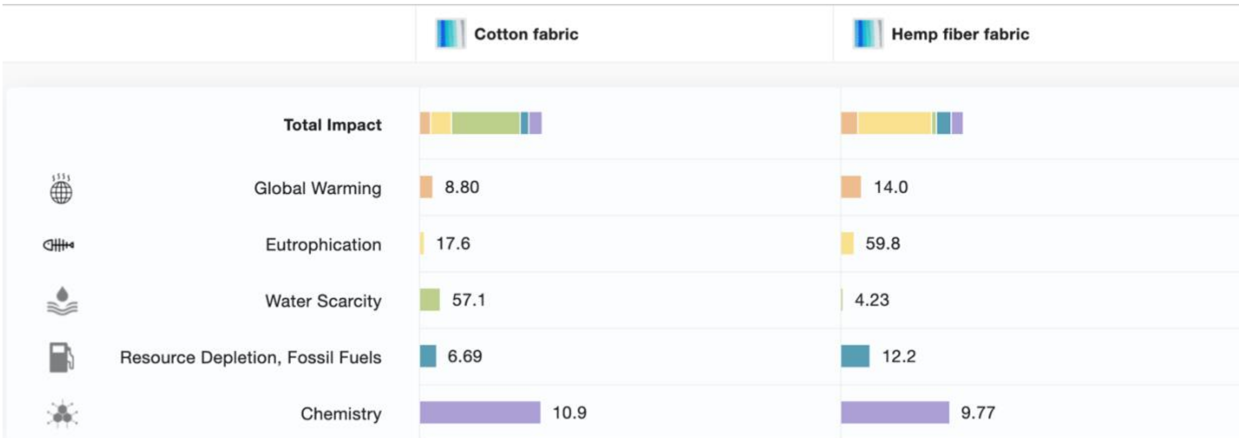

Figure 3.1.1 Higg Index comparison of cotton and hemp

3.2 Production

Synthetic fabrics are fossil fuel based and are popular in consumer consumption. They are produced from oil, coal, or gas and extruded from molten polymers. Figure 3.2.1 compares two synthetic fabrics (nylon and polyester) to a natural fabric (cotton). Cotton has about half the impact of polyester and almost a third of impact of nylon in regard to resource depletion, however, has a significantly larger impact on water scarcity.

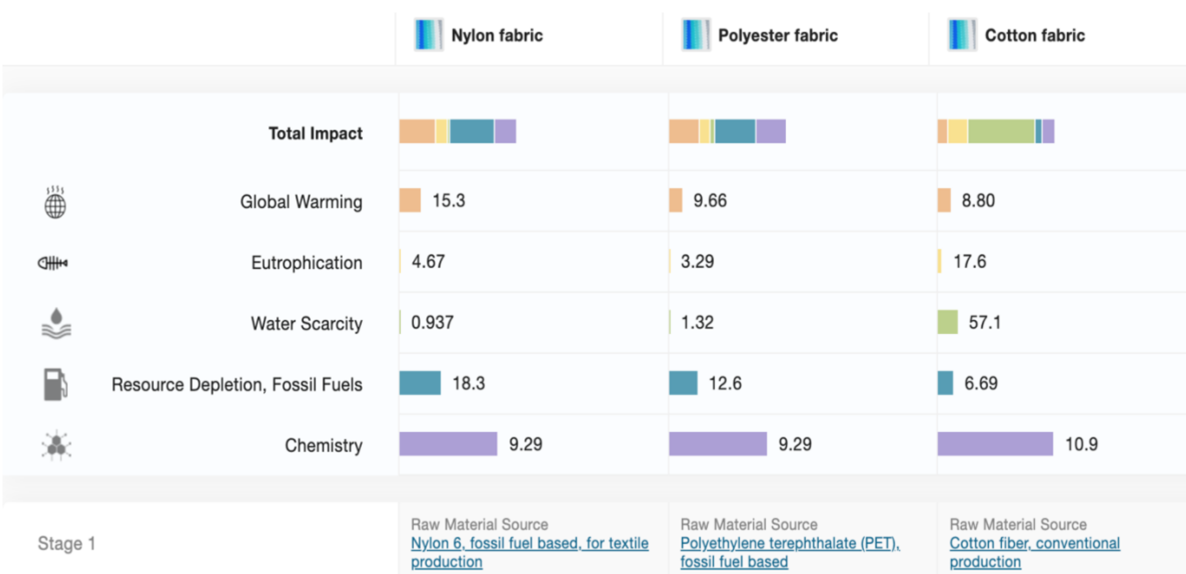

Figure 3.2.1 Higg Index comparison of synthetic and natural fabrics

During production, materials can undergo wet pre-treatment, dyeing, printing, bleaching, and washing. Figure 3.2.2 shows the varied impacts of dyeing among three fabrics:

polyamide, cotton, and polyester. All fabrics were dyed with the same chemical in order to fairly compare. Cotton took up almost twice as much water per kg of material than polyester did. It also required the most energy of all the fabrics.

Ecological costs of dyeing.

Assessed variables per kg		PA	CO	PET
Consumption of water (L)		50	70	40
Energy	Electrical (Q_E)	1.38×10^6 J	2.58×10^6 J	1.64×10^6 J
	Thermal (Q_T)	6.89×10^3 J	7.73×10^3 J	6.27×10^3 J
Fuel consumption (V_1)		1.46×10^{-4} m^3	1.63×10^{-4} m^3	1.33×10^{-4} m^3
Mass of CO_2 (mCO_2)		568×10^{-5} kg	6.37×10^{-5} kg	5.16×10^{-5} kg

Figure 3.2.2 Comparison of dye process impact in polyamide (PA), cotton (CO), and polyester (PET) [15]

The large consumption and impact of cotton is evident from this information, which makes sense that 25% of cotton waste arises during its production state [16]. Moreover, its water consumption releases chemicals into wastewater, posing a threat to water availability and water environments.

3.3 Distribution

The fashion industry sees most of its environmental impact during this part of the fabric's lifecycle through emissions of ocean and air cargo shipments. These both heavily rely on fossil fuels and contribute to air pollution. Both distribution methods are responsible for 2% of greenhouse emissions and in 2020 textiles made up 8% of ocean cargo volume and 6% of air cargo [17]. Emissions from air cargo are 40 times higher than ocean cargo, indicating companies should consider ocean transportation in the future. However, the tradeoff in smaller footprint is delayed time reaching the consumer. Ocean shipping is also currently on track to be responsible for 17% of greenhouse emissions, so it is not necessarily the better option over air. It is not simply enough to switch shipping methods, but also mitigate fewer and large shipments to lessen waste as well as explore renewable energy sources. On an individual level, consumers purchasing locally and in person would reduce the need for longer distance travel.

3.4 Use

While in the hands of a consumer, a material will make its environmental impact through washing, drying, pressing. A 100% cotton t-shirt will reduce its global climate change impact in half with the elimination of tumble drying, ironing, and combination with lower wash temperature [18]. Synthetic textiles use less energy for washing but pose a serious risk of microplastic pollution. For synthetic materials, an average wash load of 6 kilograms up to 700,000 microfibers are released [19]. Figure 3.4.1 compares a polyester-cotton blend (65% polyester/30% cotton), polyester, and acrylic garment—all of which were made from spun staple fibers. Acrylic produced almost 7 times the microplastic waste compared to the polyester-cotton blend. This might be due to the increased strength and resistance of blends; however, a downside is that they are harder to recycle than single materials, meaning that its lifecycle cannot be extended.

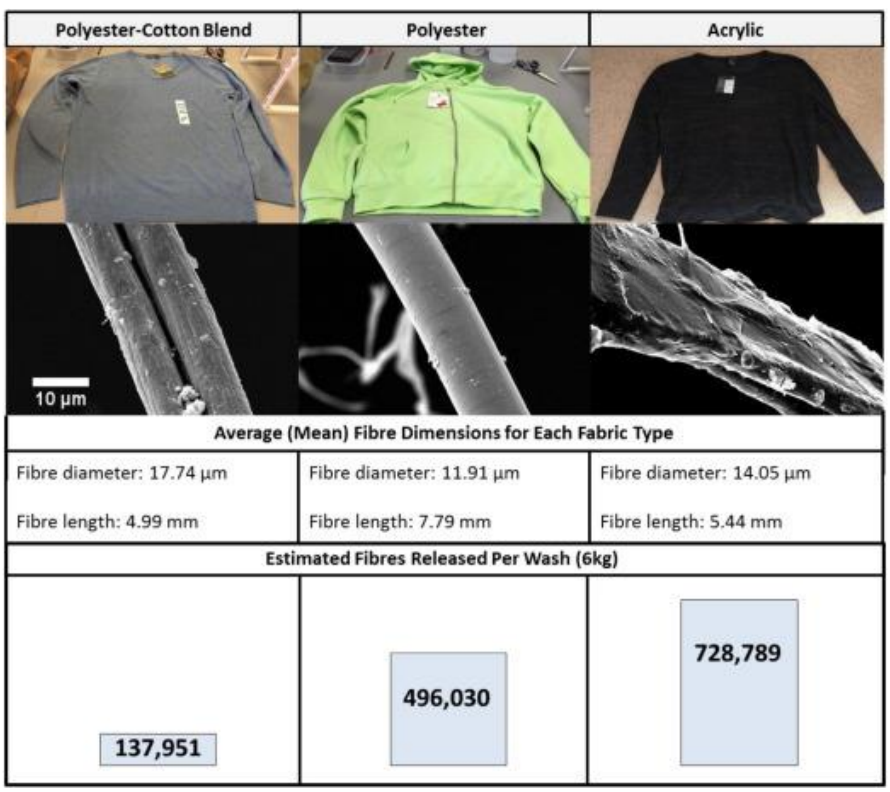

Figure 3.4.1 Three different material clothing and estimated fibers release [19]

These microfibers cannot be filtered, and an estimated half a million tons of these plastic microfibers end up in the ocean annually. They can stay in this ecosystem for as long as a few decades up to thousands of years. Ingestion by organisms in marine environments means that these microfibers can enter the food chain and subsequently interact with more animals. Clothes are experiencing a shorter use lifespan than before, revealing underutilization and excessive waste. A partial contributor to this trend is fast fashion. Enabled by outsourced cheap labor, the fashion industry has seen their total fiber production double from 2000 to 2018, with a 13.8 kg/person consumption average [20]. The average number of times a garment is worn before is disposed of has decreased by 36% compared to 15 years ago, with the United States wearing clothes a quarter as long as global average [21]. Underutilization is connected to the overconsumption culture which is seen more heavily in developed countries that have the disposable income to afford the lost value of throwing away clothes after only a few wears.

3.5 Disposal

Disposal is usually the last part of an item's life, resulting in a landfill or being incinerated. Almost 80% of garments end up in landfill, when 90% of them could have been recycled [22]. With the overconsumption and underutilization mentioned earlier, it is important to develop a circular lifecycle. Ways to do this are demonstrated in Figure 3.5.1

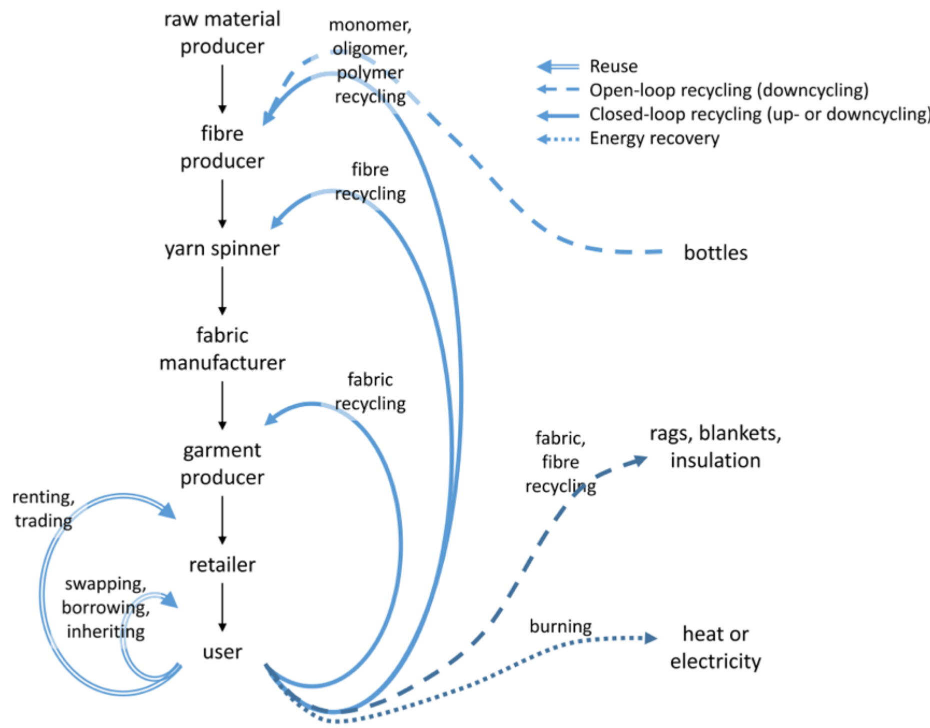

Figure 3.5.1 Textile Recycling and Reusing Options [22].

Fabric and fiber recycling still require the use of fossil fuels and virgin material. Additionally, since the waste fabric is usually mixed with dyes and contains polymer blends, it is a difficult process to recover and separate different material components and keep costs low at the same time. As a result, landfill and incineration is sometimes more ideal than recycling the fabric. Incineration reduces volume issues, and helps to recover energy, but it generates fossil fuel emissions as a downside.

Other considerations to recycling include the shift in source of environmental impact. Since cotton is largely cultivated in the United States, recycling decreases the impact there, but would increase the impact in other countries that recycle due to the consumption of fossil fuels and energy use. Other alternatives are secondhand stores, that don’t require the alteration of material but rather extends use cycle by giving it to another consumer.

Cotton recycling is hugely incentivized, but its quality is said to be affected by fabric structure. The recycling process and finishing treatments lead to lower short fiber ratio, improved tenacity and "hairiness", which all lower quality of the material [23].

One new proposed method to enable a circular lifecycle is a three-step process: leaching using nitric acid, dissolution using dimethyl sulfoxide, and bleaching by sodium hypochlorite and dilute hydrochloric dosage. This innovative not yet used approach to recycling saw reduced greenhouse gas emissions of an estimated -1534 kg CO per ton of textile waste when applied to denim jeans [24], as seen in Figure 3.5.2.

Recovered material/Energy	Kg or kWh/ tonne of textile waste	Average (kgCO_2-eq/ tonne or 1000 kW h) (Agarwal and Jeffries, 2013; EEA, 2014; Zamani et al., 2015)	kgCO_2-eq / tonne of textile waste
Polyester	162	–4,060	–658
Cotton fiber	768	–1,500	–1,152
Electricity	187	+1475	+276
CO2-eq reduction by the developed strategy (kgCO_2-eq/ tonne)			**–1,534**

Figure 3.5.2 Greenhouse gas emission analysis of three-step recycling strategy [24]

Although an appealing approach, more analysis would need to be done on other aspects, such as fossil fuel consumption and water scarcity to get a more holistic view of environmental impact.

There are two main types of textile recycling: mechanical and chemical. Figure 3.5.3 provides an overview of these methods.

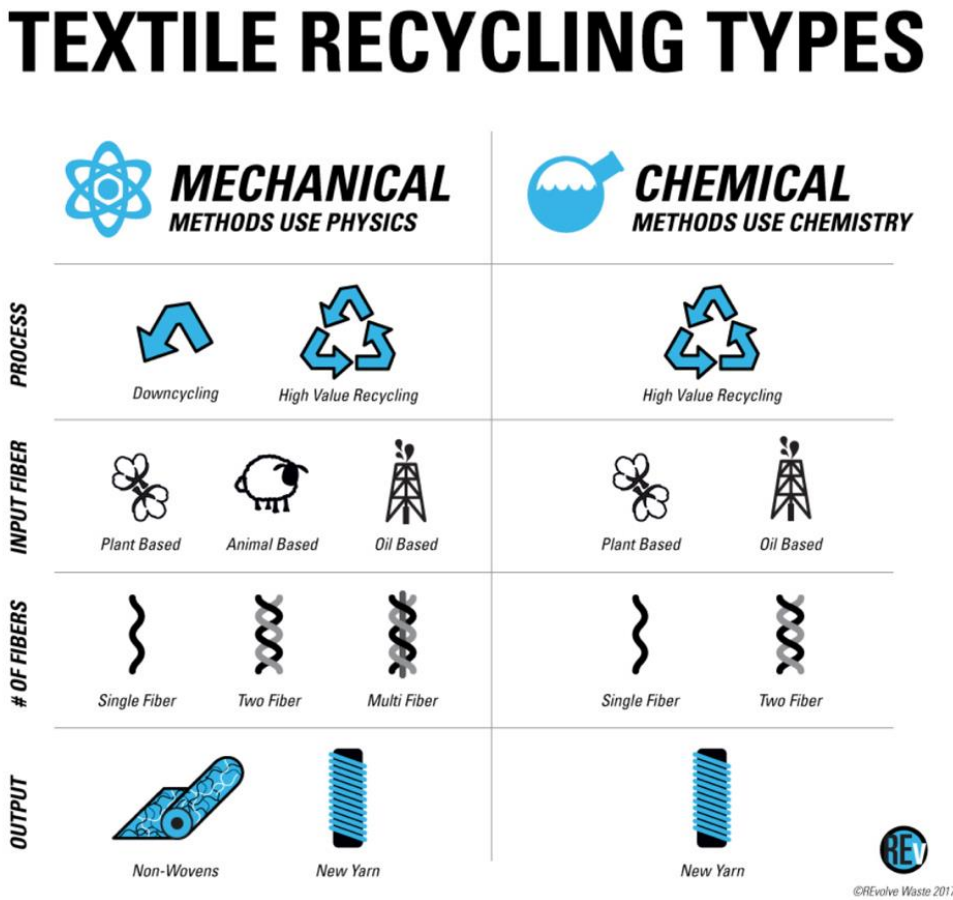

Figure 3.5.3 Mechanical and chemical recycling overview [25]

Mechanical recycling involves melting the disposed material and re-extruding it into yarn. This method does not require the use of hazardous chemicals and has low energy usage, which makes it the option with the smallest impact. Commonly resulting in downcycling, there is difficulty in preserving the fiber integrity and thus the recycled materials tend to have lower quality properties. Consequently, this process can only be performed a few times before molecular structure breaks down and becomes unsuitable for textiles. Chemical recycling requires the de-polymerization of waste material and re-polymerization into virgin material. The process has higher energy use and thus has a higher impact on abiotic resource depletion. However, the finished yarn has fewer impurities, has comparable (if not same) quality of original, and can be recycled multiple times [25]. Patagonia, in partnership with

Teijin, recycles a mix of polyester from post-consumer materials (bottles, tents, etc.) and from post-industrial waste (yarn collected from a spinning factory). This form of chemical recycling is innovative and has allowed Patagonia to produce recycled polyester products of same purity and quality of virgin polyester. Sourcing from other polyester sources is innovative and creates less abiotic resource depletion than making virgin polyester. Nylon is also made from petroleum like polyester, but it is much more difficult to recycle as a result of its polymer makeup. This results in yarns sometimes only having 50% of recycled content [26]. These popular synthetic fabrics face the trade-offs between quality and energy/chemical consumption when deciding which form of recycling to proceed with. Chemical is the most appealing method as it provides higher quality and can re-enter the life cycle for longer. It is evident recycling these crude oil-based fabrics is immediately better than producing new fabrics, however an in depth analysis whether the partial recovery of material is sufficient for long term solution is needed.

4. Industry Response

4.1 Sustainable Fabrics

4.1.1 Tencel

In response to the growing concern about fashion industry and its growing demand, fabrics that are more sustainable and environmentally friendly have begun serving as alternatives. Tencel is a cellulose fabric made from wood pulp. It is a branded lyocell fabric that undergoes a spinning process, where fibers undergo fast penetration of solvent for consistent coagulation [27]. This results in its circular cross-section and smooth surface that is gentle on the skin, which can be seen in Figure 4.1.1.1

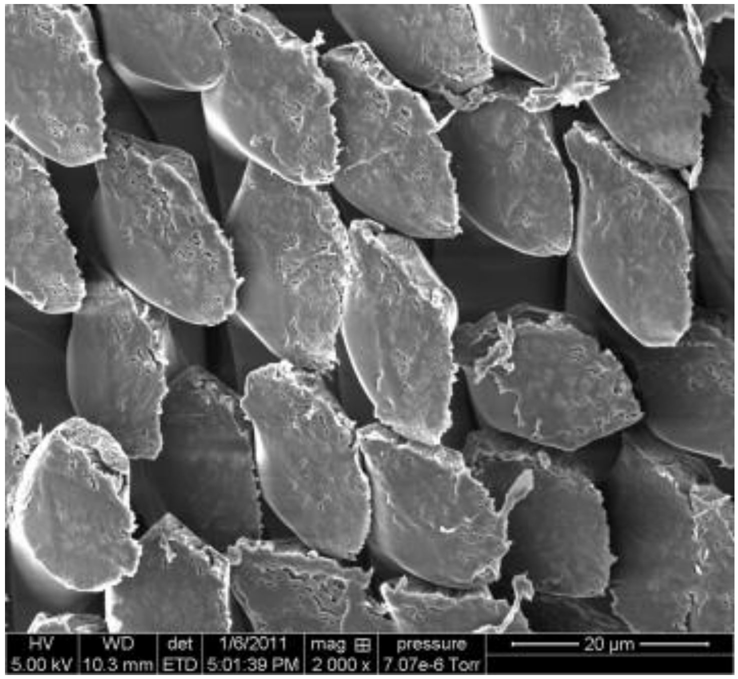

Figure 4.1.1.1 Tencel fiber cross section [27]

As with any cellulose fiber, Tencel absorbs water well and exhibits greater stability when washed than other fibers. It’s high degree of crystalline and molecular orientation gives it a high strength property, thus is resistance to failure under applied stress. Moreover, Tencel is abrasion resistant. The added functionalities makes it an appealing alternative, as well as its lower environmental impact due to almost 99% of the solvent during its spinning process being recycled [28]. Figure 4.1.1.2. provides a snapshot of the fiber production process between viscose, another man-made cellulose fabric, and lyocell. The fewer steps in the lyocell process and less inputs make its smaller environmental footprint evident in regard to chemicals, water, and energy use.

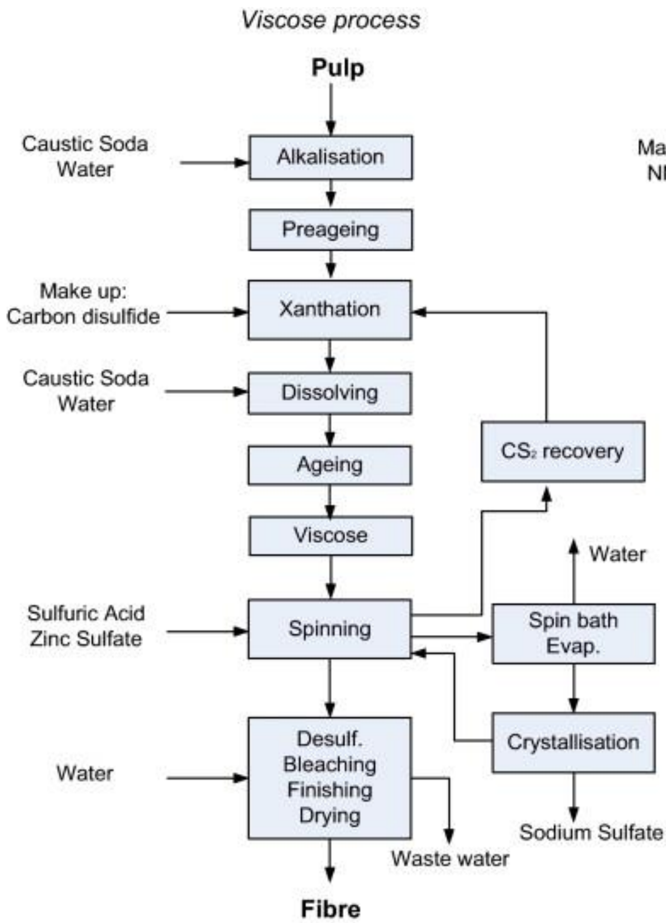

Figure 4.1.1.2. Comparison of viscose and lyocell fiber process [29]

A life cycle assessment was done on three cellulose fibers: viscose, modal, and Tencel. These results were then compared to a natural fiber and two synthetic fibers: cotton, polyethylene terephthalate (PE), and polypropylene (PP), respectively. The findings were then normalized to compare between the fibers, which can be seen in Figure 4.1.1.3.

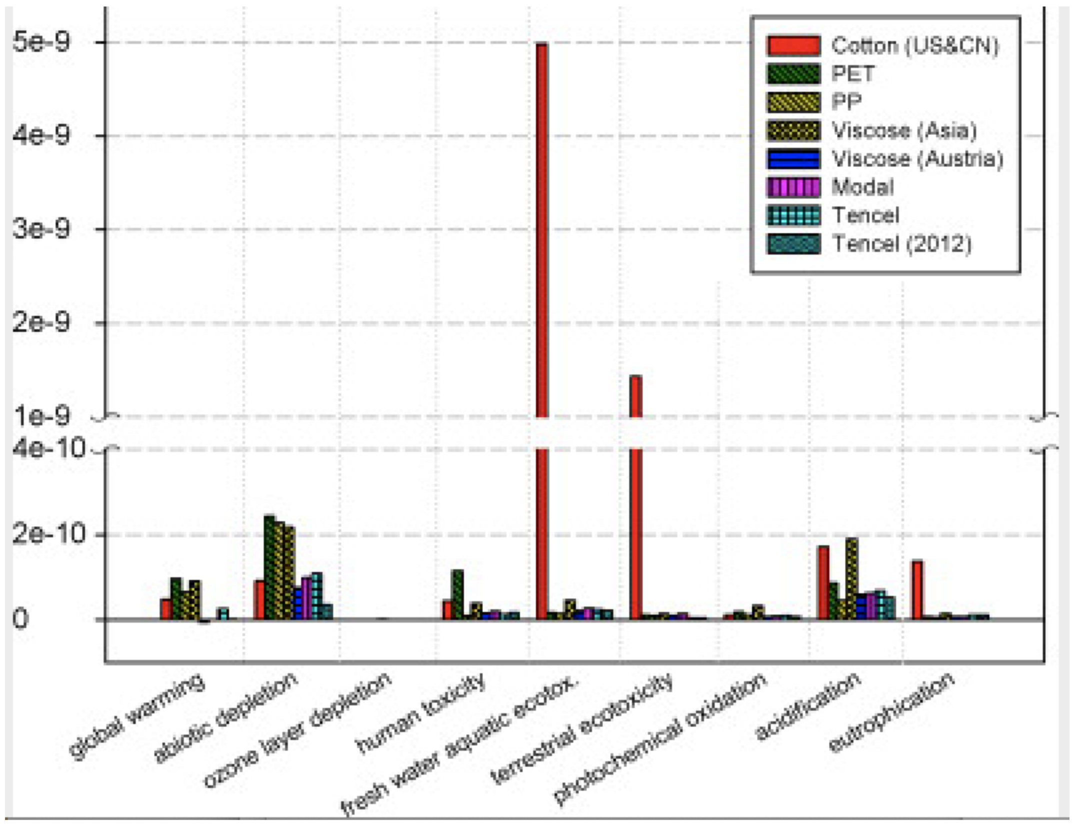

Figure 4.1.1.3. Life Cycle Assessment of cellulose fibers in comparison to cotton, PET, and PP [27]

Tencel (2012) saw low global warming, low impact on abiotic depletion, terrestrial ecotoxicity, photochemical oxidant formation, and acidification, which is probably as a result of its production characterized by low chemical use, low greenhouse gas emissions, and low energy use. Viscose (Asia) had higher impacts Tencel and Modal, making it not the best alternative. This is most likely attributed to its higher energy consumption and chemical use that can be reinforced in Figure 4.1.1.2.

4.1.2 Ingeo

Ingeo is another industry response to a greener approach to textiles. Ingeo is a polylactic acid material that is made from corn while utilizing carbon dioxide to transform into a long molecular chain. The manufacturing of Ingeo produces about 80% less greenhouse gases and uses about 52% less nonrenewable energy than conventional polymers like polystyrene [30].

Figure 4.1.2.1 demonstrates its global climate impact in comparison to popular materials, revealing how drastically more environmentally friendly it is in regard to its emissions.

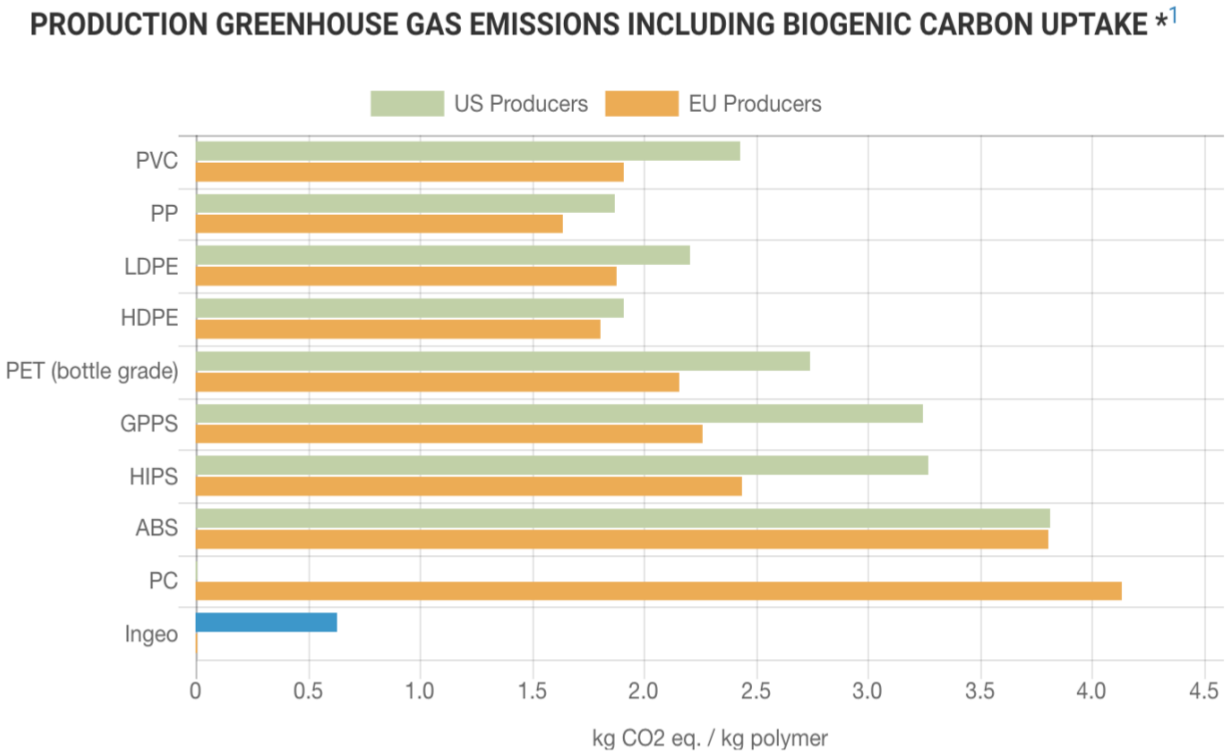

Figure 4.1.2.1 Greenhouse gas emissions of different materials [30]

However, emissions are only one facet to its sustainability measure. According to NatureWorks, the company that produces Ingeo, there are 6 possibilities for its end of life: composting, recycling, chemical recycling, anaerobic digestion, landfill, and incineration. If incinerated, Ingeo shows low residue and no volatiles, making a smaller footprint than other textiles. NatureWorks claims that when ending in a landfill, there is no statistically significant amount of methane released. In order to further explore this claim and analyze the impact of Ingeo, a study on the behavior of the Ingeo polylactides was conducted mimicking 100 years to better understand anerobic biodegradation and landfill conditions. There were two tests conducted: the first test—serving as landfill conditions—was done at 21 °C, and three moisture levels, extending to 390 days and the second test —serving as landfill conditions—serving as anaerobic digestion test— was conducted at 35 °C for 170 days [31]. The first test revealed high carbon dioxide biogas composition at the start and high methane composition at the end. The samples did not display statistically significant generation of biogas. The second test saw 94% of the material degraded by day 15 alone. These results revealed that Ingeo does in fact not lead to significant generation of methane or significant organism population under anaerobic digestion. These consistent findings reveal Ingeo as holistically a better option than other materials that would in comparison also end up in landfills. Synthetic textiles, for example, commonly end up in landfills, but their fossil fuel-based process contributes to a bigger carbon emission footprint and higher consumption of abiotic resources. Through its life, Ingeo drastically undercuts the footprint in these areas.

4.1.3 Bamboo

Bamboo is a natural sustainable fabric gaining popularity. It grows without the use fertilizers and pesticides, uses minimal water, and requires little land. Bamboo fabric contains properties that make it appealing for sportswear especially, such as good insulation, softness, durability, and odor resistant [32]. An Australian company, ettitude, manufactures and sells bamboo clothing and sheets. Using them as a case study, they performed a life cycle assessment and found when compared to a cotton sheet set, their bamboo sheet set used nearly 500 times less water. The bamboo sheet set requires 18 gallons of water, in contrast a cotton set would require 8200 gallons of water. In regard to carbon emissions, ettitude's bamboo sheet set produced less than half as many as a cotton set. Bamboo adds a weaving phase during production that enables higher quality products and a resulting longer use life. This is the only stage in the product life cycle where bamboo produced more emissions than cotton. The overall waste production was also low as 70% of the harvested bamboo is used for fiber production, and the remaining 30% is composted [33].

4.2 Clothing Brand Initiatives

With current status of the environment, clothing brands have been displaying leadership by leading programs with promises to be more conscious of their footprint and sustainability. Levi's, for example, has committed to reducing water use amount for manufacturing in areas of high water scarcity in half by 2025 [34]. Figure 4.2.1 analyzes the lifecycle of their classic 501® jeans. Since this product is made mostly from cotton, the high-water consumption is expected, and also a motivation behind their water commitment.

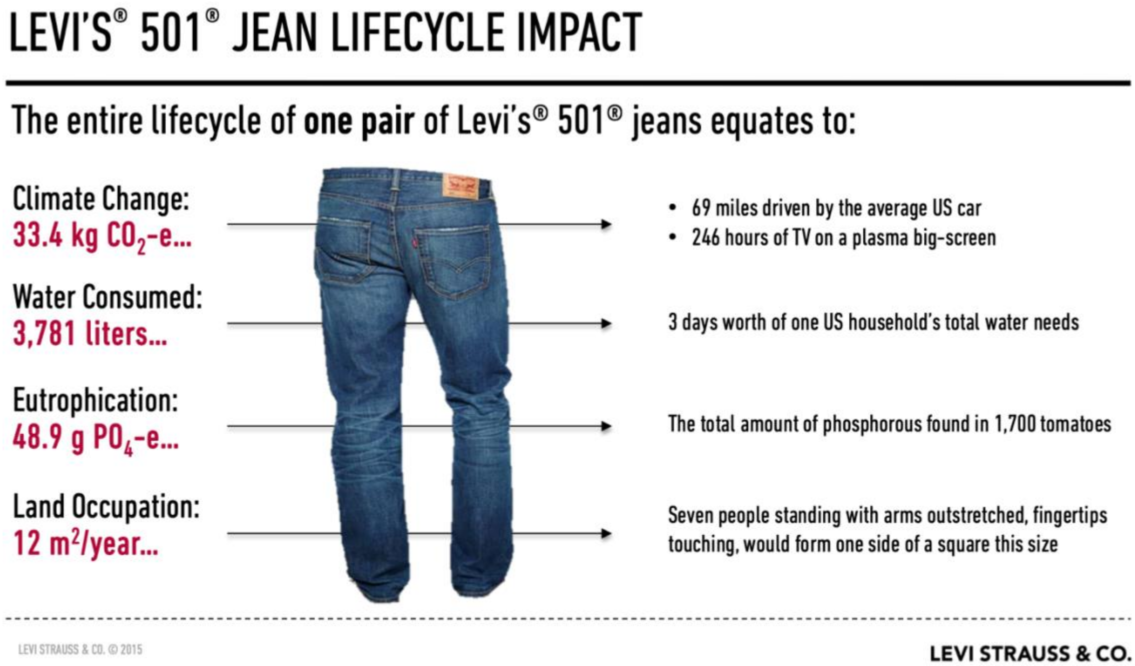

Figure 4.2.1 Life cycle impact of one pair of Levi's 501® jeans [34]

As expected, a big portion of climate change impacts comes from consumer care, which involves washing and drying. Consumer behavior varies across countries, with some European nations washing with hot water but line drying, while Americans wash with cold water but use a dryer. The varying electricity consumption results in high climate change impact, as seen in Figure 4.2.2. Levi's has started attaching labels with instructions of care to encourage minimal impact from consumers, which includes fewer washes and lower washing temperature. Moreover, their jeans are made to be high quality by excluding synthetic material to last longer and extend their use phase and enable recycling [35].

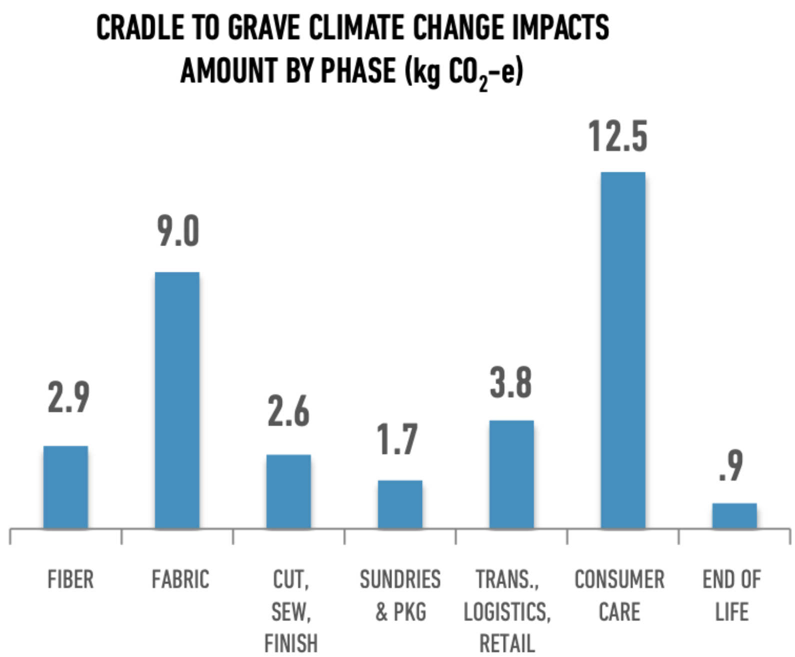

Figure 4.2.2 Climate change impact of Levi's 501® jeans

Nike, another major brand, maintains transparency with their set targets. In 2020, they achieved a 30% reduction in textile dyeing and since 2016 have avoided use of 40 billion liters. Nike is currently operating in the United States and Canada with 100% renewable energy, and globally is powered by 48% renewable energy. Since 2015, 47 million kilograms of manufacturing scraps have been recycled into new footwear products [36]. Another example of their sustainable highlights is their popular Tempo running shorts. A part of them are sold every six seconds, with each short being made of at least 75% recycled polyester [37]. Figure 4.2.3 displays Nike's share of global carbon emissions. They own up to their share of responsibility and despite their part being being a drastically smaller visual, their numbers are not small. Their product materials alone emit 4.2 million tonnes of carbon dioxide. They set up to minimize this through recycling, reduced air freight, and less consumption of fossil fuels.

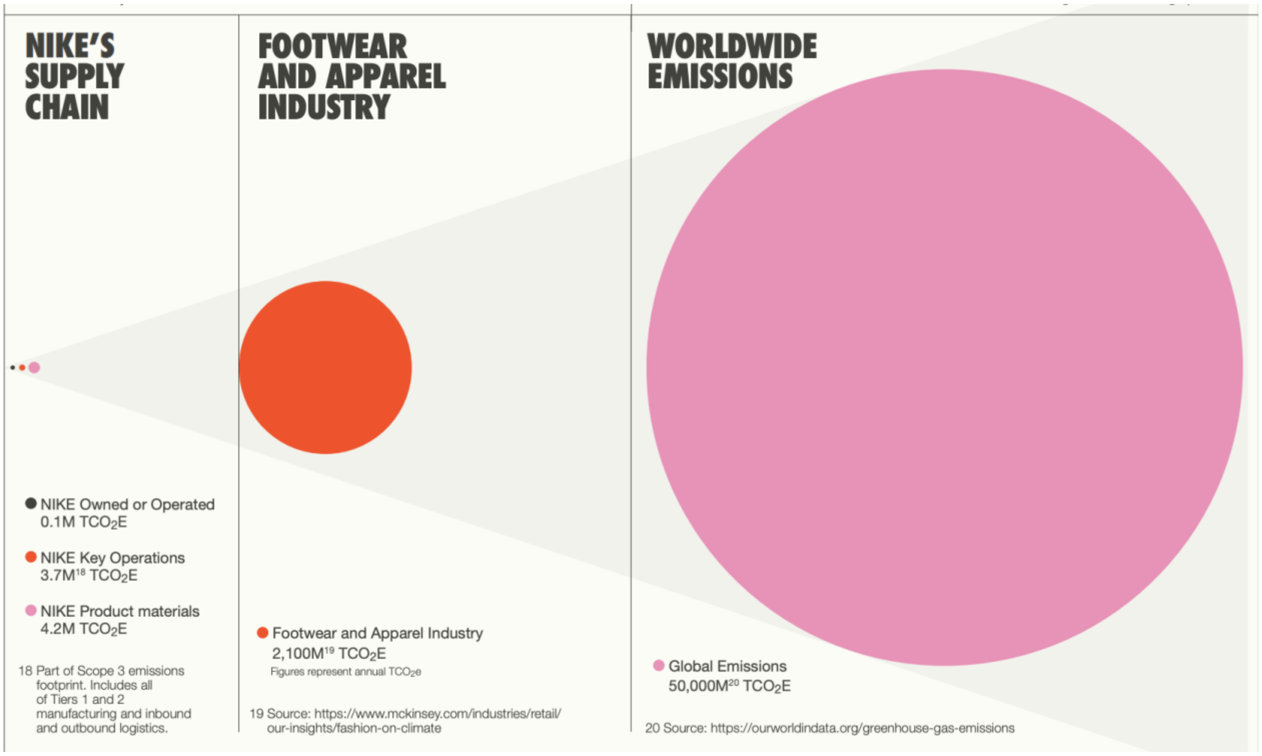

Figure 4.2.3 Global state of carbon emissions [36]

Other companies are also making similar promises. Adidas is committing to phasing out virgin polyester by 2024 [38]. In addition, they have released shoe lines Primegreen, which are made of recycled material, and Primeblue, which are made with the ocean plastic waste collected by the volunteers working with the Parley for the Oceans initiative [39]. Patagonia cites that in 2015 landfills received 10.5 million tons of textiles [40]. To minimize waste, they offer extensive repair services, do-it-yourself tutorials, and trade in opportunities.

4.3 Consumer Attitude

A closer look at whether the consumer cares is relevant as their willingness to purchase and prioritize these products in the face of fast fashion is necessary to effectively combat the environmental impact. A survey conducted in South Korea, found that all respondents agreed that the environmental problems caused by the fashion industry are serious, but the majority of consumers still overlook these issues when purchasing as fashion trends quickly change [41]. Founders of major retail companies in South Korea were also surveyed, which revealed the major barriers to purchasing sustainable options were economic, knowledge, and supply. Environmentally friendly options in clothing tend to be more costly, which creates an obstacles for those that cannot afford it. This is connected to the limited supply of sustainable options at a retail level. Additionally, most consumers don't know what sustainable products truly are. With many companies taking a green stance, the measures and extent to which they are actually beneficial becomes convoluted. Consumers are required to do research in order to make better decisions, but as discovered earlier, they do not care enough to do so. A way to combat this and provide consumers with simple, yet comprehensive knowledge, the Shades of Green instrument has been proposed as seen in Figure 4.3.1.

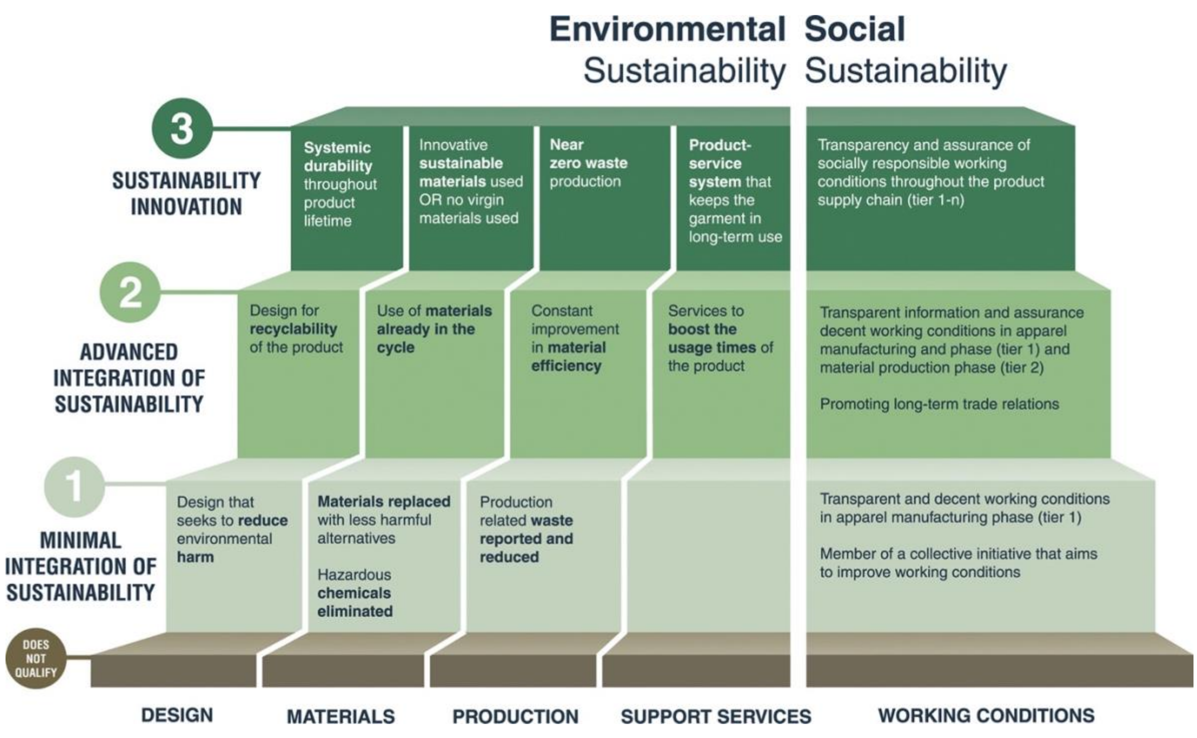

Figure 4.3.1 Shades of Green classifications [42]

The goal of the instrument would be to label brands and their products with the corresponding shade of green in order for consumers to get better clarity. The light green level refers to minimal integration and involves measures such as organic cotton use as a material a more harmful material [42]. This level has a reduction of impact but mainly short term. The medium green level starts to incorporate a long-term vision and would, for example, design for recyclability of a product. The darker green level would involve near zero waste during production and no virgin material used. This top level is advanced and embodies a fully circular economy. Shades of Green serves as a tool for consumers to understand the actual benefit that is lost in sustainable marketing through clarity and comparison. Moreover, sustainability can be comprehended as a spectrum with evolving goals as opposed to a black-or-white issue.

A survey of four Nordic firms was conducted to better understand their consumers' behavior. Revealed was that European consumers are willing to pay more for sustainable products, but this is not reflected through purchases [43]. The lack of action to beliefs serves as a big hindrance to progression of the collective effort to minimize environmental impact. Consumers do regard companies that have sustainable marketing and goals looking forward warm, indicating they appreciate firms that align with values they hold. As mentioned before, the supply of truly sustainable products is low, and some products are marketed as "green" when they are not really. The confusing and overwhelming amount of information regarding sustainable options is hard to navigate, which companies need to target in order to elicit action from consumers.

4.4 Alternative Design and Fabrication Approaches

4.4.1 3D Printed Textiles

Going beyond extensions of use and end of life, new technology to emerge includes the exploration of alternative fabrication processes, including 3D printed textiles. As an example, a lifecycle analysis of two 3D printing scenarios has been performed, the first being a nylon manufactured by Selective Laser Sintering (SLS), for which the material is required to be in powder-form and finished by means of industrial tumbling [44]. The second scenario is equal viscose and rubber input which are layered onto a mold by spray deposition. Figure 4.4.1.1 displays the eco-costs of both scenarios.

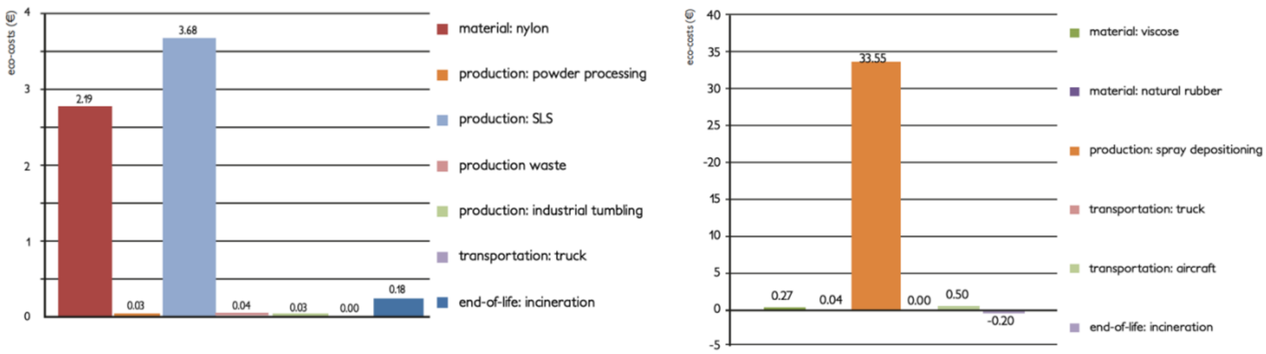

Figure 4.4.1.1 Eco-costs of SLS scenario (left) and spray deposition (right) [44]

Since both processes do not require dyeing, the production eco-cost is heavily focused on the additive manufacturing process. The SLS process allows 90% of the material used to be reused, minimizing waste. Both processes reveal low contribution in other aspects of lifecycle, serving as viable alternatives to current fabrics. Figure 4.4.1.2 depicts an example nylon garment produced by SLS.

Figure 4.4.1.2 N12 Bikini by Continuum Fashion [45]

Continuum Fashion, the designer of the bikini, promises flexibility, comfort, and waterproof properties.

4.4.2 Zero Waste Production

Typically, 15%-25% of the material needed to produce a garment is wasted due to design, pattern cutting, and production practices [46]. There is a push for automated processes for speed and precision. On the focus of automated pattern cutting, currently there are CNC machines controlled by digital design and prototyping software [47]. Figure 4.4.2.1 displays an example pattern of a jacket that will generate 15% waste. In order to approach zero waste, automation is not enough. Design of the garment needs to be considering in order to optimize use of the fabric. Changing the design to a hexagonal approach as seen in Figure 4.4.2.2 results in a 22% reduction of waste [48]. This approach reduces waste and encourages a circular economy by utilizing scraps and recycled material. Despite some level of design constraints, the incorporation of zero waste design and optimized automated cutting allows production to produce more garments and less waste, reducing environmental footprint.

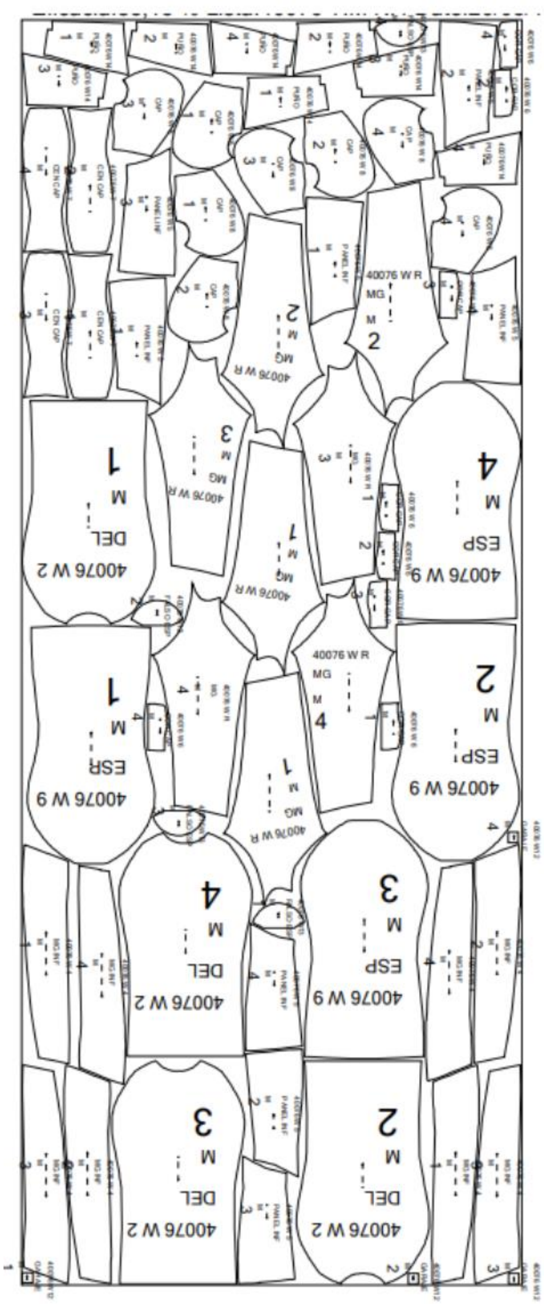

Figure 4.4.2.1 Original pattern of jacket with 15% waste [48]

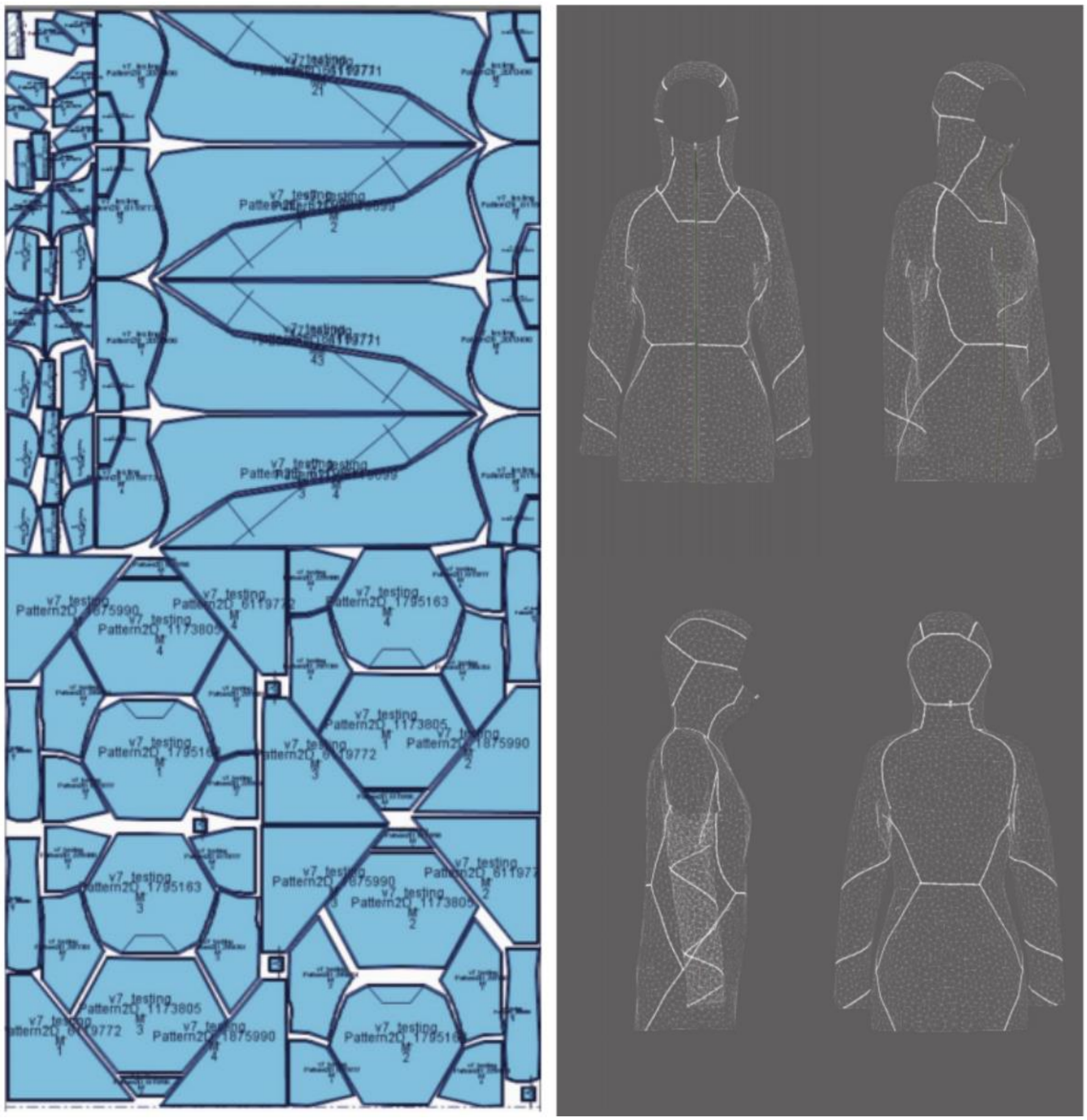

Figure 4.4.2.2 Modified hexagonal approach jacket pattern

4.4.3 3D Knitting

3D knitting works similarly to automated cutting, in which you send a program to a machine and automates the information. The computerized knitting technology allows complex designs, use of multiple yarns, and drastically lowered cost and time. Additionally, 3D knitted products have no seams or a need for finishing [49]. The most well-known example of this method is Nike's Flyknit sneakers as seen in Figure 4.4.3.1.

Figure 4.4.3.1 Nike Flyknit sneakers [50]

Nike was able to reduce material use and waste by 80% compared to their other sneakers. The company has saved also 3.5 million pounds of waste since the sneakers' launch and diverted 182 million plastic bottles from 9 landfills by switching to recycled polyester in all Nike Flyknit shoes [51]. Not only sustainable, but the sneakers are also high performing and are 19% lighter than Nike's long distance model shoes. 3D knitting is not common practice yet, but this case study demonstrates the potential for waste reduction and smart function performance.

5. Conclusion

As the global demand for fashion increases, the industry is met with the need to reevaluate their current choices. Emissions, use of fossil fuels, chemicals, and water consumption were used as metrics to analyze impact. Assuming no change, the projected demand is unsustainable and change needs to occur. Through brands incorporating green policies, exploration of sustainable fabrics, and new technology at the design level, there is progress being made. The biggest catalyzer needed for further change is consumers. There is a disconnect between the individuals acknowledging the environmental impacts and changing behavior. There is an abstract concept to it that consumers might not fully grasp, allowing them to continue their habits. Developed countries see less consumption due to lessened focus on fast fashion. The biggest hurdle for companies and the industry in general is to mobilize their consumers to change purchasing behavior. 3D printing, zero waste production, Tencel use, and other explored topics are promising rising solution, however, if there is no demand or shift in consumption, true change will not occur. Clarity and demystifying the complexity of sustainability to the consumer would allow them to see the spectrum of change and how some company initiatives are better than others. Buying Nike's Flyknit sneakers, for example, contributes more drastically to a sustainable vision than organic cotton jeans. Changes at the design and starting phase would provide a holistic, more reduced approach, as seen through technology alternatives.

References

[1] Wicker, A., 2020, “Fashion’s Impact on the Environment Is Actually a Mystery,” Vox [Online]. Available: https://www.vox.com/the-goods/2020/1/27/21080107/fashion-environment-facts-statistics-impact.

[2] “UN Helps Fashion Industry Shift to Low Carbon | UNFCCC” [Online]. Available: https://unfccc.int/news/un-helps-fashion-industry-shift-to-low-carbon.

[3] “UN Alliance Aims to Put Fashion on Path to Sustainability | UNECE” [Online]. Available: https://unece.org/forestry/press/un-alliance-aims-put-fashion-path-sustainability.

[4] “Water Footprint in Life Cycle Assessment (LCA),” WULCA.

[5] Morelli, B., Hawkins, T. R., Niblick, B., Henderson, A. D., Golden, H. E., Compton, J. E., Cooter, E. J., and Bare, J. C., 2018, “Critical Review of Eutrophication Models for Life Cycle Assessment,” Environ. Sci. Technol., **52**(17), pp. 9562–9578.

[6] Roos, S., Jönsson, C., Posner, S., Arvidsson, R., and Svanström, M., 2019, “An Inventory Framework for Inclusion of Textile Chemicals in Life Cycle Assessment,” Int J Life Cycle Assess, **24**(5), pp. 838–847.

[7] Gale, J., Bradshaw, J., Chen, Z., Garg, A., Gomez, D., and Rogner, H.-H., 2005, “Sources of CO2,” The Intergovernmental Panel on Climate Change, pp. 75–103.

[8] 2020, “Global Emissions,” Center for Climate and Energy Solutions [Online]. Available: https://www.c2es.org/content/international-emissions/.

[9] Tagliaferri, C., and Lettieri, P., 2019, “11 - Methane from Waste: Thermal and Biological Technologies Compared under a Life Cycle Assessment Perspective,” *Substitute Natural Gas from Waste*, M. Materazzi, and P.U. Foscolo, eds., Academic Press, pp. 275–315.

[10] "Fossil Fuels Account for the Largest Share of U.S. Energy Production and Consumption - Today in Energy - U.S. Energy Information Administration (EIA)" [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=45096.

[11] Hodakel, B., "What Is Cotton Fabric: Properties, How Its Made and Where," Sewport [Online]. Available: https://sewport.com/fabrics-directory/cotton-fabric.

[12] Wagenaar, D. de, 2019, "ReMade in Amsterdam," Wageningen University & Research.

[13] Allwood, J. M., Laursen, S. E., Russell, S. N., de Rodríguez, C. M., and Bocken, N. M. P., 2008, "An Approach to Scenario Analysis of the Sustainability of an Industrial Sector Applied to Clothing and Textiles in the UK," Journal of Cleaner Production, **16**(12), pp. 1234–1246.

[14] Duque Schumacher, A. G., Pequito, S., and Pazour, J., 2020, "Industrial Hemp Fiber: A Sustainable and Economical Alternative to Cotton," Journal of Cleaner Production, **268**, p. 122180.

[15] Rosa, J. M., Garcia, V. S. G., Boiani, N. F., Melo, C. G., Pereira, M. C. C., and Borrely, S. I., 2019, "Toxicity and Environmental Impacts Approached in the Dyeing of Polyamide, Polyester and Cotton Knits," Journal of Environmental Chemical Engineering, **7**(2), p. 102973.

[16] Hasanbeigi, A., 2010, "Energy-Efficiency Improvement Opportunities for the Textile Industry."

[17] 2020, *Fashion Forward: A Roadmap to Fossil Free Fashion*, Stand.earth.

[18] Allwood, J. M., 2006, *Well Dressed? The Present and Future Sustainability of Clothing and Textiles in the United Kingdom*, University of Cambridge Institute for Manufacturing.

[19] Napper, I. E., and Thompson, R. C., 2016, "Release of Synthetic Microplastic Plastic Fibres from Domestic Washing Machines: Effects of Fabric Type and Washing Conditions," Marine Pollution Bulletin, **112**(1), pp. 39–45.

[20] Peters, G., Li, M., and Lenzen, M., 2021, “The Need to Decelerate Fast Fashion in a Hot Climate - A Global Sustainability Perspective on the Garment Industry,” Journal of Cleaner Production, **295**, p. 126390.

[21] 2017, *A New Textiles Economy: Redesigning Fashion’s Future*, Ellen MacArthur Foundation.

[22] Sandin, G., and Peters, G., 2018, “Environmental Impact of Textile Reuse and Recycling – A Review,” Journal of Cleaner Production, **184**.

[23] Ütebay, B., Çelik, P., and Çay, A., 2019, “Effects of Cotton Textile Waste Properties on Recycled Fibre Quality,” Journal of Cleaner Production, **222**, pp. 29–35.

[24] Yousef, S., Tatariants, M., Tichonovas, M., Sarwar, Z., Jonuškienė, I., and Kliucininkas, L., 2019, “A New Strategy for Using Textile Waste as a Sustainable Source of Recovered Cotton,” Resources, Conservation and Recycling, **145**, pp. 359–369.

[25] 2020, “Chemical Recycling: Making Fiber-to-Fiber Recycling A Reality for Polyester Textiles,” GreenBlue [Online]. Available: https://greenblue.org/work/chemical-recycling/.

[26] 2007, *Teijin CRS Report 2007*, Teijin.

[27] Choudhury, A. K. R., 2017, “10 - Sustainable Chemical Technologies for Textile Production,” *Sustainable Fibres and Textiles*, S.S. Muthu, ed., Woodhead Publishing, pp. 267–322.

[28] Badr, A. A., Hassanin, A., and Moursey, M., 2016, “Influence of Tencel/Cotton Blends on Knitted Fabric Performance,” Alexandria Engineering Journal, **55**(3), pp. 2439–2447.

[29] Shen, L., Worrell, E., and Patel, M. K., 2010, “Environmental Impact Assessment of Man-Made Cellulose Fibres,” Resources, Conservation and Recycling, **55**(2), pp. 260–274.

[30] “NatureWorks | Eco-Profile” [Online]. Available: https://www.natureworksllc.com/What-is-Ingeo/Why-it-Matters/Eco-Profile. [Accessed: 06-May-2021].

[31] Kolstad, J. J., Vink, E. T. H., De Wilde, B., and Debeer, L., 2012, “Assessment of Anaerobic Degradation of Ingeo™ Polylactides under Accelerated Landfill Conditions,” Polymer Degradation and Stability, **97**(7), pp. 1131–1141.

[32] McCann, J., 2015, “2 - Environmentally Conscious Fabric Selection in Sportswear Design,” *Textiles for Sportswear*, R. Shishoo, ed., Woodhead Publishing, pp. 17–52.

[33] 2020, *Ettitude 2020 Impact Report*, ettitude.

[34] 2015, *The Life Cycle of a Jean: Understanding the Environmental Impact of a Pair of Levi's® 501 Jeans*, Levi Strauss & Co.

[35] 2019, *2025 WATER ACTION STRATEGY*, Levi Strauss & Co.

[36] 2020, *Impact Report--Executive Summary*, Nike.

[37] 2020, *Nike Impact Report 2020*, Nike.

[38] “Textile Recycling | Recycled Polyester | Adidas Official Shop,” adidas UK [Online]. Available: www.adidas.com/us/sustainability-phase-out-virgin-polyester-2024.

[39] 2020, “Annual Report 2020--Our Sustainability Initiatives,” Adidas [Online]. Available: https://report.adidas-group.com/2020/en/at-a-glance/2020-stories/our-sustainability-initiatives.html.

[40] “Repairs & DIY Tutorials - Patagonia” [Online]. Available: https://www.patagonia.com/repairs/.

[41] Moon, K. K.-L., Lai, C. S.-Y., Lam, E. Y.-N., and Chang, J. M. T., 2015, “Popularization of Sustainable Fashion: Barriers and Solutions,” The Journal of The Textile Institute, **106**(9), pp. 939–952.

[42] Turunen, L. L. M., and Halme, M., 2021, “Communicating Actionable Sustainability Information to Consumers: The Shades of Green Instrument for Fashion,” Journal of Cleaner Production, **297**, p. 126605.

[43] Arslan, A., Haapanen, L., Hurmelinna-Laukkanen, P., Tarba, S. Y., and Alon, I., 2021, "Climate Change, Consumer Lifestyles and Legitimation Strategies of Sustainability-Oriented Firms," European Management Journal.

[44] Lussenburg, K., Geraedts, J., Karana, E., Doubrovski, Z., and Velden, N., 2014, "Designing [with] 3D Printed Textiles," Delft University of Technology.

[45] "Continuum Fashion : N12 Bikini" [Online]. Available: https://continuumfashion.com/N12.php.

[46] McQuillan, H., 2019, "Hybrid Zero Waste Design Practices. Zero Waste Pattern Cutting for Composite Garment Weaving and Its Implications," Informa UK Limited, **22**, p. 18.

[47] Suh, M., 2020, "Automated Cutting & Sewing Developments," Textile World [Online]. Available: https://www.textileworld.com/textile-world/features/2020/03/automated-cutting-sewing-developments/.

[48] McQuillan, H., 2019, "Theoretical Models of Zero Waste Design Thinking," University of Borås.

[49] 2017, "3D Knitting the Future of Customizable, Sustainable Textiles," Shapeways [Online]. Available: https://www.shapeways.com/blog/archives/36224-3d-knitting-future-customizable-sustainable-textiles.html.

[50] Vangsnes, E., "Nike Flyknit," deskriptiv [Online]. Available: https://deskriptiv.com/nikeflyknit.

[51] Fink, C., 2016, *Nike: Sustainability and Innovation through Flyknit Technology*, New York University, New York.