Future Fashion: sustainable textiles

Introduction

Fashion is a rapidly growing industry supported by a perpetual cycle of supply-and-demand. Unfortunately, the industry and its related activities are having catastrophic impacts on the environment, causing huge greenhouse gas emissions, water pollution and notoriously displaying poor waste management. Most clothes are manufactured in developing countries while most are bought in richer western countries, hence creating a disconnect between two parts of the world and leading to these environmental consequences seeming fairly "invisible" to us in the west.

Every year, the fashion industry is responsible for 10% of all GHG emissions worldwide, including 4% of global CO_2 emissions[i,ii]. That share is expected to jump to about 25% of global GHG emissions by 2050[iii]. To put this into context, aviation and maritime shipping combined are currently responsible for as much as 5% of global GHG emissions[iv,v], including 4.4% of global CO_2 emissions[vi]. Every stage of clothing production is energy intensive, starting with the harvesting of natural fibers which relies on fuels, and the production of synthetic fibers which requires petroleum as feedstock and fossil-generated electricity used to spin and weave the fibers. The latter manufacturing stages also require huge amounts of energy in the forms of electricity and heating. Although both oil and natural gas are used, production mainly relies on coal-generated electricity, especially as most factories are situated in China where coal is the most prevalent energy source[vii]. A large share of the aviation, shipping and road transport industry is dedicated to moving raw materials, fabrics and finished clothing around the globe every year, further increasing fashion's carbon footprint. As the industry grows, it is projected that its freight use will triple by 2040.

The industry has long been notorious for its intensive water use and the consequences its activities have had on water pollution. Today around 20% of wastewater worldwide originates from the fashion industry[viii]. This share includes agricultural run offs from croplands – which often contain harmful pesticides and herbicides – and chemicals used in the manufacturing of fabrics such as bleach and dyes. There has been a consistent lack of transparency from clothes-makers leading to water pollution being difficult to monitor and mitigate.

Waste management is also a big topic for the sector as most garments and accessories are not recycled or sustainably degraded, leading to 85% of all textiles ending up in landfills every year[ix]. The World Economic Forum also reports that clothing production has grown by 60% between 2000 and 2014, and that the time in-use has halved before customers finally dispose of them. Throwing away products that could potentially be sold second hand, or fixed if needed, is a behaviour that perpetuates the whole pollution cycle even more. Added to that, any harmful chemicals used to produce and treat the fabrics can be released in the environment as the clothes degrade over time[x]. The topic of plastic pollution has been heavily covered by the news in recent years, more particularly since the discovery of five gigantic "plastic islands" in the ocean. "Microplastics" have been the focus of many articles and research projects to identify both their origins and the impacts they could have on the environment. Fashion is responsible for releasing 500,000 tonnes of microplastics in the ocean every year, mainly due to the laundering of polyester-based items[xi].

Fast-fashion is being blamed for a large part of these alarming environmental trends. It is characterised by a very fast production cycle, with collections being designed, manufactured and sold in just a couple of weeks. The famous clothes brand Zara is often presented as a prime example of fast-fashion with 24 collections produced annually.

Textiles are materials made from woven yarns or threads which are themselves produced from natural and synthetic fibers. Although natural fibers are, by definition, manufactured from biological sources, their biobased quality does not guarantee sustainability. This article investigates the sustainability of widely used natural and synthetic textiles, detailing current practices and when appropriate presenting a range of new technologies from which alternative sustainable biobased textiles could arise. Production management techniques for natural textiles will also be compared and contrasted. Examples of commercialized sustainable biobased products are also given, showing that leading brands are strengthening their commitment to a "greener" industry and showing that fashion products are starting to become more readily available to customers.

Cotton

Nearly a third of all garments produced globally are made from or contain cotton, making it the most used natural fiber in the industry[xii]. Cotton being a natural fiber, cotton-based fabrics are biobased, however the activities associated with the crops – mainly water management and chemical treatment – often render the commodity unsustainable. In this case, where the product is derived from a crop, it is paramount to understand the properties and the needs of the plant in order to maximize yields while mitigating negative impacts on the environment.

Cotton cultures are often flagged as being extremely water-intensive, therefore perpetuating both environmental and societal issues. However cotton has adapted to thrive in dry environments, hence it is not a naturally water-demanding crop. Water management practices around the world are directly responsible for the huge amounts of water being wasted every year. The US and India are two of the largest producers of cotton in the world[xiii], however their water management strategies, and therefore their impact on the environment, differ significantly. Before going further into this analysis, it is important to understand the difference between water use and water consumption. Water use relates to a given amount of water being extracted from a water source. Water consumption on the other hand takes into account the share of the water withdrawn from the original source that is permanently removed from that given source, either by being lost through evaporation or by being incorporated into living organisms such as crops. Distinguishing between these two concepts is crucial to understanding and comparing water management practices.

In 2013, water use for cotton production in India would have been enough to provide 85% of the country's population with 100 liters of water every day for a year[xiv], showing that cotton poses a huge environmental and, more importantly, human issue in the region. The majority of cotton fields are located in very dry parts of the country, where although the crop is adapted to heat, regular water supply is crucial. In these conditions, water consumption is very unsustainable as a lot of water is lost through evaporation, hence leading to more water use. Contrastingly in the US, 64% of cotton acreage does not require any irrigation as rainfall provides enough water for the whole growth cycle[xv]. In most cases for the remaining 36% of land, irrigation is only used during dry spells, leading to only 5% of all land used to grow cotton being fully irrigated. Water consumption for cotton irrigation purposes in the US has dropped by about 36% between 1980 and 2015, while cotton yield per hectare has increased by 38%. Understanding the crop's water needs at different life stages as well as optimizing spatial management of fields – to ensure favourable temperatures, humidity and soil composition for example – is key to improving water use efficiency. Nowadays 70 % of global freshwater stocks is used for agriculture, although only a fraction of this is dedicated to cotton cultures the fashion industry could definitely benefit from a more ecologically-driven approach to producing natural fibers. Global warming and the increase in soil salinity in coastal agricultural regions – such as Gujarat in India[xvi] – are exacerbating the issue further, as soils water potential is reduced.

The intensity of cotton production in the past decades has led to soil degradation around the world[xvii]. As soil nutrient content decreases and soil structure becomes compromised, two options present themselves. Fields can be extended or displaced, leading to the degradation of healthy land, or fields can be treated chemically to increase nutrient availability to plants and to protect the crops from pests and diseases. Unfortunately both options only lead to soils becoming less and less fertile. As much as 16% of global insecticide release is used for cotton[xviii], which is more than any other single crop. In India, 54% of all pesticide use annually is dedicated to cotton[xix]. Not only do these chemicals degrade soils – by killing soil organisms helping to establish and maintain soil structure – and pollute water streams, they are notoriously hazardous to human health. Up to 3% of cotton field workers (amounting to 77 million workers worldwide) suffer from acute pesticide poisoning every year, with 200,000 farmers dying globally according to the Environmental Justice Foundation[xx]. High profile companies such as Monsanto and Syngenta have been accused of commercializing harmful (and often deadly) herbicides and pesticides, and have been taken to court on multiple occasions. The companies have lost most of their trials and appeals, and were sentenced to financially compensate the plaintiffs. Defoliant chemicals are also used to kill off leaves on the cotton plants to allow the mechanical picker to harvest without much unwanted extra biomass. According to the National Wildlife Federation, these defoliants are known to cause medical conditions in workers and nearby residents. In the US "the cotton flu" is an annual recurrence for a fair share of the population, triggering asthma attacks, headaches, tremors and fatigue[xxi]. Scientific research dating back to the 1980s show that the effects of defoliants on human health have been known for decades.

Organic cotton farming provides a viable solution to the problems presented above. Organic farming practices focus on promoting a balance between crops, soils and insects to fully remove the need for external chemicals treatments. Crop rotation, which promotes soil health and prevents weeds, eliminates the need for herbicides and fertilisers. Soils are given a chance to regenerate which has the added benefit of controlling insect populations that would otherwise impact the yields negatively, therefore eliminating the need for pesticides. Defoliants are banned and leaves are left to fall naturally during seasonal freezing. Water use is also carefully managed to reduce water consumption while maximising yields, saving enormous amounts of water every year. Organic cotton is unavoidably more expensive than its non-organic counterpart, however organic farmers argue that these practices are about promoting well-being for all, employees and consumers alike, and that investing in sustainable textile is an investment for the future. Today only 1% of cotton on the market is produced through organic farming practices[xxii], with data showing an average of 572kg of organic cotton produced per hectare of land in the year 2019-2020[xxiii]. Although this represents a 31% increase in yield compared to the previous year, one hectare of land can produce 2 to 4 tons of conventional cotton, showing that there is still a way to go for organic cotton to strongly compete with conventional cotton and fast-fashion[xxiv]. In this context, it could be argued that organic cotton would require much more land than conventional cotton to meet global fiber demand, which would lead to more soils being affected. It would therefore be worth comparing scenarios to investigate whether broadening organic cotton farming would indeed provide a sustainable alternative to current conventional cotton farming practices.

Finally, clothes manufacturers and customers also have a role to play in facilitating a sustainable cotton industry. Organic and non-organic cotton fibers are both strong and versatile therefore cotton-based clothes could easily be reused and recycled to lengthen their life cycle and counteract overproduction, which is arguably at the core of this entire issue.

Semi-Synthetic Fibres

Viscose fabric (also known as Rayon or artificial silk) is soft, light, versatile and cheap to produce textile, making it an attractive material for multiple sectors of the industry requiring fabric (i.e. fashion, upholstery, carpets). The fibres used to weave the fabric are produced from cellulosic feedstock, tree wood pulp and bamboo in particular. However, although the feedstocks are biobased, viscose is not considered a natural fibre as the transformation process requires a large chemical input (i.e. sodium hydroxide and carbon disulfide). Viscose is therefore considered a semi-synthetic fibre made from regenerated cellulose.

Fibre production involves five steps during which the base cellulosic biomass is dissolved into sodium hydroxide to create a wood pulp solution. The solution is then treated with carbon disulfide to form a xanthate derivative in which is then hydrolysed using sodium hydroxide to create the fibrous cellulosic solution known as "viscose" which can then be stretched and cut into fibres. At the end of the process an almost pure cellulose fibre is produced.

The chemicals used in the process are toxic and if not adequately controlled can pollute both the air and water. The process also leads to high concentrations of the greenhouse gas nitrous oxide near viscose production sites. As a result, the sustainability of Viscose is often put into question.

Carbon disulfide (CS_2) in particular is a highly toxic volatile liquid which presents a huge health hazard to unprotected workers, resulting in several acute poisonings since viscose reached the market in the 1920s. In worst cases, 25% to 30% of CS_2 used during the manufacturing process can be lost in the surrounding environment (i.e. air and water) near the factories[xxv]. There have been multiple legal actions taken against manufacturers using CS_2 unsafely, with companies like Courtaulds Fibers being required to financially compensate some of its employees in the 2000s. Unfortunately CS_2 poisoning are not a thing of the past, and workers (which are very often from developing countries) still suffer catastrophic health conditions.

Viscose is biodegradable and was found to biodegrade quicker in burial soil and sewage sludge compared to cotton. Studies found that a number of silverfish species are keen to eat the fibres, hence speeding up degradation rates. However the most water-repellent the textile is made to be, the slower biodegradation gets. The degradation rates were also significantly reduced in landfill, where it can take the fibres decades to degrade compared to weeks or months in the conditions mentioned above[xxvi].

The raw material for the production of viscose can definitely be produced and harvested sustainably, however this is the exception rather than the rule as most feedstocks currently come from forests which have not been sustainably grown, therefore leading to the disruption of natural ecosystems. Recent studies have found that recycled cotton fibres could serve as feedstock for viscose production[xxvii], therefore ensuring a circular use of both fibres. The Next Generation Solutions project, led by Canopy and multiple high profile clothing brands such as H&M and New Look, has vowed that 50% of all new viscose-based products will be manufactured from recycled cotton and viscose by 2030[xxviii]. Furthermore, by as early as 2025, the project members state that there will be enough Next Generation feedstocks being produced to replace 90% of feedstocks coming from ancient and endangered forests.

On the chemical side of things, the Lyocell manufacturing process is increasingly being used as it offers a more eco-friendly alternative to the conventional process described above. In this case the feedstock is dissolved in N-Methylmorpholine N-oxide (NMO), which is an organic compound used as a solvent. The process does not cause any greenhouse gas emissions, and although NMO is not readily biodegradable in the environment, microbially adapted activated sludge can used to achieve its complete breakdown in waste treatment plants. Although more expensive than conventional Rayon, sustainable viscose alternatives, such as Tencel produced from the lyocell process, are already commercialised and are becoming increasingly available to consumers.

Synthetic fibers

Nearly 60% of all textiles destined for clothing items are made from synthetic fibers[xxix] i.e. plastic fibers. An exponential rise since its arrival on the market in the 1040s. That share rises to 70% for textiles produced for household products such as bedding and towels[xxx]. Synthetic fibers are manufactured via chemical syntheses, often involving fossil resources. Nowadays, 1.3% of global fossil resource use is destined to the production of synthetic fibers[xxxi].

Polyester

Polyethylene terephthalate (PET) fibers, more commonly known as polyester, are synthesised from ethylene glycol and terephthalic acid (typically petroleum-derived compounds), making polyester. The resulting material is stretched and turned into long thin plastic cylinders which are then woven to create fabric. Polyester fibers are bendy, smooth and strong, making them versatile and suitable for a wide range of items, from high fashion to sportswear. Although it gets wet quickly, polyester's adsorbent properties make it a fast drier not prone to creating a favourable environment for bacteria. All in all, polyester is arguably a very valuable and useful material, however, due to its polymer structure, it has a slow biodegradation rate which also leads to the release of microplastics in the environment.

As the fashion industry is attempting to reduce its environmental impact and its reliance on fossil resources, alternatives to traditional polyester are starting to arise. Recycled polyester (RPET), manufactured from recycled plastic, has become a go-to for large fashion bands such as Adidas and GAP. In this case, the material is given a second life therefore reducing the need for new plastic to be synthesised. In addition, about 90% less water and 70% less energy are needed to produce RPET compared to traditional PET[xxxii]. RPET is typically 15 to 20% more expensive than its virgin counterpart[xxxiii].

Biobased polyesters are a large family of biobased plastics which can be produced from compounds such as natural sugars and oils. Polylactic acid (PLA) is a widely used biobased polyester which already has applications in commercialised goods, mainly in the packaging and medical device sectors. Fermentable sugar is extracted from feedstocks such as corn and sugar cane are fermented to obtain lactic acid which is converted to cyclic lactide monomers. Monomer condensation and polymerization then lead to the manufacture of polylactic acid, which is biodegradable, recyclable and compostable. It is also considered biocompatible, as when PLA degrades naturally the resulting compounds do not cause any harm to its surrounding environment or, in the case of medical equipment such as stiches, to the body. Producing PLA is also linked to a significant reduction in energy use compared to traditional polyester fibers, saving between 25% and 55% of energy[xxxiv]. However the mechanical and thermal properties of PLA remain a limitation to its widespread use in clothing. The fibers cannot withstand temperatures higher than 60 degrees, which could pose a problem for specialist clothing used in extreme sports or scientific, industrial and engineering fields. The material is also fairly fragile and brittle, therefore it cannot withstand much stretch and would not be ideal for sportswear. To overcome both these issues, PLA blends, which combine other biobased polymers, are being developed to reach a higher melting point and become less brittle. Lactic acid being cheap and relatively easy to manufacture, PLA is the most prominent biobased polyester currently commercialised. It is expected that the market for this specific product will double within the next decade. Polycaprolactone (PCL) is another type of biodegradable polyesters produced from a lactic acid derivative, lactone. Rarely used as a stand-along polyester, it is often used in blends to increase impact resistance.

Although not as prominent as PLA, other biobased or partially biobased polyesters exist, offering different mechanical and thermal properties and varying in their applications. Poly-trimethylene terephthalate (Bio-PTT) and polyethylene terephthalate (Bio-PET) fibers contain about 30% of plant-based compounds synthesised from sugars and vegetal oils and 70% of fossil-derived compounds. Although only partially biobased, Bio-PTT and Bio-PET are a step in the right direction and could represent a good compromise while fully biobased PETs are being developed and made available on the market. However, it is important to keep in mind that PETs, whether fully fossil-derived or 100% biobased, have very low biodegradation rates and release large amounts of microplastics in the environment. Therefore the need to develop safe disposal processes for these compounds remains paramount.

Polyhydroxyalkanoates (PHAs) are naturally occurring 100% biobased polyesters produced by microorganisms that use these compounds as an energy source and carbon storage. In the wild, the biosynthesis of PHAs is often triggered by an excess of carbon input under nutrient depleted and hypoxic conditions. PHAs granules are stored within the microorganisms' cells and can be used when needed. Under optimised lab conditions, the intracellular PHA content produced by an organism can reach 80% of its dry weight. More than one hundred monomers have been identified in nature, all of them having a range of thermophilic and elastic properties. Blending these natural fibers with other biobased polymers allows to further optimise such properties, rendering the material more resistant to heat, biocompatible and stretchy.

Nylon or polyamide

Nylon (or nylons 6 / 66) belongs to the polyamides family of synthetic polymers and was the very first textile synthesised from fossil resources. It is made up of 6-aminocaproic acid, the linear form of caprolactam, and of adipic acid, which rarely occurs in nature. Dubbed the "miracle fiber", nylon revolutionised the textile industry and offered a strong, reliable and cheap alternative to silk. Mainly used in stockings for women in the 30s, nylon's hour of glory came during WWII when it was used to manufacture parachutes, tents, ropes and many other items crucial to the war effort. Over the decades nylon has shone by its versatility, being perfectly adequate for both haute-couture garments and spacesuits. Producing nylon however leads to large amounts of nitrous oxide emissions being released, which contributes to global warming and ozone depletion. Additionally, the production chain requires enormous amounts of water and energy. Finally, similarly to polyester, nylon is responsible for microplastics pollution, both in soils and water bodies.

Biobased polyamides can be produced from plant-based compounds, more specifically from castor oil which contains a high proportion of ricinoleic acid, a compound not found in any other plant. Called Nylon 11 or polyamide 11 (PA11), it is a biobased plastic produced from 100% renewable feedstock. Ricinoleic acid (making up most of the castor oil), methanol, hydrogen bromide and ammonia are all part of the synthesis process which involves several chemical transformations. The resulting nylon 11 possesses excellent properties which make it very versatile. It has low water absorbance, high resistance to heat and chemical stresses, is flexible and strong. PA11 is the lowest water absorbing polyamide on the market, including petroleum-derived polyamides. So far, PA11 has applications in the sports equipment, tubing, electrical, textiles and coatings sectors, but more research is being conducted to develop blends that will further broaden this scope. Arkema is the only company currently producing PA11 from castor oil, supplying manufacturers all over the world.

Synthetic biology also has a role to play in the effort to produce sustainable nylon alternatives, developing products with different properties and providing a safety net in the event castor oil should become unavailable. It is now possible to produce large quantities of the two main building block of nylon 6 and nylon 66 – namely 6-aminocaproic acid and adipic acid – using engineered strains of bacteria. In the last few years, three synthetic pathways have been proposed for the *in-vitro* production of 6-aminocaproic acid. *E. coli* strains have been engineered to acquire such pathways and varying degrees of success were achieved, with two pathways proving efficient and prone to being optimised under controlled lab conditions. Although research into the *in-vitro* production of 6-aminocaproic acid is relatively new, there is already proof that production in industrial quantities could be possible.

The industrial production of fossil-derived adipic acid is responsible for nylon's high contribution to global nitrous oxide (N_2O) emissions. The compound is produced from the oxidation of ketone-alcohol / nitric acid mixture, leading to the production of N_2O gas. For one kg of adipic acid produced, about 30g of N_2O is being produced as a by-product[xxxv]. In 2020, researchers engineered a strain of *E. coli* that can convert guaiacol – a naturally occurring lignin-derived compound – into adipic acid without producing any N_2O as by product. Guaiacol being a renewable feedstock present in large quantities around the world, producing industrial quantities of sustainable adipic acid is entirely achievable. *In-vitro* production pathways for the two main building blocks of nylon 6 and 66 are being developed and optimised and could soon be a fully-functioning supply chain for commercialised biobased nylon.

Acrylic and elastane

There are several other textiles commonly used by the fashion industry. This articles only covers a few and will focus on biobased alternatives to animal-derived material in the second installment of this three-part series. It is however worth ending this section by mentioning acrylic fabric and elastane. Two widely used materials.

Just like polyester and nylon, acrylic textile (also known as acrylonitrile fibers) is a synthetic fiber. Its properties include durability and chemical resistance, and low water absorbance and breathability. Unlike polyester and nylon, acrylic is particularly difficult to recycle, making it less environmentally friendly once it has been disposed of. There are currently no records of any research looking into biobased acrylic, however research into biobased acrylonitrile monomers are scaling up as it is a precursor for the production of carbon fibers. A very sought after commodity.

Elastane, more commonly known as Spandex or lycra, are synthetic fibers which are light and very elastic. Lycra is never used as a stand-alone textile for the production of clothes and accessories, on the contrary it is always used in blends to add flexibility and breathability, making it ideal for sportswear. A partially biobased (70%) alternative to elastane can be manufactured from corn-derived dextrose. It is especially designed for blending with cotton yarns. Just like with biobased polyamides, elastane fibers can also be manufactured from castor bean oil.

There is no doubt that the Fashion industry has become aware of the sector's environmental impact. There is an increasing number of campaigns and official commitments aiming to push sustainable biobased textiles at the forefront, with leading fashion brands paving the way. As new technologies are being refined and optimised, there is a call for legislative support for companies attempting to establish circular and sustainable business models.

Building a circular textile industry

In 2017, the Ellen McArthur Foundation published a report imagining what a newly reformed fashion industry could look like[iii]. Forty partners, including leading fashion brands, experts, public bodies and NGOs, came together to lay out a strategy that would enable the fashion industry to transform into a sustainable circular economy. The report goes over every aspect of textile and clothing production – from growing feedstocks for natural fibers, to waste disposal and recycling – to identify the key areas of the value supply chain that should undergo change. The policies and consumer engagement required are also explored.

Inspired by efforts such as this report, the EU Commission will vote on a new circular economy strategy for textiles at the end of 2021[xxxvi]. The Union strongly believes that promoting technological breakthroughs while helping companies build circular business models is the key to transitioning towards a sustainable textile industry. Key aspects of the new framework will promote resource use efficiency, GHG emissions reduction, chemical use reduction, and re-use and recycling for products reaching the end of their life cycle. Waste and overproduction will also be addressed. Businesses will be offered incentives to adopt new sourcing, manufacturing and retailing practices. The Commission believes that policies will play a pivotal role in helping businesses access sustainable natural and synthetic fibers for textile production and that full transparency on the origins of such products will need to become non-negotiable. Consumer engagement and education are also expected to play a vital role in the establishment of this new strategy as its success will rely on buyers' participation. Clear standards and labelling will become the main communication strategy to inform customers and change behaviours. Finally the EU Commission is also integrating a human and societal aspect in its action plan by taking into account work conditions. Fashion has been notorious for its involvement in forced labour and human rights violations throughout the last decades and the EU now believes that there cannot be a new circular fashion without the enforcement of new humane and fair working conditions for all employees and stakeholders. This is will therefore be one of the pillars of the new strategy.

The EU's commitment to this new strategy has been welcomed by stakeholders whom have been instrumental in building the framework. Discussions and consultations are still ongoing to refine the terms of the strategy and to ensure the best possible outcome. There is no defined timeline as to when circular fashion businesses will become the rule rather than the exception, but stakeholders argue that although change is definitely possible, the rate of change will heavily depend on policy-makers and their will to see this new circular industry into a reality.

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