DECARBONIZING THE TEXTILE AND FASHION SYSTEM

Material-driven guidelines in an ecological dimension-oriented perspective exploring the field of Biomaterials

Thesis project by
Gaetana Marzocchi

Co-supervisor: Prof.ssa Casciani Daria
Supervisor: Prof.ssa D'Itria Erminia

POLITECNICO DI MILANO - SCHOOL OF DESIGN
Master of Science - Design for the Fashion System

Academic year 2021/2022

POLITECNICO
MILANO 1863

“When we least expect it, life presents us with a challenge to test our courage and our will to change; at a time like this, there’s no point in pretending nothing happened or saying we’re not ready yet. The challenge won’t wait. Life doesn’t look back”

\- Paulo Coelho

.Table of contents

Aknowledgements

Special thanks to professor Erminia D'Itria for guiding me in the development of this project and for the valuable advices.
I express my sincere gratitude to my loved ones for supporting and encouraging me to complete this journey.

.Abstract *(English)*

The textile and fashion industry is the subject of growing criticism because of its negative environmental impacts for the intense use of resources associated with sourcing, production processes and disposal of materials.
The scenario of a sustainable textile development is a complex effort, including a lot of idealism. Sustainability and textile industry is often considered an "oxymoron".
The question has led this industry to a desire, driven by a need, to move towards a circular economy model for textiles that will implement recycling concepts and alternative practices in order to protect resources, environment and people.
This transition can not ignore the concept of 'life cycle thinking' for fabrics by generating and devolping a closed-loop system in which the designer becomes the main actor.
The project focuses on an ecological dimension-oriented perspective, based on the environmental impacts of processes and systems. On the basis of this assumption this paper investigates the existing and innovative solutions aimed to "decarbonize" the textile industry, focusing on the world of 'Biomaterials' which represent a step forward towards the future in terms of circular material innovation.
The qualitative study is basically conducted by theoretical data, i.e. texts from academic publications, literature review and reports on the topic. In addition to these, websites and journalistic articles are used. A case study methodology, conducted by open-ended structured questionnaires, is carried out in order to analyse the current circular material behaviours of the Como's textile supply chain. The Como's textile district is taken into consideration because it is a point of reference, in Italy, in Europe and in the world for the production of all finished products linked to artisanal and industrial know-how.
The research phase, which includes the theoretical framework and the case study methodology, aims to discuss the advancement from old productive processes towards new circular solutions by presenting innovative realities already adopting a circular system and the manufacturing industries of the supply chain, still considered newborn to the concept of circularity.
From the in-depth data, two archetypal fibres have emerged as the most impactful from an 'unsustainable' point of view: Cotton and Polyester. Sustainable alternatives to these two conventional fibres are proposed, in order to present circular material-driven guidelines that take into consideration all the phases of the supply chain such as the sourcing, the processing and the end of use.
The material-driven guidelines lay the foundations for the development of the last section of this project that also represents its purpose: a new mindset among designers aimed to reach a systemic change. Material-driven life cycle guidelines for designers are proposed in order to help, support and facilitate them in exploring solutions that are invaluable for people and are regenerative for our world. The design thinking, showed by the structured guidelines, allows the designer to create sustainable, resilient, long-lasting value in the circular economy, always keeping in mind that he needs to think about end of life from the very start.

***KEY WORDS*:** *Circularity, Decarbonization, Biomaterials, Lyfe cycle thinking, Material innovation, Textile supply chain, New mindset, Material-driven guidelines;*

.Abstract *(Italiano)*

L'industria tessile e della moda è oggetto di crescenti critiche a causa del suo negativo impatto ambientale dovuto all'intenso utilizzo di risorse legate all'approvvigionamento, ai processi produttivi e allo smaltimento dei materiali.
Lo scenario di uno sviluppo tessile sostenibile è uno tema complesso, che include molto idealismo. La sostenibilità e l'industria tessile sono spesso considerate un "ossimoro".
Tale problematica ha portato questa industria al desiderio, spinto da un'esigenza, di muoversi verso un modello di economia circolare per il tessile volto ad implementare concetti di riciclo e pratiche alternative al fine di proteggere le risorse, l'ambiente e le persone. Questa transizione non può ignorare il concetto di "life cycle thinking" per i tessuti generando e sviluppando un sistema a ciclo chiuso in cui il designer diventa l'attore principale.
Il progetto si concentra su una prospettiva orientata alla dimensione ecologica, basata sugli impatti ambientali di processi e sistemi. Sulla base di questo presupposto questa tesi indaga le soluzioni esistenti e innovative volte a "decarbonizzare" l'industria tessile, concentrandosi sul mondo dei "Biomateriali" che rappresentano un passo avanti verso il futuro in termini di innovazione dei materiali circolari.
Lo studio qualitativo è basato principalmente su dati teorici, ovvero testi tratti da pubblicazioni accademiche, revisioni letterarie e reports sull'argomento. Oltre a questi, vengono utilizzati siti web e articoli giornalistici. In aggiunta, viene presentata una metodologia di casi studio, condotta mediante questionari strutturati a risposta aperta, al fine di analizzare l'attuale condotta della filiera tessile comasca sui materiali circolari. Il distretto tessile comasco è preso in considerazione perché è un punto di riferimento, in Italia, in Europa e nel mondo, per la produzione di tutti i prodotti finiti legati al know-how artigianale e industriale.
La fase di ricerca, che include il quadro teorico e la metodologia dei casi studio, si propone di discutere l'avanzamento da vecchi processi produttivi verso nuove soluzioni circolari mostrando realtà innovative che già adottano un sistema circolare e le industrie manifatturiere della filiera, considerate ancora neonate sul concetto di circolarità.
Dai dati di approfondimento, sono emerse due fibre archetipiche come le più impattanti da un punto di vista di 'insostenibilità': Cotone e Poliestere. Vengono proposte alternative sostenibili a queste due fibre convenzionali, al fine di presentare linee guida circolari orientate ai materiali che prendano in considerazione tutte le fasi della filiera come l'approvvigionamento, la lavorazione e la fine dell'uso.
Le linee guida materiche gettano le basi per lo sviluppo dell'ultima sezione di questo progetto che ne rappresenta anche lo scopo: una nuova mentalità tra i designers volta a raggiungere un cambiamento sistemico. Vengono proposte linee guida sul ciclo di vita dei materiali per i designers al fine di aiutarli, supportarli e facilitarli nell'esplorazione di soluzioni che hanno un valore inestimabile per le persone e sono rigenerative per il nostro mondo. Il 'design thinking', mostrato dalle linee guida strutturate, consente al designer di creare valori di sostenibilità, resilienza e durabilità nell'economia circolare, tenendo sempre presente che deve pensare alla fine vita del prodotto fin dal principio.

PAROLE CHIAVE*: *Circolarità, Decarbonizazzione, Biomateriali, Lyfe cycle thinking, Innovazione di materiali, Filiera tessile, Nuova mentalità, Linee guida materiche;

.Introduction *(English)*

Environmental impact and climate-changing factors are becoming an essential issue in textile, yarn and, most in general, in fashion industry. The positioning of this multi-trillion dollar industry is not clear, but it is certain that it is among the most polluting in the world.
Given its size and nature, the industry faces a number of social and environmental challenges. These challenges are complex and interrelated, but most broadly fall under: land use, water use, chemical use, biodiversity loss and greenhouse gas (GHGs) emissions.
For this industry, one of the main issue to be addressed is the Fast fashion: this concept is in line with the so-called low fashion that uses production processes that prove to be destructive, from fabric dyes, which contain highly carcinogenic components, to the raw materials used for the creation of garments, not recyclable and non-biodegradable.
This complex scenario has led to a desire, driven by a need, to move towards a circular economy for textiles that will implement recycling concepts and technologies to protect resources, the environment and people as a response to the publication of damning reports on the negative impacts of fashion consumption.
This transition can not ignore the concept of 'life cycle thinking' for fabrics by generating and devolping a closed-loop system in which the designer becomes the main actor.
The Circular Economy system for textiles is a production and consumption model based on the Cradle-to-Cradle concept, that involves sharing, lending, reusing, repairing, reconditioning and recycling existing materials and products for as long as possible. The purpose of this new economic model is to extend the life cycle of products by reducing waste to a minimum, allowing them to generate further value by reintroducing them into the economic cycle one they have finished their function. In the specific case of textile supply chain, the transition to a type of circular economy is based above all on the sustainable potential of new bio-based materials.
The term "bio-based" refers to materials or products wholly or partially derived from biomass: plants and vegetables, especially concerning new developments in the field of bioplastics, which use biomass such as corn, sugar cane, or cellulose as raw material to replace fossil sources such as oil. It is important to note that bio-based does not necessarily mean biodegradable. In the textile field, the term generally refers to the production of manmade fibers, such as nylon and polyester, where the replacement of fossil fuels is one of the main fields of innovation.
In this work is examined the development of these new alternatives to conventional materials considering the environmental impact of sourcing, production processes and disposal because a fashion product is sustainable if it results from a process that considers all the steps in its production, evaluating materials and processes, maintenance, cleaning, use and disposal practices. In materials, this holistic approach profoundly impacts all the phases of the different supply chains.
These new biobased applications, proposed by innovative startups or companies, represent the best innovative solutions aimed to 'decarbonize' the textile industry. Unfortunately, these are often small companies that cannot interface with the speed of this system and large-scale production, failing to keep up with the intricate textile supply chain that supports the fashion world.
In order to understand the degree of sustainable advancement of this other side of the coin, a case study methodology, conducted by open-ended structured questionnaires, is carried out with the purpose to analyse the current circular material behaviours of the Como's textile supply chain. The Como textile district is a global player in particular for high-end products and one of the most predominant italian textile supply chain in the world.
The research phase, which includes the theoretical framework and the case study methodology, aims to discuss the progress from old productive processes towards new circular solutions by presenting innovative realities already adopting a circular system and the manufacturing industries of the supply chain , still considered newborn to the concept of circularity.
All the data collected during the research phase showed that the two most impactful fibers in the sector are the

archetypal ones of Cotton and Polyester. Sustainable alternatives to these two conventional fibres are proposed, in order to present circular material-driven guidelines that take into consideration all the phases of the supply chain such as the sourcing, the processing and the end of use.
At this stage, designer plays an essential role in the transition to the sustainable textile industry, since they are the ones who generate new trends and thereby, the range of future products. For this reason, it is fundamental that designers and large producing brands have a sustainable approach. The last part of this project also represents its purpose: material-driven life cycle guidelines for designers are proposed in order to help, support and facilitate them for creating solutions that are invaluable for people, give businesses a competitive advantage, and are regenerative for our world. The design thinking proposed by these guidelines allows the designer to create sustainable, resilient, long-lasting value in the circular economy. Guidelines help this figure to reframe its mindset, ask the right questions, take on projects, and start exploring the sustainable possibilities.

1.

Environmental impact of Fashion & Textile system

1.1 A fashion industry Eco-Critical perspective

The textile industry is the subject of growing criticism because of its intensive use of resources - both natural and fossil derived - and the negative environmental and societal impacts associated with manufacturing, use and disposal of clothes.
Globally, 53 million tonnes of fibers are consumed annually for making clothing responsible for 10% of greenhouse gas (GHGs) emissions and 20% of wastewater generating large amount of waste.
In Europe, 180,000 tonnes of textile waste generated in 2016, of which only 15-20% were collected for recycling and less than 1% was recycled into new clothes.
Textile consumption is set to continue to rise globally by 63% by 2030 (Boston Consulting Group and Global Fashion Agenda, 2017).
The root cause of this constant criticism is to be attributed to the 'Fast Fashion': a business model based on offering consumers frequent novelty in the form of low-priced, trend-led products (Niinimäki et al., 2020). This disposable fashion supports the logic of always producing new low cost garments intended to last a single season.
By accelerating the rate at which new collections are designed and produced and by constructing cheap and fragile garments, fast fashion makes clothing repair unnecessary (because garments are discarded before they get damaged), uneconomical (because new garments are so cheap) or impossible (because the garments are too flimsy).
Fast Fashion is responsible for approximately half of the fashion industry's emissions. This sector is especially harmful due to its fragmented supply chains, use of synthetic materials, and consistent overproduction.
The production processes prove to be destructive, from the dyes of the fabrics, which contain highly carcinogenic components, the raw materials used, their extraction and production processes, to create the garments, in particular polyester (a synthetic material derived from petroleum), clothing construction, shipping, retail, use, to the disposal of the garment.
When considering sustainability, the matter is not only about the environmental cost of industrial production and disposal, the evaluation must consider also the social correlation that development has, in fact the approach is also negative from a social point of view: many fast fashion companies relocate their production processes to Far East countries, where working environment conditions are certainly less high than those of industrialized countries.
Efficient mass manufacturing in lower cost has brought about low end-prices of garment. Cheap product prices lead consumers to impulse purchases and unsustainable consumption behavior: overconsumption, very short use time of products and premature disposal of the product. The total volume of textile and fashion production at the global level is estimated to be more than 30 million tons annually, and therefore the environmental impacts of this industry are remarkable.
Recent research from the Intergovernmental Panel on Climate Change (IPCC) shows that Fast Fashion is a major contributor to a growing environmental crisis, leading to an increase in the severity of natural disasters and the destruction of ecosystems beyond repair. The root cause of these damages is closely related to GHGs emissions: the carbon footprint (also called GHG inventory, i.e. of GreenHouse Gases) is a measure that expresses in CO2 equivalent the total greenhouse gas emissions directly or indirectly associated with a product, an organization or a service. According to a 2020 McKinsey report, the fashion industry will need to reduce its total CO2 output to below 1.1 billion metric tons by 2030, to prevent irreversible damage to the climate.
If current production levels are maintained, fashion's GHGs emissions are expected to rise by 2.7 billion metric tons by 2030, a trajectory that will push global average temperatures above the IPCC's 1.5C limit.
The low-carbon environmental protection of the whole industry has a significant impact on climate change. Therefore, it is necessary to evaluate the carbon footprint of the whole life cycle of the textile industry in order to improve the environmental value of products, and then put forward suggestions for energy conservation and emission reduction to achieve sustainable development.

1.2 Carbon footprint assessment of textile sector

The term of carbon footprint was first used in the concept of ecological footprint proposed by William Reese and other scholars and it is used to evaluate the total emission of GHGs by human activities. Ecological footprint is a biologically productive regional space that can continuously provide resources or absorb east areas, which means to maintain the survival of person, region, country or the world.

Carbon footprints usually account for the direct and indirect six GHGs emitted because of production and activities in a certain period of time, which is usually expressed as CO2 equivalent.

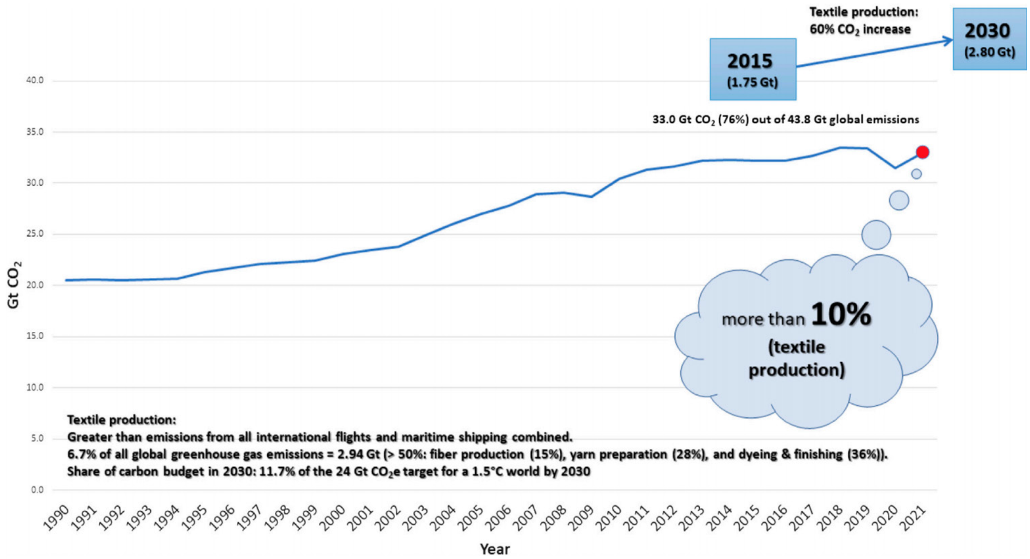
Textile industry is closely related to GHGs emissions, playing different market roles in different stages of the whole life cycle, including cotton planting and cultivation, textile material research and development, textile material processing and production field.

The textile and garment sector accounts for a significant proportion of global carbon emissions, estimates range between 6 and 8 per cent of total global carbon emissions, or some 1.7 billion tonnes in carbon emissions per year.

The detrimental ecological footprint of this industry is caused by high energy, water and chemical use, the generation of textile waste and microfibre shedding into the environment during laundering. Furthermore, it has been estimated that up to 20% of industrial wastewater pollution is caused by textile dyeing and finishing.

Textile production occurs through geographically long and complex supply chains that include growers and processors of raw fibres, yarns and textiles, weavers, knitters, dyers and finishers, product manufacturers and distributors. While textiles have various end uses, from interiors and automotive fit-outs to geo-textiles, agri-textiles and hygienic textiles, the sector is essentially fashion driven, as most global fibre production (60%) is destined for clothing.

Figure1.1 illustrates the textile industry's massive contribution to GHGs emissions, compared to global energy production, a red alert for the need to reduce textile production's impact on climate change globally.



One of the main problems is the use of synthetic fibres that has grown exponentially, and polyester has now surpassed cotton as the most widely used fashion fabric. However, carbon emissions from synthetics are much higher than cotton because they are made from fossil fuels such as unrefined petroleum products, thereby contributing to climate change

Figure 1.1 Textile contribution compared to global energy related emissions
Researchgate.net

through carbon emissions. It is estimated that 5.5 kg CO_2e is emitted to produce one polyester t-shirt, compared 2.1 kg CO_2e for a cotton t-shirt (Kirchain et al., 2015).
In academic circles there are three mainstream views on the concept and connotation of carbon footprint: first, carbon footprint is the CO_2 emissions generated by burning fossil fuels in the process of human activities; second, carbon footprint is defined as the CO_2 conversion of CO_2 and GHGs emitted by products in the whole life cycle of raw material acquisition, production, distribution, use and recovery; and third, the focus of the concept of the carbon footprint is to measure the impact of human activities on climate change based on direct and indirect CO_2 conversion.
Despite the research on carbon footprint evaluation of textile industry is relatively lacking there is data that estimates that the whole life cycle production process of the textile industry (from fiber processing to clothing products) is about 4.84 tons of standard coal/ton of fiber, accounting for about 4.4% of the total energy consumption of the national industry.
Facing the increasing global warming, the textile industry urgently needs to control the low-level expansion of high energy consumption and high pollution industries, eliminate backward production capacity, adjust the industrial structure and take the road of sustainable development. Therefore, the research on the evaluation of carbon footprint of a textile industry based on the whole life cycle has certain significance for the development of energy conservation and emission reduction.

1.2.1 LCA (Life cycle assessment)

When analyzing the carbon footprint in textile industry it is possible to assert that this is a subset of the more complete Life Cycle Assessment (LCA), an analytical and systematic methodology that evaluates the environmental footprint of a product or service along its entire life cycle.
This system is based on a calculation system that range from the extraction phases of the raw material constituting the product, to its production, distribution, use and its final disposal, returning, the environmental impact values associated with its life cycle.

Figure 1.2 Components of life cycle analysis
ScienceDirect.com

This kind of methodology has been broadly applied to assess the environmental effects produced by the related fabrication industry, it can calculate the environmental footprint of a service, accounting for the footprint of everything needed to provide that same service. LCA objectively quantifies the energy and environmental loods -and therefore- the potential environmental footprint associated with a product/process/activity along the entire life cycle, from the acquisition of raw materials to the end of life (from cradle to grave) or, in a more correct logic of circularity, "from cradle to cradle".

The LCA mainly consists of:
- **Identify the ecological influence of different product phases on their life cycle.**
- **To make industry decisions, government organizations to improve sustainable product process and design.**
- **Established the new benchmarks for desired balance between productivity and sustainable production.**

At the end of analysis, the environmental footprint value of a product/service is returned according to different "impact categories", which represent all the different impacts that this generates in the various environmental sectors. Once the "system boundaries" (i.e. the field of analysis) have been defined, an LCA study makes possible to measure the environmental impact generated by the various production processes involved in it, identifying those with the greatest impact and understanding the environmental performance of each production cycle in an objective and technically argued form.

The ultimate goal is to menage the impacts that have been calculated in two ways: through their reduction and compensation or following the logic of Life Cycle Thinking (LCT), which allows to choose production methods and materials characterized by a lower environmental footprint.

In the specific case of textile sector, the LCA must examine such material supply chains' health and environmental impacts to conclude the higher effects on the ecotoxicity and disposal sensitivity analysis.

When analyzing the textile industry it's widely acknowledged amongst the most polluting factors for the sustainable supply chain in the environment. Recycling is one way to lower carbon dioxide emissions, on of the primary drivers of climate change. Textiles produced from synthetic fabrics are mostly disposed of via trash landfill or incineration, implying that fabrics must presently be made up of virgin material. The synthetic fibers commonly used in the textile industry are decomposed in landfill after a single usage, thus a higher need of virgin material. PET is used primarily in fibers (60%), but various recycle and reuse assessments can be made in LCA of PET bottles consisting of only 30% of the total market share of that product. LCA on new textile procedure has been done to evaluate the textile wastages by conditioning their properties using various processes chains and considering technical steps has been made with ecological preferences. This research will suggest a 60% reduction in environmental impacts and proven sustainable ecological declarations.

The LCA system is, therefore, an innovative approach that fits perfectly within the parameters of moving away from the current linear productive paradigm towards a circular economy.

1.3 Exploring the current industry model

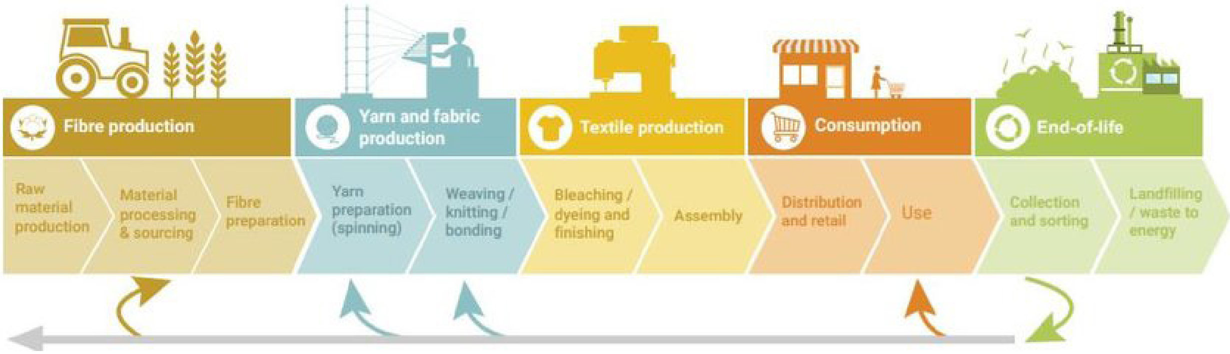
The traditional linear economic model is based on the typical "take-make-dispose" scheme. This model depends on the availability of large quantities of easily available and low-priced materials and it is characterized by an intensive exploitation of raw materials, which causes excessive emissions of carbon dioxide into the environment.
At the base of the linear economy is the production of a good that will produce, at the end of its useful life, a waste that will not be reused in any way in the production process.
Each of these phases will lead to excessive carbon dioxide emissions into the environment and the ultimate goal of this economic system being mass production and therefore overproduction.
In the specific case of textile and fashion industry, globally 20% of industrial water pollution is caused because of the dyeing and treatment of textiles.
In the linear system this industrial sector uses mostly non-renewable resources – 98 million tons in total per year – including oil to produce synthetic fibers, fertilisers to grow cotton, and chemicals to produce, dye, and finish fibers and textiles. While textile and fashion manufacturing has moved to lower-cost countries on the other side of the globe, so also have many environmental problems.
Textile manufacturing, in particular, causes the key problems, while harmful and toxic chemicals are used and waste is not treated properly. This causes human tragedies for workers and the neighboring communities and their environment.
In the linear system (design-manufacturing-sale-dispose) we are wasting valuable materials in huge amounts. Not only materials, however, but also many other resources, for example water and energy needed for manufacturing are wasted if the product life-time is very short. It has been estimated that 80% of all products turn into "waste" and are thrown away within the six first months. Garments' life cycles have also drastically shortened.

The linear model is based on the concept of "fast"(fast design and manufacturing, fast consumption, easy disposal), in fact highlights that garments are not made to last for long in the current linear system and most of our garments are designed to be laundered only 10 times. Such is the new "norm" in the fast fashion business.
The craze for buying new fashion items every week causes an overload in our wardrobes with the consequence that many contents are useless and unused.
While the linear model results in an oversaturated and oversized fashion system with big environmental impact, it is imperative to develop better use of resources and change the system. It's necessary to create a better balance and use all resources more wisely. Closing the loop and building a new understanding of how fashion can be redesigned in the context of a circular economy.

Figure 1.3 **Current linear economy**
Stockholm Environment Institute, 2019

1.3.1 Linear activities in textile value chain

The textile industry commonly refers to the production of yarn, textiles and fabrics, while the clothing industry (also referred to as the garment/apparel/fashion industry) refers to the production of garments. The sector also includes other types of textile products, such as household textiles and technical/industrial textiles (for instance, textiles for industrial filtres, hygiene products, textiles for the car and medical industry).
In this project, the analysis focuses on the textile industry related to the sourcing (the extraction of raw materials or supply), the processing (yarn, knitting, weaving, finishing) and the end of use (the disposal of the material).
There is a tremendous confusion over the sustainability impacts of cultivating and extracting textile materials. Synthetic fibers are commonly seen as 'bad' and natural fibers as 'good'. This perception os influenced by a complex set of factors including raw material renewability, biodegradability and stereotyped associations made with chemicals, factories and pollution. Certainly while there is no dispute that producing synthetic fibres impacts on people and the environment, natural fibre cultivation and processing also causes substantial impact. Cultivating 1kg of cotton for example, draws on as much as 3800 litres of water. In comparison, producing 1kg of polyester uses little water, approximately 17 litres per kg of fibre. Polyester manufacture does, however, consume almost twice the energy needed to make the same amount of cotton. Thus, the key sustainability challenges in fibre production are different for different materials (Fletcher, 2014).



The production of raw materials is responsible for a large share of the environmental impact of the textile and clothing industry, not least from growing crops for natural fibres. Cotton, which according to a 2015 report by European Clothing Action Plan (ECAP) accounts for more than 43 % of all fibres used for clothes on the EU market, is considered especially problematic because it requires huge quantities of land, water, fertilisers and pesticides.
Polyester, which is made of fossil fuels and is non-biodegradable, accounted for 16 % of fibres used in clothes according to ECAP. Its main advantages are that, unlike cotton, it has a lower waterfootprint, has to be washed at lower temperatures, dries quickly and hardly needsironing, and it can be recycled into virgin (new) fibres. However, several studies have recently also shown that one load of laundry of polyester clothes (also nylon and acrylic) can discharge

Figure 1.4 **Linear representation of activities along the Textile value chain**
UN Environment Programme, 2020

microplastic fibres, which release toxins into the environment and can end up in human food chain. Estimates show that every year approximately half a million tonnes of plastic microfibres from washing clothes end up in the ocean.
Manmade cellulosics (MMCs), derived from cellulose made from dissolved wood pulp of trees, make around 9 % of fibres used in clothes on the EU market. Most commonly used is viscose, also known as rayon. They are made from renewable plants and are biodegradable, but the main challenge is also the sustainable sourcing of cellulose, as the global production of MMCs more than doubled from 1990 to 2017.
Spinning raw materials into yarns, weaving them into fabrics and applying finishing techniques such as dyeing or giving the fabrics strength and shine are energy-intensive processes in which large amounts of water and chemicals are used. More than 1 900 chemicals are used in the production of clothing, of which 165 the EU classifies as hazardous to health or the environment. According to the 2017 Pulse of the Fashion Industry report, dyeing can require up to 150 litres of water per kilogram of fabric and, in developing countries, where most of the production takes place and where environmental legislation is not as strict as in the EU, the wastewater is often discharged unfiltered into waterways.
Reliable and recent data on what happens to clothes once their owners decide to get rid of them are not readily available. Most clothes in the EU seem to be still thrown away and burned in incinerators, or end up in landfill where they release methane. The JRC quoted estimates by the Textile Recycling Association that only between 15 % and 20 % of textiles disposed of were collected for reuse or recycling in 2005.
In according to Fletcher (2014), to summerize, the problems related to this linear scheme can be highlighted as follow:

•Large quantities of water and pesticides required for growing cotton;
•Emissions to air and water arising from producing synthetic and cellulosic fibres;
•Adverse impacts on water linked to natural fibre production;
•Significant use of energy and nonrenewable resources for synthetics;

1.4 Demand for a radical change

The critical scenario of the Fashion & Textile industry has led to a need to move towards a radical circular sustainable change in order to protect resources, the environment and people.
The theme of a sustainable development is a complex effort, including a lot of idealism, in fact sustainability and fashion/textile industry is often considered an "oxymoron".
Fashion often conflicts in concept with the philosophy of sustainable development, it remains ambiguous and inherently paradoxical in nature. As the nature of fashion is based inherently on the continuous process of change and the pressure to became new or be perceived as new, the fashion industry always strives for novelty, producing new garments in response to fast-moving consumer demand. Conversely, the term "sustainable" is essentially associated with longevity, it is derived from the function of ecosystems that assist themselves over periods of time. The goals of sustainability are open-ended and multi-faceted, considering the triple bottom line of environmental, social and economic benefits for current generations and the needs of future generations.
Despite the paradox of these two terms, it is undeniable that many steps forward are leading to change.
After a series of controversies surrounding fast fashion's impact in the early 2010 s, the leaders of this industry adopted various sustainable initiatives and claimed to be more "eco-friendly": they may reduce the environmental impact of their entire supply chains in order to create a more environmentally-conscious industry.
In according to Meadows(1999), the transforming of any system must start from the core, from the level of paradigms which are the sources of the system. Meadows considered that is important to point out the ailures in the old paradigms and persistently advocate for better alternatives. The real challenge in sustainable fashion is to aim for chain on a deeper level and in long term, starting from design philosophies that take sustainability into account.
A sustainable design takes into consideration three areas: People, Planet and Profit, including also ethical and value-based thinking. While a true sustainable thinking is rather wide and need a holistic understanding and approach on many levels, it is more common to focus one narrower approach to eco-design and sustainability, for example focusing on the environmental impacts of manufacturing, substituting conventional materials with eco- materials, or focusing on ethical issues in manufacturing.
The turning point has begun in the early 2010s: after a series of controversies surrounding fashion and textile environmental impact, the industry's leaders adopted various sustainable initiatives and claimed to be more "eco-friendly". In order to create a more environmentally-conscious industry, they may reduce the environmental impact of their entire supply chains. This will require effective sustainable supply chain management (SSCM), a system which integrates sustainable policies throught supply chain operations. Brands can take comprehensive approach to SSCM by focusing on two key areas: reducing indirect impact created by upstream and downstream activities, and reevaluating garment design to make current sustainability more effective. To significantly reduce their impact, brands must invest in long-term decarbonization and energy infrastructure, engage with suppliers and consumers, and re-evaluate the design standard for products. If adopted at the industry level, these reforms will significantly mitigate fast fashion's impact on the planet.
This transformation process must start from the core and, consistent with the current state of the fashion system, must start at the material level, the most impactful.

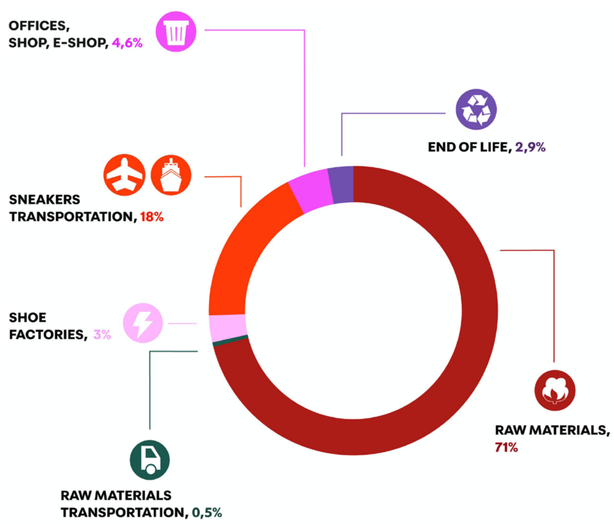


Figure 1.5 Proportion of VEJA's CO_2 emissions in 2019
project.veja-store, 2019

2.

'Decarbonizing' the Textile system through a Circular Economy

2.1 Textile industry towards a circular economy

The CIRCULAR ECONOMY is a production and consumption model that involves sharing, lending, reusing, repairing, refurbishing and recycling existing materials and products as long as possible.
The purpose of this new economic model is to extend the life cycle of products by reducing waste to a minimum, making them generate further value by reintroducing them into the economic cycle once they have finished their function. In according with Ellen McArthur Foundation the circular economy is a systems solution framework that tackles global challenges like climate change, biodiversity loss, waste, and pollution. It is based on three priciples, driven by design: eliminate waste and pollution; circulate products and materials (at their highest value); regenerate nature.
A Circular Economy, in fact, is regenerative by nature, based on principles of closed loops. According to these principles, a product is designed to have multiple life cycles or to be biodegradable. Accordingly, after the use phase, the product will continue in technical or biological cycle. The realisation of a circuclar economy, in which materials are retained in a closed loop, requires the development of sustainable and scalable high-quality production associated with effective recycling technologies and systems (Ellen McArthur Foundation, 2021). In this context, recycling is a necessary step in enabling a circular resource flow. Within the technical cycle of the cicrcular economy model, textile recycling is structured into mechalical and chemical processes and it is defined by closed-loop processes (Ellen McArthur Foundation, 2017) in which the material is recycled in the same product, so textiles are transformed into textiles, for example fibre-to-fibre recycling.
In addition to closed-loop recycling, other recycling classification are discussed in Sanding and Peters (2018):
• Closed loop recycling: the material is recycled in a more or less identical product.
• Open loop recycling: the material is recycled in another category of the product.
• Upcycling: the product from recycled materials is of higher value of the original product.
• Downcycling: the recycled material is of lower value compared to the original product.
The biological cycle is based on resources that can decompose and build nutrients transform into new renewable resources. Circularity in the biological cycle builds on "biological nutrients" such as food waste to regenerate soil, through processes such as composting and anaerobic digestion.
For textiles, composting is a poor use of resources and should not be part of a circular economy system, which keeps the value of textiles in the system.
The technical cycle, instead, is based on non-renewable petroleum-based materials that can only be recovered and repurposed.
Circular Economy means adopting a new, more strategic and future-oriented mindset in all aspects of a company's activity. While in the linear model it is easier to focus on a narrow core, in a circular economy the core has to be in the lifecycle, use, and regeneration of products and closing the material loop:

> ***Sourcing from return chains, growing presence in used product markets, creating value from any waste materials along the value chain and maintaining deep involvement with products in use are just some of the strategic shifts companies make to evolve to a circular model. Companies have to think beyond the traditional core and build an ecosystem of partners that operate and monetize the entire product lifecycle (Lacy & Rutqvist 2015, 149).***

A circular economy approach in fashion aims to develop a more sustainable and closed-loop system where the goal is to extend the use-time of garments and maintain the value of the products and materials as long as possible.This

means that all materials will be recycled in several rounds. Products are designed to be included in a system where all aspects support circularity. The original design needs to take account of several lifecycles. In this context, the designer adopts circular approaches in which the materials need to fow within the system and waste needs to be collected and appreciated as a valuable material for recycling and material recovering.
All the products need to be collected back after their useful time is over. It is fundamentally a design paradigm based on the idea of nutrient management, which enables product materials to be up-cycled over and over again – with minimal impact and the loss of quality.
According to the oerformed analysis, and the emerged core-role of materials is coherent to address the importance of 'Life cycle thinking'.

Figure 2.1 Model of a circular economy
Europarl.eu (European Parliament), 2023

2.1.1 Life cycle thinking for materials

The transition towards a type of sustainable fashion cannot ignore the notion of life cycle thinking. The circular economy, in fact, is based on the concept of "**Cradle to Cradle**": a philosophy developed by Braungart and McDonough (2008) and it suggests that instead of simply saving natural resources, attention should be paid to the lifecycle of materials. Instead of throwing products away, their material should be reused. The most difficult products are the hybrid ones that consist of materials of both types. The cradle to cradle concept proposes that products should be designed so that there is no waste, or that wastes produced can be used by another production process. It aims to break the linear model of resource use from extraction to disposal by closing the loop for every product or service entering the economy and ensuring that after its end-of-(useful)-life, every product serves as either nourishment for nature, or as high quality materials for new products.
This concept takes into account all the phases of production: design, manufacturing, logistics, retail, use and disposal. The key item is to design life cycles instead of products, in this way sustainable design includes consideration of the use phase and end-of-life thinking. Moving towards a circular economy means taking a system perspective on fashion, where all actors are included: designers, producers, manufacturers, suppliers, business people and even consumers.
In order to lead this industry towards a sustainable way, the European Commission has defined principles of environmental design as follows:
• Use low-impact materials whenever it is possible: non-toxic, sustainably produced or recycled materials which require little or no natural resources (such as energy and water) to transport and process, and whose use does not threaten bio-diversity.
• Focus on resource efficiency: create manufacturing processes, services and products that consume as few natural resources as possible.
• Invest in high quality and durability: longer lasting and better functioning products, which age aesthetically and therefore reduce the impact of product replacement.
Reuse, recycle and renew: design products that can be reused, recycled or composted.
A good model for the fashion sector is presented by RSA (Royal Society for the Encouragement of Arts, Manufactures and Commerce, "Great Recovery" programme 2013). The model presents four model systems: the frst includes consumer behaviour, and its goal is to extend the product use phase; the second includes companies and new kinds of business models to extend or intensify the use of products; the third challenges manufacturers by bringing in new ways to extend the use-time of the product through remanufacturing; the fourth level concentrates on material recovery, using waste to manufacture new fbers and yarns. This is the most interesting level, and a lot of new development work is going on in this sector looking at how to use textile waste as a source for new fiber production.

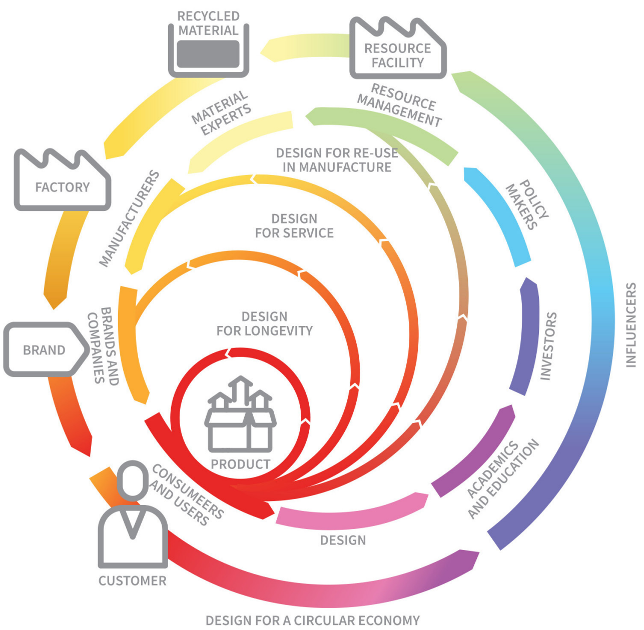


Figure 2.2 The four model of DCE
Design in a Circular Economy (RSA 2016)

The transition to this form of economy impacts numerous areas from mobility, agriculture, land use and waste treatment to long-term economic development. A circular economy cannot be implemented by individual institutions or companies, but requires an overarching cooperation and communication process, as well as a holistic approach in designing value-added chains.
When constructing a new understanding of the circular economy, all levels need to take into account: consumption, design, business, industry and waste management. This needs a systemic perspective and tight collaboration between diferent stakeholders. On the other hand, new understanding and new networks open diferent business and design opportunities. It can be summed-up that the transformation towards circularity needs creativity, new way of thinking and acting, new networks, large collaboration and brave experimentation.
In practice, this type of economy implies reducing waste to a minimum. When a product reaches the end of its life, its materials are kept within the economy wherever possible. These can be productively used again and again, thereby creating further value.
Measures such as waste prevention, ecodesign and re-use are necessary for reducing total annual greenhouse gas emission, reducing pressure on the environment, improving the security of the supply of raw materials, increasing competitiveness, stimulating innovation, boosting economic growth and creating jobs.
This is a key point for this project, as it is focuses on an ecological dimension-oriented perspective, based on the environmental impacts of processes and systems.

2.2 'Decarbonization' of fashion & textile industry Existing and innovative solutions

The global fashion industry is a multi-trillion dollar industry, producing over 100 billion garments annually. Given its size and nature, the industry faces a number of social and environmental challenges. The key environmental challenges are complex and interrelated, but most broadly fall under: land use, water use, chemical use, biodiversity loss and greenhouse gas (GHGs) emissions.
The GHGs emissions of the fashion industry are globally significant and evidence has shown that change is required at an unprecedented rate and scale; however, the decarbonization opportunities in the fashion industry are wide-ranging and diverse. Recent analysis from The World Resources Institute (WRI) and Apparel Impact Institute (Aii, 2021) has mapped solutions to decarbonize the industry and guide the industry to align with a 1.5°C pathway by 2030.
The possible solutions can be divided into existing solutions and innovative solutions.
The existing solutions are classified as follows:

• Renewable energy
This is energy derived from natural sources that are replenished at a higher rate than they are consumed. Sunlight and wind, for example, are such sources that are constantly being replenished. Renewable energy sources are plentiful and all around us. It represents one of the key to addressing the climate crisis.

• Sustainable materials and processes
These refer to alternative materials and processes aimed at reducing GHGs emissions bringing many benefits in terms of environmental impact. In this specific case they refer to the concept of recycling. Textile recycling can help reduce the environmental impact of the textile industry, as it uses fewer natural resources and reduces the amount of fabrics that end up in landfills.

• Maximization of energy efficecy
This point is referred to all the improvement actions that can be done on the facilities in order to reduce the energy consumption required to perform the same process. Beyond energy reduction, maximize energy efficiency proves to be a key process in substantially reducing the carbon footprint of the textile industry.

The innovative ones are classified as follows:

• The phase out coal through dry processing
This alternative process improves the heating value of the coal reducing coal mercury, sulfur, and ash content.
In addition, this process results in lower $CO2$ emissions. Most of the coal drying processes that have been developed to date depend on high-grade or process heat to reduce coal moisture content or employ complex equipment layouts using expensive materials to recover the latent heat of vaporization. This significantly increases the cost of thermal drying, which is the main barrier to large-scale industry acceptance of this technology.

• Accelerate the development of next generation materials
This is a key point in decarbonizing the industry in longer term. The benefits are in developing alternatives raw materials and the use of innovative processing of alternative feedstocks replacing the more impactful conventional ones. This next generation materials is represented by the use of sustainable methods and treatments (e.g.cotton) or in the use of biobased derived feedstocks (e.g.polyester).

2.2.1 Renewable energy

Renewable energy is generated from natural, carbon-free resources, such as wind and solar, and can replace conventional sources of electricity generation, such as natural gas or coal. Renewable electricity projects can either be located off-site and feed into the grid or located at the manufacturing site and deliver electricity directly to the manufacturer. On-site renewable electricity projects typically use rooftop solar technology, although wind and other technologies are possible for on-site installations as well. The cost of this solution have fallen dramatically in the last decade — solar prices decreased more than 80% from 2010 to 2023 — and in many cases, it now costs less to generate electricity from renewable sources than from conventional fossil fuel sources.
The improvement in terms of environmental impact is underestimated. Some studies show that switching production to renewable electricity across the fashion supply chain abates ~27% of all emissions.
Therefore, while there are many industry-specific actions that should be pursued, the need to transition to renewable electricity underpins all actions of supply chain.

TYPES OF RENEWABLE ELECTRICITY GENERATION

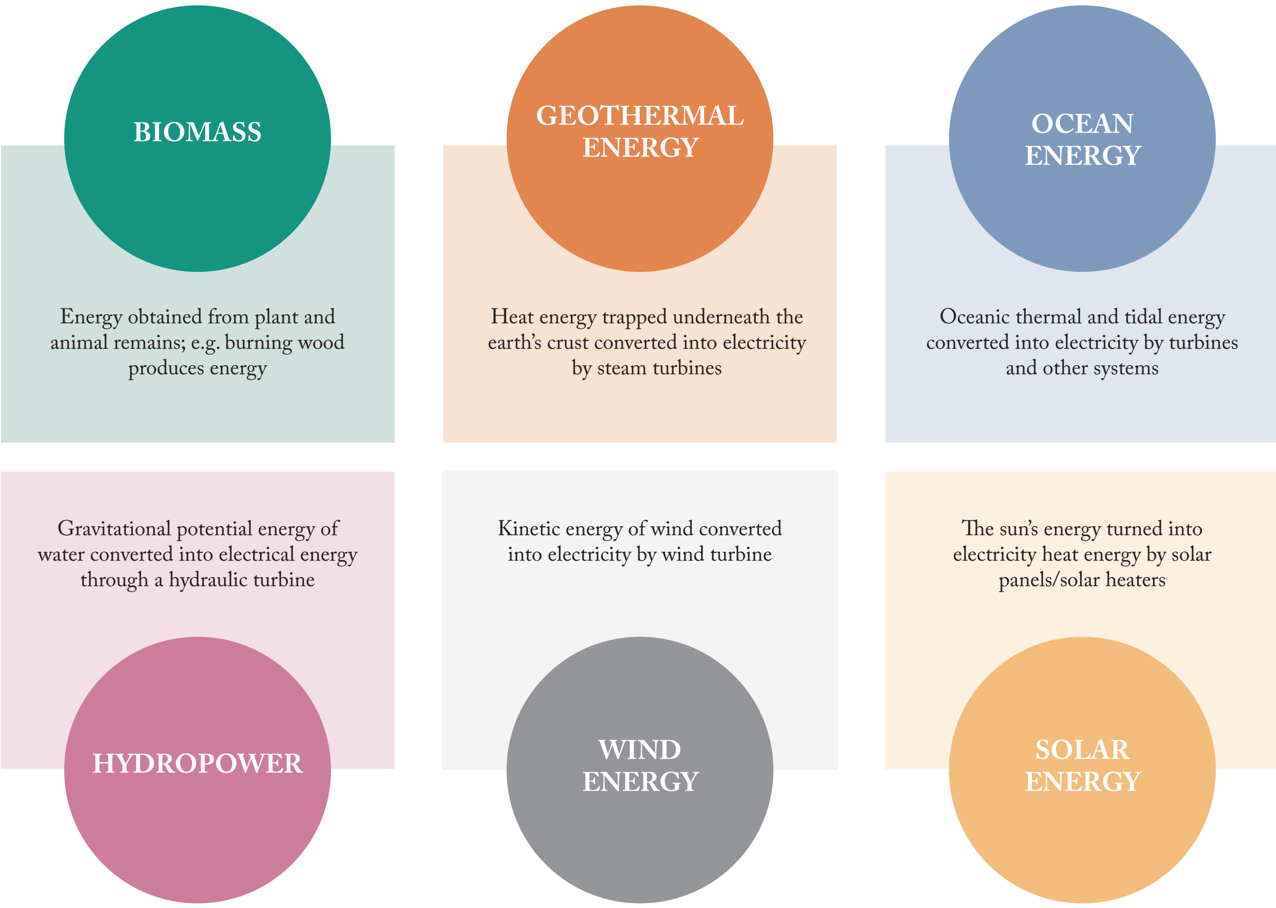


Figure 2.3 Types of renewable electricity generation
Science fact (2020)

2.2.2 Sustainable materials and processes

Sustainable materials and processes are those with lower GHGs emissions compared with conventional alternatives and they include:

•Mechanically-recycled Polyester
•Mechanically-recycled Nylon
•Organic/preferred Cotton
•Mechanically-recycled Cotton
•Viscose sourced from sustainable fibres

That existing sustainable materials and processes will reach 46% market share by 2050 compared to 17% in 2020. At 46% market share this solution alone could reduce total emissions within the apparel industry by 16%.

RECYCLED FIBERS MARKET SHARE

A key driver of sustainable materials and processes is through recycling old fibres into new uses.
This will require an increase in recycling rates and infrastructure. Furthermore, many recycled synthetic fibres (e.g. polyester) are made from recycled plastic bottles which are in high demand for a variety of other recycling applications beyond apparel. Recycled materials currently make up a relatively small portion of total material production:

RECYCLED COTTON
MARKET SHARE 2020

OTHER RECYCLED SYNTHETICS
MARKET SHARE 2020

RECYCLED POLYESTER
MARKET SHARE 2020

Figure 2.4 **Recycled fibers market share**
Source: Textile Exchange (2021)

2.2.3 Maximise energy efficency

Energy efficiency improvements are readily implementable changes that can be made in facilities to reduce the energy required to perform the same process. For example by metering, optimising and fixing broken equipment, and re-using byproducts.

The impact potential of energy efficiency varies by programme, facility size and tier. However, savings typically average ~15% of total energy use with current techniques. Energy efficiency is one of the 'low-hanging fruit' of GHGs reduction strategies as it can result in significant savings with a relatively low investment. Additionally, energy efficiency improvements are particularly well suited for reducing 52% of total emissions.

However, whilst there may be long-term carbon and economic benefits to be gained, manufacturers may not have the initial capital required to invest in efficiency, nor the technical expertise to identify and implement opportunities.

A program that is helping to overcome those barriers by building capacity and providing funding is Clean By Design.

CLEAN BY DESIGN

Clean by Design, created by the Natural Resources Defense Council (NRDC) and now a programme of the Apparel Impact Institute, is a turnkey green supply chain programme which improves the energy, water, and chemicals usage in textile mills. Clean by Design programmes deliver a 10-20% reduction in energy, water and chemicals usage on average. Clean by Design has identified ten best practices for reducing environmental impacts and operating costs at mills:

1. **Metering and leak detection**
2. **Cooling water reuse**
3. **Heat recovery from hot water**
4. **Maintain heat traps and systems**
5. **Heat recovery from exhaust gas and heating oil**
6. **Improve boiler efficency**
7. **Improve insulation**
8. **Condensate collection and recovery**
9. **Optimise compressed air**
10. **Process and wastewater reuse**

2.2.4 Phase out coal through dry processing

The innovative almost dry processes can drastically reduce the emissions at this stage of the supply chain. During the processing stage, fibres, yarns, fabrics or garments go through multiple steps to achieve the performance and aesthetic properties desired by the industry. These steps can be broadly categorised into pretreatment, dyeing, printing and finishing, as explained in the follow Figure 2.5.

ACTIVITY	DESCRIPTION	EXAMPLE PROCESS
PRETREATMENT	Pretreatment is done before a dyeing and printing process. It is mainly done to clean the fibre and make the dyeing or finishing step more efficient.	**Plasma** **Supercritical CO2**
DYEING / PRINTING	Dyeing / Printing is the application of dyestuff on textile materials such as fibres, yarns and fabrics with the goal of acheiveing colour with desired colour fastness.	**Digital Spray** **Digital (Gravure) Printing** **Supercritical CO2** **Ultrasonic** **Foam**
FINISHING	In textile finishing, a treatment is applied to a textile to give it a specific desirable quality or functionality, making it more suitable for its intended end use.	**Plasma** **Digital Spray** **Ultrasonic** **Ozone** **Laser**

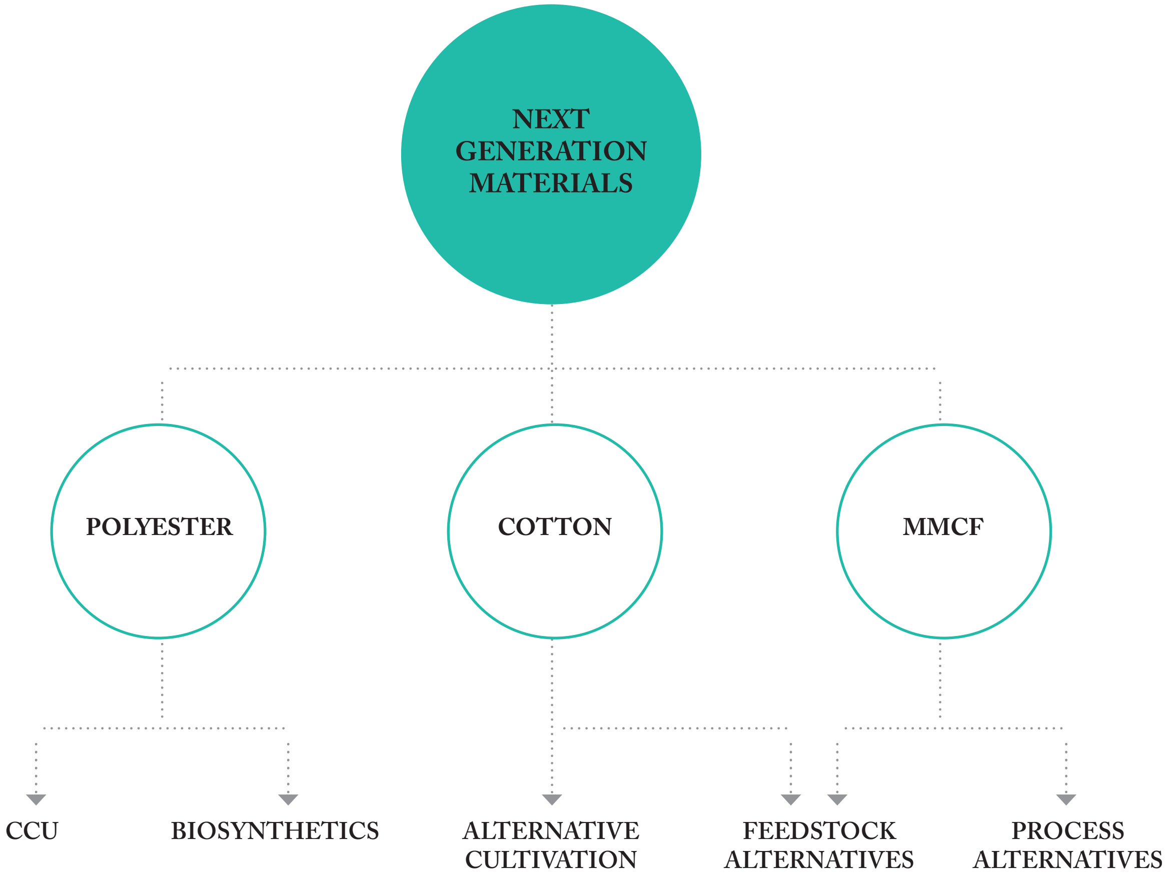
Traditionally, all these processing steps take place in very large tanks or baths filled with water that is constantly kept at a high temperature. The (petroleum derived) chemistry used in these processes, such as synthetic dyes, are also a key contributor.

The key solutions to drastically reducing energy, as well as water use, is moving from wet processes to almost dry processes. In other words, moving away from processing in heated baths and tanks filled with huge volumes of water, to completely different processing technologies that require very little to no water, and subsequently also significantly less energy to heat up the entire process. Figure 2.5 provides an overview of the important dry processes in the pretreatment, dyeing/printing, and finishing space identified by Fashion for Good.

Figure 2.5 **Dry processing steps**
Fashion For Good analysis (2021)

2.2.5 Acelerate development of next generation materials

The raw material stage includes the extraction of all unprocessed inputs to create the final products derived from the most commonly used materials — cotton, polyester, and Man Made Cellulosic Fibres (MMCF) which, according to the Textile Exchange's Preferred Fiber & Materials Market Report 2021 (2021), made up over 80% of the global fibre market in 2020.
Optimisation of the raw material stage based on existing solutions can have a significant impact. However, to drastically decarbonize the industry in the longer term, the next generation of new materials are required. Key raw material areas can be distinguished to demonstrate the different innovation areas.



POLYESTER-FOCUSED INNOVATION
Two main key innovation areas can be categorised into Carbon Capture and Utilisation, and the use of biomass derived polymers.

Figure 2.6 Innovation areas for key raw materials
Fashion For Good Analysis (2021)

•Carbon Capture and Utilisation (CCU) — This emerging field of innovation is the process of capturing CO2EQ to be recycled and converted for further use as feedstock for chemicals or polymers. While CCU mainly addresses carbon, other GHGs, such as methane can be captured and utilised as well.
•Biosynthetics — Biosynthetic materials include the production of chemicals for "synthetic" polymers, such as precursors for nylon and polyester, for example, those obtained via catalytic conversion of biomass or bio-fabricated using living microbes in fermentation processes. Biomass can consist of food crops, non-food crops, agricultural by-products or biogenic waste (i.e. sewage sludge, fermentation residues).

COTTON-FOCUSED INNOVATION
The key innovation area to reduce the GHGs impact of cotton production lies in alternative cultivation methods and the use of innovative processing of alternative feedstocks. These are exemplified by the following:

•Alternative cultivation methods:
- **Soil treatment:** the use of safe, biodegradable mulch to improve water retention and create a micro-climate. Or, regenerative practices such as agroforestry which promise to increase the organic carbon content in soil.
- **Seed treatment:** draws on beneficial microbes that live inside plants to improve their natural resistance to disease. - Precision agriculture: improved drip irrigation instead of flood-or-furrow irrigation.

•Alternative feedstocks:
Alternative natural fibres such as bast or agricultural waste derived fibres (e.g. rice straw and hemp) can be processed in innovative ways (for example, through cottonisation) to resemble cotton's properties. For more information on the potential of agricultural residues as textile fibre feedstock.

MMCF-FOCUSED INNOVATION
The cellulosic fibre industry has begun to implement closed loop systems to reuse chemicals, as traditional processes are chemically and energy intensive. Therefore, the next generation innovation areas are alternative feedstocks replacing tree-based cellulose sources with waste feedstocks. Secondly, alternative processes can achieve significant reductions in chemical as well as energy and water use.

•Alternative feedstocks:
Next generation MMCF fibres can be made from a variety of feedstocks, replacing the need for conventional wood. These include, but are not limited to: food waste, bamboo, agricultural or hemp waste and algae.

•Alternative processes:
Process innovation can drastically reduce the emissions associated with the production of next generation MMCFs. For example, mechanophyiscal processes can use only water, heat and pressure in the production process — replacing the need for any GHGs emitting chemicals.

2.3 New circular practices and possibilities

One of the ways to improve practices in the textile industry, in order to mitigate its negative environmental impacts and to align this activity with the sustainable development goals (SDGs), is to develop new materials and rethink existing materials.
Researchers are therefore constantly looking for solutions and innovations aimed at achieving sustainability in the textile production chain in order to ensure sustainable production and consumption standards, such as reducing waste generation, improving waste management capacity (capacity development) and rationalizing inefficent fossil fuel subsidies.
One of the most effective methods turned out to be making use of materials from renawable, recycled and reused resources. This alternative approach can prevent or mitigate the negative impact of solid waste and its successful implementation requires a review of the life cycle of a product, seeking one or more opportunities for reused based on the market.
Considering an industrial ecosystem based on these principles, turnes out to be useful to a reduced need for raw materials, leading to reductions in the levels of production and energy emissions.
In addition to this first alternative, two other possibilities have emerged: the first is that which has emerged in the area of biotechnology and,above all, of biofabrication which makes use of microorganisms to manifacture textiles for clothing; the second is that of smart textiles. In this case nanotechnology has high potential for application in the textile sector, with the rising trend in the development of smart wearable electronic textiles, as that at personal health monitoring.
In this project, the approach that is taken into consideration is that of the area of bio-based materials. The last 5 years, in fact, have seen a pronounced increase in excitement around "biomaterials" for the fashion industry. As brand cosider their environmental and social impacts, along with rising ethical concerns from consumers, the search for more 'sustainable' alternatives is driving innovation. Wider trends are further contributing to interest in biomaterial; from climate change and the potential for lower carbon footprint vs fossil based symthetic materials, the war on plastics, to the rapid growth of veganism and a rush to find alternatives to animal derived materials.
In addition to bio-materials vector, which emerged strongly from the research, two other dimensions were identified: upcycling fashion and engeneering of smart textiles. Due to the specific perspective of the thesis - the bio-based materials - these two themes have not been explored in depth, but are addressed in this section.

2.3.1 Upcycling fashion practices

The first point to clarify is that the concept of upcycling is different from that of recycling.
Recycling requires energy and resources to gather, sort and process the waste only to make something less out of it. In this case, the materials and objects are not designed to be reused or recycled but are destined for disposal, according to the linear economy model.
Upcycling, instead, is a process where waste or useless products are converted into new materials or products of equal or better quality or a higher environmental value.
Upcycling is necessary as a substitute for producing new things to meet the increasing demands being a greener way of recycling. Moreover, by making use of already existing materials the consumption of new raw materials for new products is reduced which can result in a reduction of energy usage, air pollution, water pollution and CO2 emissions hence making it an incremental step towards achieving zero waste .
It also avoids used products being sent to landfill, thus extending their life cycle.
Upcycling projects involve creative ways of textile waste management by using post-industrial (garment cutting waste, excess fabric and rejects due to quality issues) or post-consumer waste (disposal after use) or a combination of the two. The first case highlights the combination of different areas such as design, engineering and material sciences because some researchers have noted the practice of reuse in other sectors, such as the production of thermal insulators, textile waste in concrete reinforcement or decorative products. In the second case, new products can be promoted through platforms such as reuse companies, collaborative consumption, sharing economy, material exchange, online platforms and direct exchange through sales, leases or donations for second-hand clothes.
In the case of upcycling production process design plays an important role because, by giving importance to the aesthetics and functionality of a product, the designer is able to effectively promote the culture of reuse in consumers.

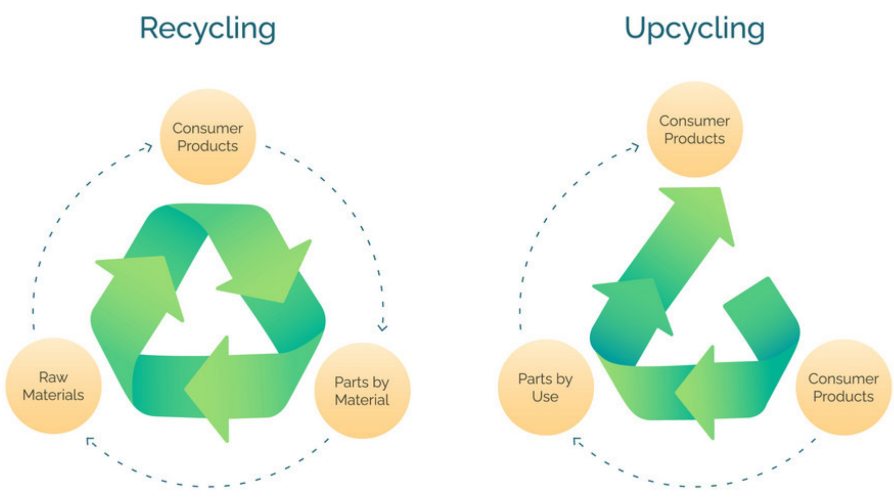


Figure 2.7 **Recycling and upcycling**
Vectorstock.com

2.3.2 Engineering smart textiles

The development of so-called smart fabrics that offer high performance, with properties such as flexibility, durability, wash resistance, comfortable feel and lightweight components, is a new and complex trend. It is increasingly gaining the attention of research groups, especially in the area of smart clothes, and the human-machine relationship.
The use of innovative structures to produce smart textiles can be considered advantageous in relation to conventional approaches. They can capture various types of information, such as data on body activity and biological signals, and can monitor, in real time, remote or short-range environmental data without disturbing the user. Thus, they offer potential for use in sportswear or clothing to address certain health issues.
The applications of technologies in the textile sector are varied, among the most significant are those used in the medical field and those applied for self-cleaning clothes.
In the first case wearable smart sensors offer an ideal platform for activity monitoring health care applications because they facilitate non-invasive sampling and analysis of body fluids, such as swet, saliva and tears, and provide personalized diagnosis and accurate therapy.
In the second case, the use of self-cleaning textiles appear to allow reductions in the consumption of water, energy and chemical, such as detergents.
'Smart' or 'Functional' materials usually form part of a 'Smart System' that has the capability to sense its environment and the effects there of and, if truly smart, to respond to that external stimulus via an active control mechanism. Smart materials and systems occupy a 'Technology space', which also includes the areas of sensors and actuator.
Smart textiles can be made by incorporating smart materials, conductive polymers, encapsulated phase change materials, shape memory polymers and materials and other electronic sensors and communication equipments. These materials interact – according to their designed feature with the stimuli in their environment. All smart materials involve an energy transfer from the stimuli to response given out by the material. They are integrated and complex materials. They have the ability do some sort of processing, analyzing and responding. Even they can adapt to the environment. They got full ability to change themselves depending on — temperature, pressure, density, or internal energy—change.
The amount of energy transferred to make this change is determined by the properties of the material. This relationship between the amount of energy required and the degree of the specific change governs the behaviour of all materials, including smart ones. If they get energy or any stimuli from the outer environment they do not do any change on it. They just resist it or absorb it. For example, a material's specific heat (property) will determine how much heat (energy) is needed in order to change its temperature by a specified amount.
It has been estabilished that smart textiles are associated with sustainable development goals because the goal is to achieve health and weel-being, ensuring a healthy life and promoting well-being for all at all ages and they can promote inclusive and sustainable industrialization and foster innovation by using nanotechnology in reductions water use and energy.

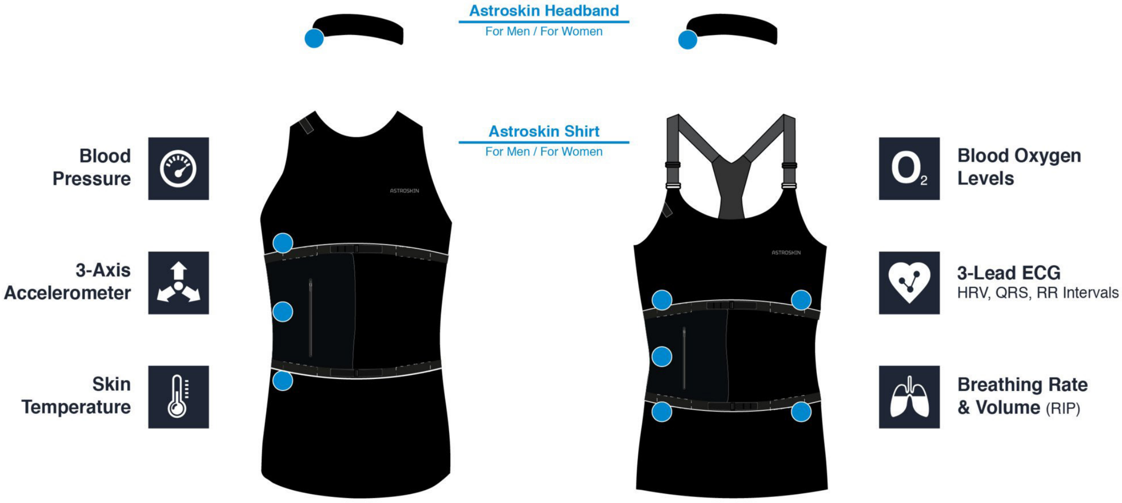


Figure 2.8 presents an incredible example of smart textile.
The Astroskin system is based on the Bio-Monitor designed for the Canadian Space Agency (CSA) to monitor the astronauts' health in space on the International Space Station (ISS). The smart shirt is realized by the company Hexoskin, the world leader in biometric clothing for physical training, sleep tracking and general health monitoring. The smart garments come in a wide variety of sizes for men and women. The garments, which can be machine-washed, include cutting edge blood pressure monitor, pulse oximetry, respiration, 3-lead ECG, skin temperature, and activity sensors for 48 hours of continuous real-time monitoring. The system also includes iOS apps for iPhones and iPads, data synchronization software, and a web dashboard.

Figure 2.8 Astroskin Shirt
Hexoskin.com

2.3.3 Biomaterials: the ' decarbonization' promising solution

Biomaterials represent the future for textile industry from an environmental sustainable point of view.
In comparison with conventional materials, these alternatives present advantages in all the production phases, from sourcing, processing to the end of use.
These innovative alternatives comes from sustainable or biobased raw materials, and therefore are sustainable sourced from the very start. In according with the concept of 'life cycle thinking', these materials are designed to disappear at the end of their useful life.
The growing interest in bio-based materials can be also mostly attributed to their advantages and benefits in the fight against resource depletion and climate change. By using bio-based materials, manufacturers may in fact be able to increase the functionality of their goods while using fewer resources in the process (CEN - European Committee for Standardization, 2021).
The term "bio-based" refers to materials or products wholly or partially derived from biomass: plants and vegetables, especially concerning new developments in the field of bioplastics, which use biomass such as corn, sugar cane, or cellulose as raw material to replace fossil sources such as oil.
The product can be intermediate, material, semifinished or final product. It is important to note that bio-based does not necessarily mean biodegradable.The property of biodegradation does not depend on the resource basis of a material but is rather linked to its chemical structure. In other words, 100% bio-based plastics may be non-biodegradable, and 100% fossil-based plastics can biodegrade.
This research focused on biobased materials understood as: "Biobased materials include everything from conventional as well as non-animal "leathers" that contain fruit or vegetables waste combined with synthetic polymers, through to a pure cotton fabric indeed a polyester-cotton-mix".
In this perspective, Lee and her team included in the family of biobased materials the biofabricated and the biosynthetic ones. Biofabricated ingredients only include microbially produced building blocks for both "natural" and "synthetic" polymers: suc as, respectively, silk and nylon. Biosynthetic materials include the production of chemicals for "synthetic" polymers, such as precursors for nylon and polyester, obtained via catalytic of biomass or fabricated using living microbes in fermentation processes.
From these definitions, one understands the complexity associated with the dimension of biomaterials and how the simple terminology does not explicity define their production, their life cycle and, consequently, their level of sustainability.
Therefore, when we talk about sustainability and biological terms as they apply to a product, it is essential to understand the process of each specific material through in-depth analysis. This can support in navigating through the different terminological approaches, inputs, and impacts related to biobased materials.
There is a widespred ignorance in relation to biomaterials not just on the part of consumers, but also by fashion brands and even some material innovators themselves. The interest in "biomaterials" has grown dramatically during the last five years. Due to growing customer ethical concerns, firms are looking for more sustainable solutions while also considering their environmental and social implications. In addition to these specific developments, interest in biomaterials is being stimulated by a variety of other factors, including the fight against plastics, veganism, and the aim to use less animal-derived products (Biofabricate et al., 2020).
In the absence of an existing guide to biomaterials, and specifically the most recent innovations about biofabricated materials, this report aimed to both clarify definitions and understand what are the benefits they can bring to textile and fashion world.
'Biomaterials' represent a step forward towards the future and it is the most stimulating approach to consider because it is still to be explored and, in many cases, in an experimental phase. However, it is a fact that the bio-based approach can lead to the creation of completely new fibers on the market aimed to look for alternatives to the use of oil, thus saving in GHGs emissions and also making us less dependent on a raw material that also causes social and political inequalities. Bio-based materials allow for a reduced consumption of CO_2, also due to the need for less energy in the production cycle, less consumption of water and chemical products: all aspects that today have great value in creating products with a reduced environmental impact.

3.
Biobased innovation as a promising opportunity in the Fashion & Textile system

3.1 Methodology

This project aims to map circular material-driven guidelines for designers in order to help, facilitate and guide them through the passage towards more circular and sustainable practices.
The project focuses on an ecological dimension-oriented perspective, based on the environmental impacts of processes and systems. On the basis of this assumption this paper investigates the existing and innovative solutions aimed to "decarbonize" the textile industry, focusing on the world of 'Biomaterials' which represent a step forward towards the future in terms of circular material innovation.
The data analyzed in this work has been collected through a theoretical framework (CHAPTER 1-2) and a study case methodology, carried out through structured interviews to manufacturing indutries of Como (Lombardia) textile supply chain (CHAPTER 4).
The entire research follows three key criteria emerged from the literature review phase: Sourcing, Processing, End of life of materials, focusing in particular on the most impactful archetypal fibres of Cotton and Polyester and their sustainable alternatives in order to develop the material-driven guidelines. The focus is to consider the 'life cycle' of materials because a fashion product is sustainable if it results from a process that considers all the steps in its production, evaluating materials and processing, maintenance, cleaning and disposal practices.
The thesis explores a specific dimension (CHAPTER 2): the biomaterials. These alternatives provide new ways of thinking about traditional textile production but, since they are innovative solutions, it was necessary to analyze the trend and real progress of the production chain in terms of sustainability in order to understand whether the textile scenario can actually fits into the schemes of a circular economy.
From the methodological point of view, the work followed three main steps to produce interatively knowledge:
1. A literature review on the current sustainable eco-alternative to fashion and textile production processes;
2. A map of selected ccompanies in the European area with the identication of case studies;
3. The systematization of the collected data to understand how the bio-based materials innovations are implementing sustainability in the sector.

Literature review and building the Theoretical framework

A prior systematic review was out to build the study's theoretical framework. It aimed to analyse the textile&fashion supply chain from an "unsustainable" point of view in terms of environmental impact of production processes and carbon footprint assessement.
The existing and innovative solutions for the 'Decarbonozation' of the entire supply chain are explored in order to achieve a system with the purpose of following the principles of a circular economy.
The phase collected informations from ResearchGate, Science Direct and Google Scholar and it made use of chapters of books, reports, journalistic articles, publications and websites on the topic.
As a result of this phase, ten keywords are identified and researched: Circular, Impact, Materials, Decarbonization, Manufacturing, Biomaterials, Recycling, Biodegradability, Textile, Processing.
The keywords identification proved difficult expecially on the research of 'Biomaterials' because the term it is often associated with chemestry, engeneering and medical field. However, research on the environmental impact of materials on the subject of carbon footprint has proved to be more direct.
After this first reading, by excluding the papers related to technical, chemical and medical field, 16 publications was selected.

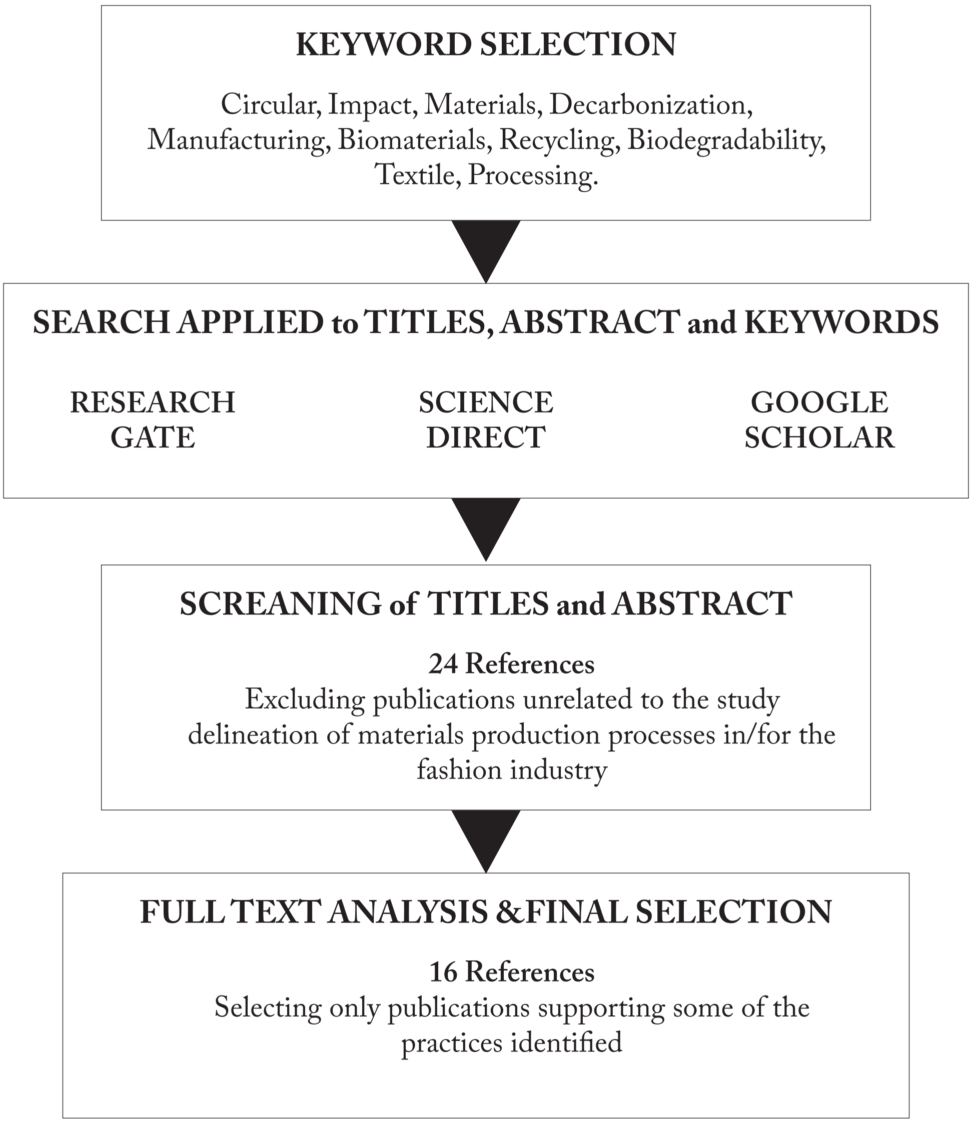

KEYWORD SELECTION
Circular, Impact, Materials, Decarbonization, Manufacturing, Biomaterials, Recycling, Biodegradability, Textile, Processing.
SEARCH APPLIED to TITLES, ABSTRACT and KEYWORDS
RESEARCH GATE
SCIENCE DIRECT
GOOGLE SCHOLAR
SCREANING of TITLES and ABSTRACT
24 References
Excluding publications unrelated to the study delineation of materials production processes in/for the fashion industry
FULL TEXT ANALYSIS &FINAL SELECTION
16 References
Selecting only publications supporting some of the practices identified

TABLE OF FULL TEXTS FINAL SELECTION

TITLE	TYPE	SOURCE	YEAR	SELECTION CRITERIA	ENVIRONMENTAL IMPACT	NEW TECH. OR SYSTEMS	MANUFACTURING PROCESSES	RAW MATERIALS	DISPOSAL PROCESSES
Mechanical, chemical, biological: Moving towards closed-loop bio-based recycling in a circular economy of sustainable textiles	Article	Science Direct	2021	Data availability Level of maturity		X	X	X	X
Sustainable supply chain management in the fast fashion Industry: A comparative study of current efforts and best practices to address the climate crisis	Report	Science Direct	2022	Data availability Level of progress	X		X	X	
Investigation of environmental potentials on supply chain of textile and yarn industry using smart and sustainable life cycle assessment	Article	Google Scholar	2022	Data availability Level of maturity	X		X		
Review of carbon footprint assessment in textile industry	Article	Google Scholar	2020	Data availability Level of maturity	X				
Natural fiber textile reinforced bio-based composites: Mechanical properties, creep, and environmental impacts.	Article	Science Direct	2018	Data availability Level of maturity	X	X	X		
Biobased Innovation as a Fashion and Textile Design Must: A European Perspective	Article	Google Scholar	2022	Data availability Level of progress		X	X		
Upcycling of textile materials	Paper	Research Gate	2015	Data availability Level of maturity					X
A Life Cycle Thinking Approach to Analyse Sustainability in the Textile Industry: A Literature Review	Article	Science Direct	2021	Data availability Level of maturity			X	X	X
Smart Textiles and Nano-Technology: A General Overview	Article	Research Gate	2015	Data availability Level of maturity		X			
Biobased building materials for sustainable future: An overview	Article	Science Direct	2021	Data availability Level of progress		X	X		
Defining Circular Economy Principles for Biobased Products.	Article	Google Scholar	2022	Data availability Level of progress		X			
The development of recycling methods for bio-based materials – A challenge in the implementation of a circular economy: A review	Article	Google Scholar	2022	Data availability Level of progress			X		X

Close the loop: Evidence on the implementation of the circular economy from the Italian fashion industry	Research Article	Google Scholar	2021	Data availability Level of progress			X	X	X
Perceptions and attitudes towards sustainable fashion design: challenges and opportunities for implementing sustainability in fashion	Article	Google Scholar	2019	Data availability Level of maturity			X	X	
New materials for clothing: Rethinking possibilities through a sustainability approach	Article	Science Direct	2021	Data availability Level of progress		X	X		
Designing Sustainable Fashion: Possibilities and Challenges	Research Article	Google Scholar	2013	Data availability Level of maturity			X	X	

The second step started directly from the results of the previous one by mapping the current knowledge flows in industry (see Chapter 4). During this further stage were identified 14 companies, located in 4 nations of the European continent.
They were all textile companies working in the fashion field not only in relation to the design domain but also in the technology/ engineering one.
All the mapped companies have distinguised themselves for the sustainable maturity of their practices. Among all the identified HEIs, 4 were selected as best practices. All of them stand out for the way they are pursuing implementations of sustainable practices within their system, addressing the impact of materials-led innovations on fashion sustainable transformation adopting often the technological dimension as support. The following inquiry phase was a qualitative work that was further implemented through specific information that emerged from semi-structured qualitative interviews conducted with 10 out of the 14 identified companies (see Chapter 4). All the cases were characterized by a strong commitment to material-driven innovation toward sustainability.
The results from this further phase supported the identification of the study Material-driven guidelines.
The last step, the systematization of the findings from literature review and mapping informed the design of Material-driven guidelines for designers.

3.2 What is a bio-based material?

As explained in the previous paragraph, a biobased material is 'a material or product wholly or partially derived from biomass: plants and vegetables, especially concerning new developments in the field of bioplastics, which use biomass such as corn, sugar cane, or cellulose as raw material to replace fossil sources such as oil'.
Biobased materials include everything from conventional as well as non animal "leathers" that contain fruit or vegetable waste combined with synthetic polymers, through to a pure cotton fabric or indeed a polyester cotton mix.
To better understand what this term refers to, it is necessary to clarify which specific definitions fall into its family focusing more on those that refer to the textile sector.
For this reason the text, in the biobased family, takes into consideration the Biofabricated and the Biosynthetic materials.
The Biofabricated materials can be subdivided into Biofabricated ingredients and Bioassemled materials.
Biofabricated ingredients only include microbially produced building blocks for both "natural" and "synthetic" polymers; such as, respectively, silk and nylon.
Bioassemled materials include "leathers" grown by mycelium, bacteria or mammalian cells.
Biosynthetic materials, instead, include the production of chemicals for "synthetic" polymers, such as precursors for nylon and polyester, obtained via catalytic conversion of biomass or biofabricated using living microbes in fermentation processes.
Everything falls under the all encompassing, but least specific umbrella term: "biomaterial".
All biomaterials are biobased, but the biological component can broadly vary from less than 10 to 100%.

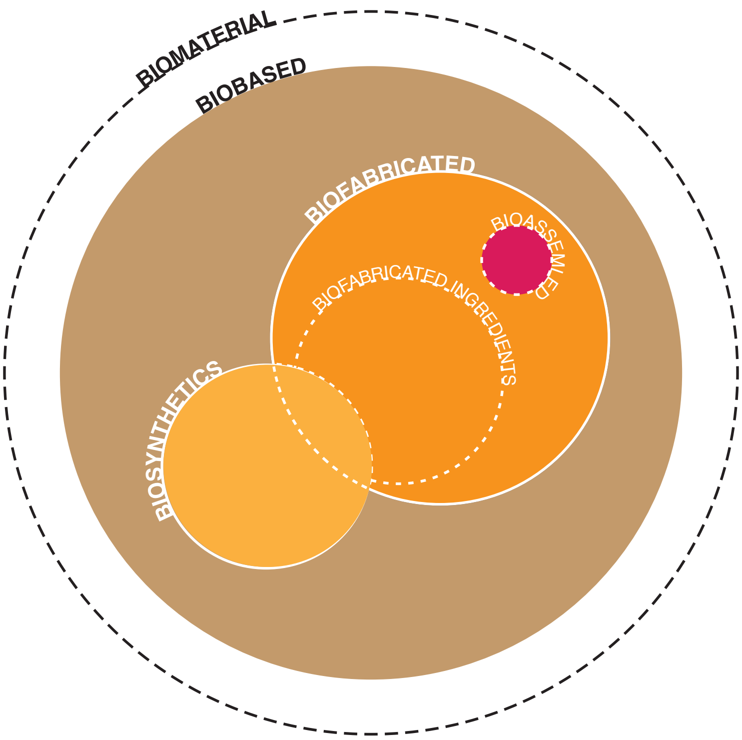


Figure 3.1 **Understanding Biomaterials classification, graphically adapted**
Biofabricate et al., 2020

The last 5 years have seen a pronounced increase in excitement around "biomaterials" for the fashion industry. As brands consider their environmental and social impacts, along with rising ethical concerns from consumers, the search for more 'sustainable' alternatives is driving innovation. Wider trends are further contributing to interest in biomaterials, from climate change and the potential for lower carbon footprints vs fossil based synthetic materials, the war on plastics, to the rapid growth of veganism and a rush to find alternatives to animal derived materials.(4)
In recent years, the prefix "bio" is entered in the field of fashion and textile.
It is used by material innovators or startup explaining their technologies or from brands seeking to understand and communicate innovations in their internal teams and their customers and, then, it is widely spread by the media.
In some parts of Europe this term also indicates "organic", in other cases it is associated to "biodegradable", so, in general, there is a lack of aligned understanding of these "bio" terms and this uncorrect use causes confusion all round, in fact biobased doesn'e necessarly means biodegradable.
Ambiguity around "bio" terminology also lends itself to opportunistic manipulation of language to suit a specific interest, or conversely, that all the terms became meaningless if used interchangeably, thus benefiting no one.
In the specific case of fashion and textile industry the term "biomaterial" is generally used to describe an end product; a finished material.
The term is often associated to the medical field, but outside the medical sector, accademic definitions for "sustainable biomaterial" range from "Biological materials in a variety of scales and types" to "the use of natural, renewable resources to produce innovative materials and bioenergy in a sutainable manner (Biofabricate et al., 2020).
The general assumption in fashion is that a biomaterial either contains biomass or biologically derived ingredients, or was made using some kind of biological process, or is biodegradable, or all of the above.
In general, today, "biomaterial" is a term used to indicate materials that have non specific biological association.
The generic nature of the term has meant that subgroups were created that gave greater definition to the reference sector. The textile and fashion industry is focused on biobased materials and, specifically, refers to Biofabricated materials and Biosynthetic ones.
From these definitions, one understands the complexity associated with the dimension of biomaterials and how simple terminology does not explicity define their production, their life cycle, and consequently, their level of sustainability.
It's important to highlight that when we talk about sustainability and biological terms as they apply to a product, it is essential to understand the process of each specific material through in-dept analysis. This can support in navigating through the different technological approaches, inputs, and impacts related to biobased materials because a fashion product is sustainable if it results from a process that consider all the steps in its production, evaluating materials and processing, maintenance, cleaning, and disposal practices.

BIOMATERIAL

"Biomaterial" is a term used to indicate material that have non specific biological association. In the field of fashion, the term 'biomaterial' is generally used to descrbe an end product; a finished material. It is often associated to the medical field, which is confusing and shows how the nascent the term is in relation to apparel textiles. Outside the medical field, academic definitions for "sustainable biomaterials"range from "Biological materials in a variety of scales and types" to 'the use of naturale, renewable resources to produce innovative materials and bioenergy in a sustainable manner'. The general assumption in fashion, is that a biomaterial either contains biomass, or biologically derived ingredients, or was made using some kind of biological process, or is biodegradable, or all of the above (Biofabricate et al., 2020)
"Biomaterial" today is an increasingly common shorthand term to indicate a material has something of a biological association but without providing any specifics. This ambiguity, while perhaps useful for marketing purposes, is problematic if trying to understand the relative merits of biomaterials from different suppliers, or indeed for innovators wanting to differentiate their technology versus that of a competitor who is perhaps using a less sophisticated/cheaper/ less sustainable technology (Biofabricate et al., 2020).
In cocnclusion, the world biomaterial suggests a need for more context, or further qualifiers.

BIOBASED

The term "bio-based" product refers to products wholly or partly derived from biomass, such as plants, trees or animals. "A composed, in whole or in significant part, of biological products, including renewable domestic agricultural materials, renewable domestic and forestry materials or an intermediate ingredient or feedstock".
Bio-based material seem to have a wider range of meanings and applications but, in general, standards for biobased products are seen to help transparency by providing common reference methods and requirements in order to verify claims about these products (e.g. biodegradability, biobased content, recyclability, sustainability (Biofabricate et.al, 2020).

BIODESIGN

"Biodesign" refers to the incorporation of living organisms as fundamental components in design, boosting the function of the final product. The term comes from the biomedical field and it started to be used outside this field being enacted in leading art and design schools around the world to encompass the study of design and biology with application in everything from advertising and architecture to food and fashion.
Outside the medicine field, 'Biodesign' mostly falls into the following categories: design ***of*** biology - at biotechnology companies such as Ginko Bioworks, their "organism designers" "design" or "write" the DNA code that determines what a cell will be or do; design ***for*** biology - designing systems that manipulate biological growth for product benefits; design ***with*** the product of biology - for example working with dyes and materials produced by living organism, plus many projects that speculate on biodesign "futures" but which are not reality today (Biofabricate et.al, 2020).

BIOSYNTHESIS

"Biosynthesis" is a process. It describes the production of complex chemical compounds from simpler molecules, This happens inside the cells pf living organisms such as bacteria, plants or animals.
the main purpose of this process is to create biobased 'drop ins' for existing pethrochemical derived materials. The aim is to use an alternative bioprocess to create a synthetic polymer that is chemically similar por identical to, for example, polyester. The resulting materials are typically called 'Biosynthetics' (Biofabricate et.al, 2020).

BIOSYNTHETICS

"Biosynthetics" are synthetic polymer materials comprised, in whole or in part, of bio derived compounds. These compounds can either be made with an input of biological origin (biomass), and/or where the process is performed by living microorganism (Biosynthesis). In fashion and texile field, it refers to fully manmade fibers or fabrics derived not from agricultural or animal (natural) sources but rather from fossil fuels. These materials are generally created by chemically synthetizing polymers which can be extruded into fibers and then woven, knitted etc. So chemical synthesis is a process, but the resulting materials are also known as synthetics (Biofabricate et.al, 2020).
For 'biosynthetics', instead of deriving from building blocks of manmade, synthetic materials, like nylon, from a crude oil origin, the same building blocks are derived from a biological origin. For example, sugar is converted into a compound using chemical synthesis. This compound is further transformed into a polymer that is chemically identical to that of fossil fuel origin, and therefore can be 'drop in' to synthetic fiber production (Biofabricate et.al, 2020).

BIOFABRICATION

"Biofabrication" or "biomanufacture" is the most applied to fashion and textile sector. in this context, it is referred to 'living organism' such as bacteria, yeast, algae, micelium or mammalian cells.
"Biofabricated ingredients" are building blocks produced by living cells and microorganisms, e.g. complex proteins like silk or collagen which are processed by fermentation producing an ingredient or material, but the organism or cell itself is not intended to be part of the final product. Extracellular matrices, living cells and tissues, as well as biological molecules, can be used as raw materials in biofabrication. The term, in fact, means making or constructing something from a raw or semi finished material or creating something that is different from its components (Biofabricate et.a,2020).

BIOASSEMBLY

“Bioassembly” is a subset of biofabrication. It is similar to it but was distinguished by both scale and self organization. “Bioassembled” material is a macro scale structure that has been grown directly by living microorganisms such as mycelium or bacteria. Whereas biofabrication may refer more generally to the use of living organisms like bacteria or yeast to produce complex molecular building blocks that can be purified and further transformed, via chemistry and materials science into materials, with bioassembled materials, biology is doing more of the work to build structure in the end material (Biofabricate et.al, 2020).

BIOMATERIAL

‘Biomaterial’ is a term used to indicate materials that have non-specific biological association

BIOBASED

Biobased materials are wholly or partly derived from biomass, such as plants, trees or animals

BIOFABRICATED MATERIALS

Biofabricated materials are produced by living cells (e.g. mammalian) and microorganisms such as bacteria, yeast and mycelium

BIOSYNTHETIC

Biosynthetics are synthetic polymer materials comprised, in whole or in part, of bio-derived compounds. These compounds can either be made with an input of biological origin (biomass), and/or where the process is performed by a living microorganism.

BIOFABRICATED INGREDIENTS

Biofabricated ingredents are building blocks produced by living cells and microorganisms e.g. complex proteins like silk or collagen. They need further mechalical or chemical processing in order to make a macroscale material structure.

BIOASSEMBLED

A bioassembled material is a macroscale structure that has been grown directly by living microorganisms such as mycelium or baceria.

Figure 3.2 “Defining bio”, graphically adapted
Biofabricate et al., 2020

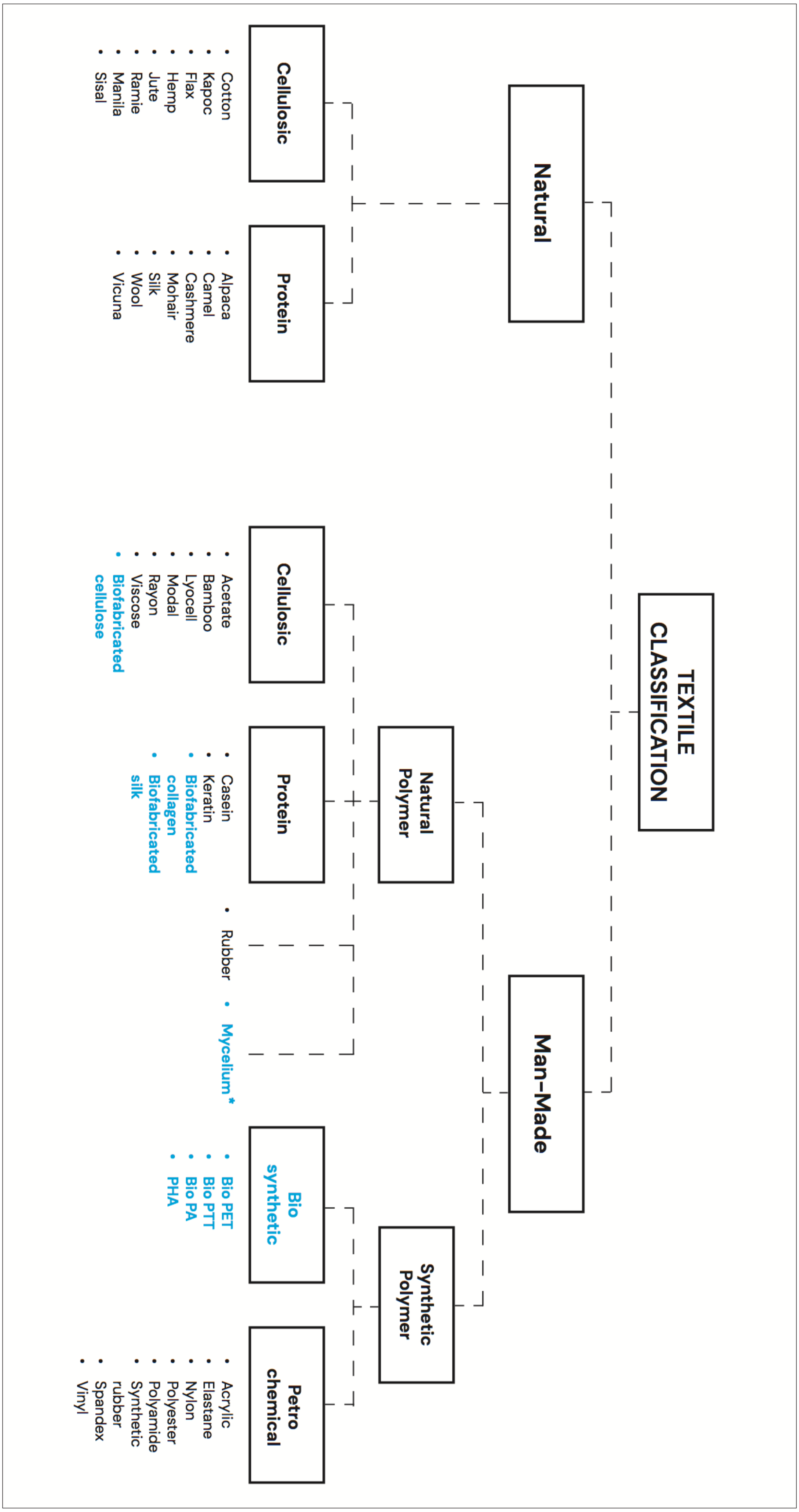


Figure 3.3 Textile classification chart
Biofabricate et al., 2020

3.3 Biomaterials as potential alternatives

The growing interest in biobased materials from all the sectors in which they can be applied revolves around the fact that they can represent a less impactful alternative to conventional materials, in terms of environmental impact of production, use and disposal.
The Journal of Industrial Ecology (Vloume 16) shows the advantages of bio-based materials by using the methodolgy of Life Cycle Assessment(LCA) and the result is that:
•Biobased materials save nonrenewable energy; they enable the manufacturing industry to substitute renewable feedstock for part of its fossil fuel-based or mineral-based feedstock.
•Biobased materials generally exert lower environmental impacts than conventional materials in the category of climate change (if GHGs emissions from indirect land usechange are neglected).
•Biobased materials may exert higher environmental impacts than their conventional counterparts in the categories of eutrophication and stratospheric ozone depletion.
•Biobased materials can contribute more to non renewable energy savings than to a decrease or increase of impacts in the environmental impact categories.
•The environmental impacts of biobased materials span awide range, partly due to the diversity of plausible methodological choices and assumptions made in the reviewed LCA studies.
•Biomass cultivation with conventional farming practices is the key contributor to the high eutrophication and stratospheric ozone depletion potentials of biobased materials. These impacts can be reduced by improving fertilizer management and employing extensive farming practices. However, it should be considered that agricultural extensification by, for example, decreasing the application of agrochemicals, may result in lower crop yields, thus increasing land requirements for biomass production. The entire life cycle of biobased materials offers the potential for decreasing environmental impacts.
Progress in biotechnology, technological learning, up-scaling of production facilities, and process integration will likely reduce both the environmental impacts and the cost of biobased materials. Addressing persisting challenges may enable biobased materials to substantially decrease the environmental impact from the production, use, and disposal of industrially manufactures materials.
It has been observed that this pragmatic material is the unsurpassed alternative not only due to the reduction of the carbon and energy emissions but also because it provides thermal comfort with less energy consumption for the functioning of the buildings to replace the conventional materials. The usage of plant-based building materials is an augmentation towards an eco-friendly, sustainable and effective multifunctional materials.
The advantages of using biobased materials are many but it must still be taken into consideration that depending on the type of material, blending biobased and petroleum derived materials can create challenges at end of use that render them neither compostable nor recyclable.
It should be born in mind that biobased products are not automatically compostable and petroleum based products are not automatically non compostable. The chemical structure of the ingredient or material and the physical form are most important when determining whether a product is either or greater transparency and understanding around the final material components is required to understand its true environmental impact.
Sometimes biobased practices require complex chemical processing, and, in the end, the biobased fibers cannot be used alone but need to be blended with other fibers to produce the finished fabric and the result is an unsustainable yarn or textile that loses its unsustainable characteristic during the production phase. It is, therefore, necessary to consider all the factors of before, during and after; so also what will happen once the finished, processed, and used product reaches the end of its life. Stakeholders in the supply chain should be thinking about creating products with the end of use in mind, addressing how they can build a circular system and how to fit these materials into that system. It is also important for innovators to be able to have an open and transparent dialogue with their partners and ask the brands questions around their sustainability strategies and impact.

3.4 Models of a circular economy for biobased materials

Biobased innovations could be seen like the basics for a future circular system in which productive textile processes could nurture the industry's transition to a sustainable and circular paradigm in the context of the circular bioeconomy. The consideration of the role of bio-based products can play in this transition is however still largely lacking in the current development of circularity monitoring approaches.
In order to evaluate the circularity performance of biobased products it is important to consider both intrinsic circularity and impact of this circularity.
For this reason, Ellen MacArthur Foundation proposes a model of circular economy that differentiates between two types of cycles:

• **Biological cyles,** in which organic materials and products are returned in the bioeconomy, in the process regenerating natural systems.

• **Technical cycles,** in which product, components and materials are kept in the market at the highest possible quality and for as long as possible, through repair and maintenance, refurbishment, remanufacture, and recycling.
The "Butterfly" diagaram of Ellen MacArthur Foundation Figure 3.4 explains the distintion between these two cycles. It seems to be exisiting only the biological cycle, but in reality biomass also is part of technical cycle and is used in production of chemicals, plastics and materials.

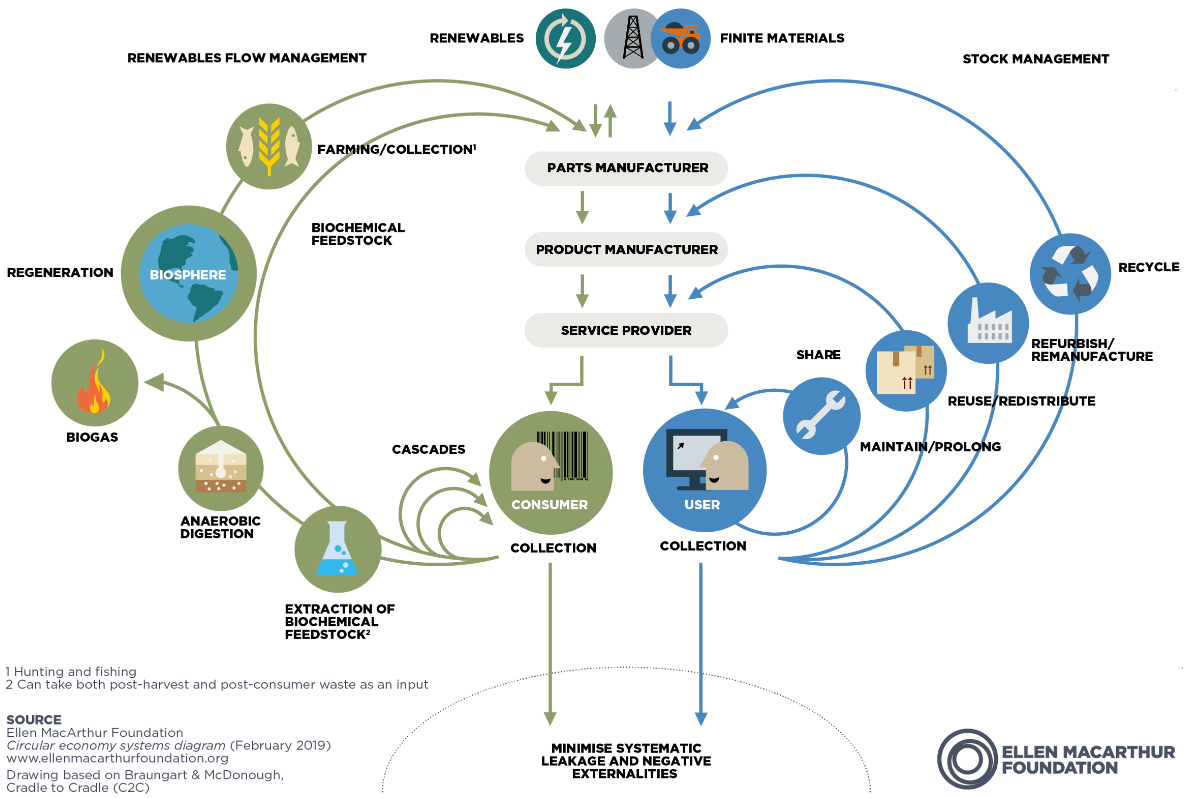
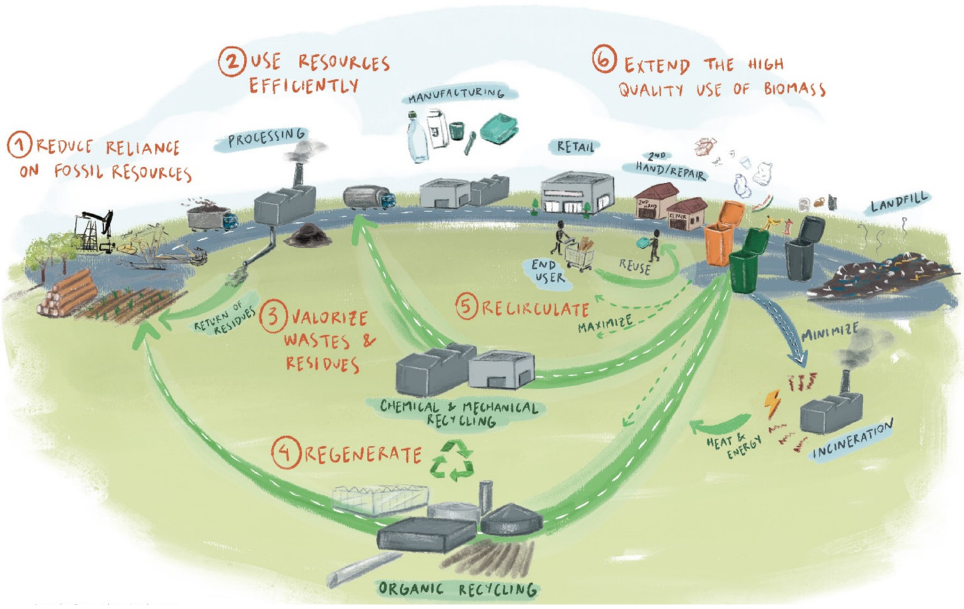


Figure 3.4 Circular economy systems diagram
Ellen McArthur Foundation, 2019

It is necessary, as the diagram in Figure 3.4 shows, to evaluate both technical and biological materials by using a consistent analytical methodology and tools. For this purpose, so-called Material Circularity Indicator (MCI) is used. It is based on six circular economy principles:

•Reduce reliance on fossil resources
•Use resource efficently
•Valorize waste and residues
•Regenerate
•Recirculate
•Extend the high quality use of biomass

Improving this methodology not necessarly translate as an improvement of the circularity, but a widespread use of this method could form part of such a system improvement.
It's important to understand that, by following these principles, it's possible to reduce consumption and emissions by closing the loop of materials; biobased products play a primary role in reducing reliance on fossil resources.
Biomass provides renewable carbon to the economy and can replace fossil carbon, thereby and virgin feedstock input demand in the circular economy can be supplied in a renewable way.



Transitioning from fossil resources to renewable resources such as biomass is an important aspect of the circular economy in all possible sectors, from industrial sectors, chemicals, pharmaceuticals bioenergy and, in this specific case, to textile sector.
Energy and transport fuels from fossil resources can largely be replaced by renewable energy and hydrogen, which are non-carbon-based solutions. The use of biomass is indispenable to meet the carbon demand of materials and chemicals that cannot be supplied with renewable energy (solar, wind, hydrogen and geothermal).
What is clear, therefore, is that the bioeconomy, reffered to ' biobased economy', and the circular economy show synergies and that bioeconomy is essential for reducing reliance on fossil resources, enabling valorization of wastes and residues and providing possibility of cascading use.
The realisation of a circular economy, in which materials are retained in a closed loop, requires the development of sustainable and scalable high-quality textile production associated with effective recycling technologies and systems (Ellen MacArthur Foundation, 2021).
Considering that circularity research for textiles is mainly focused on thechnical cycle rather than the biological one, the biobased processes for textile recycling are less exploring but, in this context, recycling is a necessary step in enabling a circular resource flow.

Figure 3.5 Biobased product system and the defined circular economy principles (Illustration)
Natasha Sana (clapvisual.com)

3.4.1 Recycling methods for Biomaerials

The circular economy is defined by a closed-loop process, a social system in which products and their components are designed, manufactured, used and managed to circulate for as long as possible.
Unfortunatelly, whereas the recycling processes are essential in this system, the development of recycling methods for bio-based materials remains a challenge in the implementation of a circular economy.
Circular economy research for textiles has mainly focused on the technical cycle, based on non-renewable petroleum-based materials that can only be recovered and repurposed, while the biological one is less explored.
Several methods of recycling are available for the end-of-life management of bio-based products, which include mechanical (reuse of waste as a valuable raw material for further processing), chemical (feedstock recycling) and organic (anaerobic digestion or composting) ones. The use of chemical or mechanical recycling is less favourable, more costly and requires the improvement of systems for separation of bio-based materials from the rest of the waste stream. Organic recycling can be a sustainable alternative to those two methods. In organic recycling, bio-based materials can be biologically treated under aerobic or anaerobic conditions, depending on the characteristics of the materials. The choice of the recycling method to be implemented depends on the economic situation and on the properties of the bio-based products and their susceptibility to degradation.
Others two methods that can be used are the inceneration (energy reconvery) and landfilling, but the first one should only be used when other methods can not be implemented and the second one should be avoided because it is banned in many countries.It is important to determine of biobased products on recycling, a method which is consistent with the requirements of a circular economy.
Reviews of circular processes rarely evaluate biobased processes for textile recycling or tend to focus on one fibre type, which mostly demonstrates open-loop processes and separation of fibre blends, such as cotton and polyester that give specific properties to textiles.
By using this methods of recycling it's possible to demonstrate the potential of multi-disciplinary approach for recycling where textile materials would be regenerative i.e. textile fibres would have the potential to be recycled to novel virgin-quality material instead of downcycled to lower quality products. This approach involves the use of enzymatic and biological processes not only to decompose the textile at the end of life but also to produce it.
This represent an opportunity for further reasearch into biochemical, enzymatic and biological systems focused on innovative textile processes proposing a new model for textile recycling that modify the current concept of separate biological and technical cycles in the circular economy.

3.4.1.1 Mechanical processes

Mechanical process is the most established method process for textiles.
The most used methodologies are the fibre recycling and the transformation of agricultural by-products into textiles.
Fibre recycling usually refers to mechanical recycling process in which the fabric is taken apart and the fibre is preserved. This process can be applied for all textile materials. The most common methods, in this case, are shredding and cutting. One of the limit represented by these methods is that fibres in the shredding process are shortned and therefore the production of new yarn often necessitates blending the recycled fibre with virgin fibres, in order to obtain the necessary strenght and quality for apparel.
The mechanical method is often used at industrial scale creating a semi closed-loop recycling for cotton fibres, mixing the recycled with virgin cotton fibre and spun into new yarn, or for the recycling of wool.
Wool doesn't need the mix with a virgin fibre when it is recycled for the first time. This fibre-to-fibre method is adopted

by Italian wool producers in the area of Prato.
For synthetic fibres such as polyester or acrylic, synthetic wastes are recycled in an open-loop process where the fibre is downcycled into a non-woven fabric or insulation materials.
Recent innovative approaches developed this method for transforming food by-products into value-added materials into textile fibres. In this case is proposed an open-loop mechanical recycling method for the extraction of fibres from agricultural by-products and waste for textile production.
An example of this methodology is Pinatex, a Philippine company that uses pinnaple leaf to produce Pina cloth garments, or Spinnova, a Finnish company which proposes a machanical process inspired by a spider web to use fibre suspension and rheology for the production of cellulose that is converted into textile fibers 'using technologies' available in pulp and paper industry.
In the specific case of mechanical process a large number of environmental impacts need to be considered (land, energy, chemical, water use etc.) and it is difficult to have a complete picture, other than that the process itself is relatively low energy in comparison with the energy used in virgin fibre production.

3.4.1.2 Chemical processes

Analyzing the chemical processes for textile recycling there are more opportunities to maintain materials in a closed-loop. In this case there are two processes that can be used: Monomer and Polymer recycling.
In the first case, the polymer chain is disassembled in order to obtain intact monomers. They can be transformed into new virgin polymers by the process of polymerisation. This kind of process has been adopted to transform different types of textiles waste into fibres.
An example of this method is the development of Econyl fibre which is made from Nylon 6 discarded carpet and fishing nets.
The polymer recycling is a process in which the fibre is taken apart using mechanical processes, such as shredding, followed by chemical dissolution with specific solvents. It is mostly used for cellulose, synthetic and blends of fibres.
One of the most significant example of this process is represented by the production, by Lenzing, of the Tencel fibre in the lyocell process. It's the perfect example of a man-made fibre in which chemical polymer recycling of post-consumer or pre-consumer waste is added to wood pulp.
In terms of sustainability, the environmental impact of chemical recycling processes are not so clear because of the toxicity of the solvents used for dissolution, energy required and water use. There is now a need for governmental policy to support the scale-up and uptake of these technologies. Current investments are being put in place to increase novel polymer recycling technologies from a pilot to a commercial scale by 2030.

3.4.1.3 Biobased processes

Bio-based processes are composed of three main headings: biological (compost and anaerobic digestion), biochemical (enzymatic depolymerisation) and fermentation (from feedstock to products).
In the biological decomposition, composting is a biological process where aerobic microorganisms transform organic materials into carbon dioxide (CO2), ammonia, water and heat in the presence of oxygen, water and nitrogen.
Composting of waste textiles is limited to natural and semi-synthetic fibres and it represt the better alternative to incineration because it can produce organic fertilisers that can improve the level of soil organic matter, long-term soil fertility, and productivity.
The products from these processes cannot be reused to make materials, so they could not constitute a step in a closed-

loop recycling. However, they constitute an alternative to incineration and landfill as long as the amount of GHGs emitted is well managed which will need to be assessed when scaling up. Given this circularity of textiles encompasses closed-loop processes in order to retain the value of materials for longer, biological decomposition such as composting should be the final step in returning nutrients back to the soil.

Enzymatic depolymerisation uses cellulosic biomass as a feedsock for fermantation by using chemical pretreatment before the enzymatic step that converts the cellulose into sugars. In the case of cellulosic textiles, pretreatments are less developed but interest in the area is expanding, and mainly consist of size reduction of cost and environmental impact of textile waste pretreatments to enable the development of a commercially viable biochemical recycling route of waste textile.

The advantages of this type of process is that the cellulose fraction became soluble and can be separated from other fractions in the textile blends without the need for manual sorting. Interestingly, recovered the flame-retardant pigment from dyed viscose. In a similar concept, a blend of wool-cotton-polyester textile waste could be recycled by sequential and selective use of enzymes to depolymerase the wool and cotton before recovering the polyester synthetic fibre fraction and fermenting the glucose to ethanol.

Fermentation, instead, is a metabolic process that produces chemical changes in organic substrates through the action of enzymes. Pratically, it is the use of microorganism such as bacteria and fungi as well as eukaryotic cells, to make products useful to humans.

The advantage of bio-based processes is that they have typically very low energy demand, use benign solvents and chemicals and are based on renewable sources rather than fossil carbon.

3.5 Emerging biobased alternatives in the Fashion system

In the field of biobased materials the textile sector mainly examined is the Biofabricated materials.
The most 'bio' term applied to the fashion industry is 'biofabrication', also known as 'biomanufacture'. In the context of material fabrication for fashion, the "living organism" referred to can include bacteria, yeast, algae, mycelium and mammalian cells.
In according with Biofabricate et al., 2020, there is still a general lack of knowledge and understanding about biomaterials in general within the whole fashion business, thus the quest for greater information is not limited to just biofabricated materials but to the entire field of biobased emerging materials.
It is necessary to understand the positioninig of biomaterials in the textile conventional classification of materials in order to categorize them into the specific sector to which they belong. Figure 3.3 shows a textile classification chart based on the industry accepted groupings as defined in legislation such as the Textile Fiber Products Identification Act (TFPIA) in USA. The chart shows the conventional textile classification and the addition of bioalternatives in order to understand the process of biofabrication into the different categories of textile classification.
To date, there are many innovators who have invested, tested and developed new technologies in the field of biobased materials. Some can be defined as true innovators creating new materials that did not exist in the fashion sector, while others focused not on radical changes, but on improving already existing practices and systems. The radical innovators developed new technologies or systems to produce biobased materials, allowing a rise in new materials that previously did not exist or were not considered within the fashion industry. They reconsider the manufacturing processes through trends such as digital transformation, which have allowed different realities to come across and contaminate each other, feeding back into the textile production value chain as a replacement of virgin materials. An important aspect of these innovators is that they study how to recycle any type of material from the waste of production processes to the post-consumer waste, involving third industries supply chains producing biomaterials with high sustainability characteristics which fit perfectly the concept of "Closed-Loop Supply Chain".
This section shows a brief overview of biobased alternatives in fashon field in order to understand the advancement of this emerging sector.

•ALTERNATIVE SILK
It is well known that traditional silk is obtained from silkworms that are killed in the manufacturing production process. Instead of the traditional silk, so-called "peace silks" are produced with non-violent methods and a number of fashion brands have turned to plant-based alternatives. Stella McCartney, for example, uses a lab-grown version of silk, and Salvatore Ferragamo uses a silk-like cellulose fabric made from citrus peels (Orange Fiber).
One of the best innovation, however, is silk made from rose petals. Dyed with natural pigments, the biodegradable fabric is made from petal remnants that are broken down and spun into fibers. Rose silk is soft and lustrous and is grown entirely without chemicals (Kulczycki, 2021).
Another incredible alternative is the spiber silk fiber, a protein fiber derived from the glands of a spider. Airbus and the German company AMSilk are "weaving" a surprising synthetic spider web that promises to enter shortly inside the aerospace productions.AMSilk, currently first industrial supplier to world of silk biopolymers, has developed over the years revolutionary material to leave
from the DNA of weaver spiders, the BioSteel, a synthetic fiber with characteristics very similar to the canvas of the spider. This material is hydrophilic, biodegradable and biocompatible. This fiber is incredibly strong, has a high tensile strength and toughness. At the same time it is very elastic, making it competitive with the most modern high performance synthetic fibers.

•BIOPLASTICS FROM ALGAE

Plastic fibers could one day be completely replaced by one of the world's most efficient organisms: algae.
Unlike most bioplastic production, which requires valuable drinking water, algae grows in salt water, which means its cultivation does not pollute freshwater resources. Pulverized, mixed with fats from various algae species and polished with vegetable waxes, the algae-based bioplastic is waterproof and resembles PVC vinyl. But the algae can do much more than that: through their photosynthesis, they can even sequestrate CO2 from the atmosphere and thus have a positive impact on climate change (Kulczycki, 2021). The fiber is fully biodegradable and eco-friendly, and it may be dyed with non- chemical pigments like crushed insect shells and woven into the fabric for subsequent garment usage.

•VEGETABLES-BASED LEATHER

Human rights violations are a well known side-effect of the fast fashion industry and animal cruelty is another ethical issue that should be considered in sustainable fashion. When it comes to plant-based leather, there are an abundance of innovations. After Desserto (cactus leather), Piñatext (pineapple leather), and Vegea (grape leather), a new trend has now emerged in the vegan and biodegradable leather market, namely: mushroom leather.
The plant-based and sustainable leather alternative will, among others, soon be represented in the sneakers collection of Adidas. But also the traditional house Hermès – renowned worldwide for its luxurious leather production – has announced the first handbag made of sustainable fungi leather for the upcoming fall/winter collection. Hermès' innovative material, called Sylvania, was created in collaboration with the California-based company MycoWorks. The purely organic leather material is based on the raw material mycelium: extremely fine, thread-like fungal cells. Mycelium's moisture-absorbing, non-toxic, fire-resistant and waterproof properties make it a sustainable and durable alternative to leather – entirely biodegradable and cruelty-free (Kulczycki, 2021).

•SOY CASHMERE

Although wool can now be sourced sustainably and transparently, there are often non-transparent supply chains involved, with cashmere production in particular being associated with mass deforestation of native grasslands in Mongolia. This is where the athleisure brand KD New York stepped in and paved the way for plant-based cashmere in 2019. The wool is made from waste soy protein from tofu production, which is then broken down into cellulose and spun into fiber. The wool is not only an ethical and biodegradable product but is even antibacterial, moth resistant and machine washable (Kulczycki, 2021).

Figure 3.6 Hermès + MycoWorks mushroom-based 'leather' bag made from ReishiTM, Fine MyceliumTM
Mycoworks, 2021

3.6 Rooted applications in Fashion&Textile sector

This section presents in more detail three companies/start up that fit perfectly into the world of biobased materials. These are innovators that, from experimentation, have managed to successfully introduce their innovative product or technology on the market despite the industry is still reliant on the development of these new disruptive solutions to accelerate the transformation to sustainable circular practices.
Fortunately, these realities fall within the circle of companies that are part of the exponential growth of material innovation trackling biological alternatives to fossil fuel, plant and animal; dyes, chemicals, fibers and fabrics alternatives. The companies analyzed in this section demonstrate that there is a significant opportunity to reduce footprint by proposing lower impact materials. The brand's impact can be ssplit into five tiers:

• Tier 0: **Store, warehouse, offices**
• Tier 1: **Assembly**
• Tier 2: **Manufacturing**
• Tier 3: **Raw material Processing**
• Tier 4: **Raw material Production**

Kering's 2019 publicy Environmental Profit & Loss (EP&L) data reveals that the Tier 4 raw material production makes up 65% of the group's overall footprint. A significant portion of this total relates to the use of leather and animal fibers, where the greatest impacts are in terms of land use and greenhouse gas emissions, mostly caused by raising livestock and material waste throughout the supply chain. Biofabricated leather/animal fibers thus have an important potential for impact reduction, eliminating the need to source from livestock and enabling more efficent production processes (Biofabricate et al., 2020).
The challenge for innovators is in understanding deeply what the consumer is looking for today and then how to walk towards that. History teaches us that material innovation is a constant journey of interation and improvements.
It took DuPont ten years to create lycra, a further three to bring it to market, but 60 years later the material still continues to evolve and improve.
The drive for "more sustainable" replacements can lead to material innovation in considering the full implications of a particular technology or process in a holistic manner, creating a new generation of no harmful products.
The three companies examined are: Orange fiber, Econyl, Re-fibra technology.

Figure 3.7 Magazine advertisement for DuPont Lycra (1961)
Courtesy of Science History Institute

What nylon did for your legs LYCRA® will do for your figure!

SPANDEX

Remember, remember—when Du Pont nylon led you tenderly by the toes to stockings such as you had never before known? □ Now, "LYCRA"* spandex fiber gives this same loving consideration to the rest of you. With bras and girdles so light, so gentle, they seem only an echo. Yet so persuasive in molding and holding you can only surrender. So enduring, they seem ever new. And blissfully free from care. □ All this is the beauty of "LYCRA"—the new elastic fiber from Du Pont.

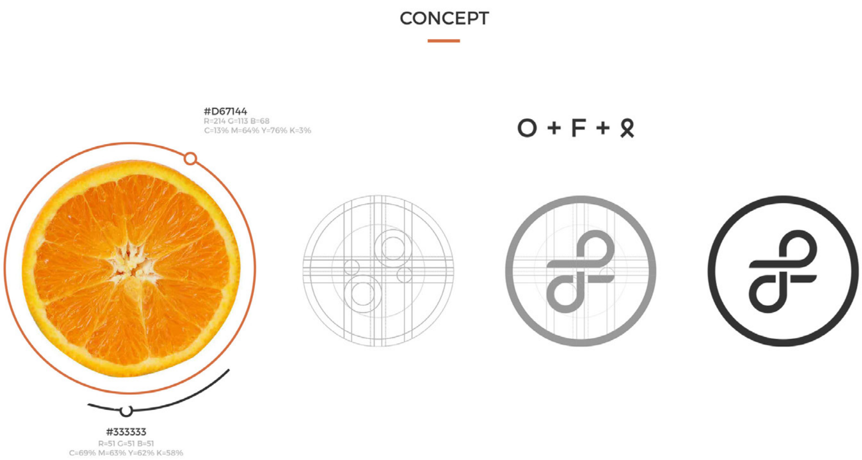
*"LYCRA" is Du Pont's registered trademark for its spandex fiber.

BETTER THINGS FOR BETTER LIVING ... THROUGH CHEMISTRY

DU PONT

3.6.1 Orange Fiber

'Orange Fiber' is a sicilian textile brand, founded in 2014, that produce a sustainable fabric from citrus by-products. The company has patented a technology to produce a spinnable cellulose that remains silk and impalpable, creating an high quality fabric. They start from the by-products of the citrus industry (oranges) representing 60% of the weight of the whole fruit that remains after the production of industrial fruit juice, which otherwise would have to be disposed of with economic and environmental costs.
The technology is based on the extraction of cellulose from two different sources: from the whole citrus peel, which includes both albedo and flavedo, or only from albedo.
The characteristics of this process is that cellulose is obtained by chemical extraction, performed in the absence of chlorine, which includes treatment of the raw materials obtained from citrus fruits with hydrogen peroxide under basic conditions. Cellulose obtained by this process can be blended with cellulose obtained by different methods, for example, cellulose extracted from wood.



The company, thanks to the versatility of the material it produces, has estabilishaed various partnerships with fashion brands and designers who makes sustainability their cornerstore.
One of the best example is the collaboration with Lenzing Group, world leader in the production of specialty textile fibers form wood and they collaborate to produce the first TENCEL™ brand lyocell fiber composed of orange cellulose and wood cellulose. The fiber is produced using the same award-winning closed-loop manufacturing process as standard TENCEL™ Lyocell fibes, and it helps to promote sustainability in the textile and apparel supply chain and to redifine the boundaries of innovation in fiber manufacturing cellulose.

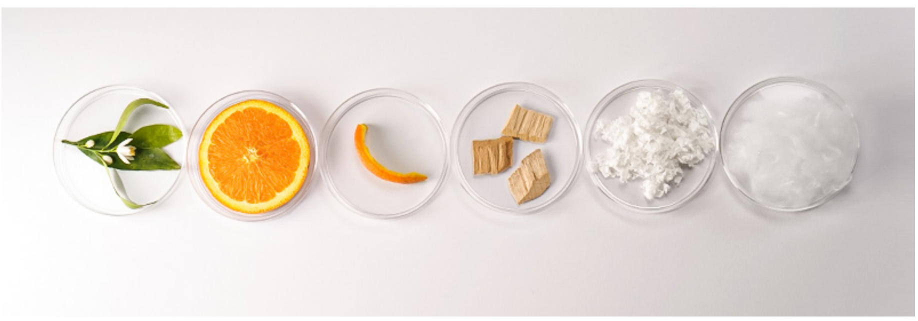


Figure 3.8 Orange Fiber "Concept" / Figure 3.9 Orange Fiber "Process"
Orangefiber.com

Figure 3.10 By-products processing
Orangefiber.com

Therefore, the strenght of this production is the ability to amortize costs and resource exploitation through the use of waste from third-party industries. Moreover, compared to the production of natural cellulose cotton fiber, the process proposed by 'Orange Fiber' has many economic and environmental advantages.
In terms of numbers, 1Kg of yarn obtained with Orange Fiber technology requires about 90% less water for irrigation instead of 11.000 L. of water used in a classical production technique to obtain 1Kg. of cotton fabric.
The company boasts many collaborations such as the one with the Italian brand Salvatore Ferragamo. They collaborate in 2017 for the realisation of a sustainable capsule collection of women's clothing. The brand presented the Orange Fiber collection to celebrate the 47th edition of the Earth Day 2017. With the help of this new fiber the brand has created a twill with a silky appearence and touch, realizing a project that, at the same time, also supports those ethical values linked to reasearch on sustainability and renewable sources destinated to became the new driving force for the future of quality Made in Italy.
'Orange Fiber' initiative represents companies that are tracing an exact direction towards circularity. Such an approach has a double-positive action simultaneously on the part of consumers. On the other hand, it compensates for the needs of companies in the agri-food industry facing increasing burdens and challenges to dispose of their waste correctly.

Figure 3.11/3.12/3.13 Ferragamo Orange Fiber Collection 2017
Orangefiber.com

3.6.2 Econyl

ECONYL® is a brand of Aquafil, world leader in the synthetic fibers sector, a company famous for the quality, innoation and sustainability of its products.
Aquafil is one of the first company to adopt a 'Life Cycle Thinking' approach, the framework that consider a holistic view of a product and evaluates its environmental impact from "cradle to grave" (or from cradle to cradle). After the evaluation of the negative impact of the nylon value chain caused by the extraction of raw maerials, they concentrate their research for the creation of the ECONYL® Regeneraion System: a highly innovative industrial process that allows the replacement of caprolactam (the main component for producing Nylon 6 derived from petroleum) with alternative raw materials from the recycling of various types of nylon waste.

The full Life Cycle Assessment of the ECONYL® (Figure 3.14) yarn was the first step of the long term collaboration between Aquafil and LCE, providing the company with quantitative information about the product's environmental impact. ECONYL® environmental profile was benchmarked against a normal Nylon fiber, showing that the use of a recycled yarn leads to significant benefits in terms of reduced consumption of natural resources and greenhouse gasses emissions.
The technology recovers nylon waste, regenerates it giving it a new life. The result is a recycled nylon, which has the exact same characteristics as virgin source nylon but can be infinitely regenerated, recreated and remodeled.
The process is based on four points:

• TO RESCUE:
It begins with the recovery of waste from all over the world such as fishing nets, fabric scraps, used carpets and industrial plastic. Once cleaned, the recovery process of all the possible nylon begins.

Figure 3.14 Life Cycle Engineering | ECONYL LCA/EPD
Econyl.com

• TO REGENERATE:
Through an innovative process the nylon fabrics are regenerated until they return to their initial qualities. ECONYL® nylon has the same characteristics as nylon from fossil fuels without any difference in quality or performance.

• TO REMAKE:
The regenerated ECONYL® nylon is again transformed into yarn and perfect polymer for the fashion, design and textile flooring industry.

• TO REIMAGINE:
Fashion brands and manufactures use ECONYL® regenerated nylon to create completely new products. That same nylon can be recycled indefinitely, without ever losing any of its qualities.

The future goal of Aquafil is to create products that contain ECONYL® and that can be used at the end of their life cycle can go back to step one of the generation process.
Nowadays, a lot of brands use ECONYL® fiber to produce their collections supporting the idea of an innovative business model based on the principles of the circular economy.
In this process, a question arises: **"What are the sources of waste used for producing ECONYL® regenerated nylon?**

FISHING NETS FROM AQUACULTURE AND FISH INDUSTRY
Two different types of fishing nets are used in the process: nets from the oceans rescued by volunteer divers and nets coming from aquaculture and fish industries. The company collaborate with fishing farms and it start to collect their large amount of useful fishing nets.
While working with the fishing industry Aquafil discover the relevant environmental problem of the ghost nets in the seas and oceans. Here is where the Healthy Seas Foundation came out.
Healthy Seas, a journey from waste to wear, is an initiative that Aquafil founded in 2013 with another business (Star Sock) and an NGO.
The purpose of the initiative is to clean the oceans and seas of marine litter such as derelict fishnets responsible for the needless death of marine animals. The fishing nets recovered in collection points from the sea bed by volunteer divers are first cleaned and sorted and then sent to Aquafil's Slovenian regeneration plant.
The fishing nets washing line is one of the most impressive parts of the ECONYL® Regeneration System, and a good example of Aquafil commitment to face and overtake the many challenges of post-consumer products recycling.

OLD CARPETS DESTINATED FOR LANDFILLS
Aquafil Group is committed to help reduce this waste by implementing a closed-loop supply chain where carpets are recycled. Aquafil has two carpet recycling facilities — in Phoenix and Woodland, CA — that can each process up to 36 million pounds of carpet annually and break old carpets down into three main components: polypropylene (PP), Nylon 6 and calcium carbonate.
1. Nylon 6 is sent to the ECONYL® Regeneration Process in Slovenia with other waste, like reclaimed fishing nets or textile scraps, to make ECONYL® nylon for infinite uses.
2. Polypropylene (mainly used for the backing of carpets) goes into injection-molding production.
3. Calcium carbonate (used to stabilize the carpet) goes into road construction and concrete.
Moreover, thanks to the pioneering partnership with Tarkett, the two companies are closing the loop on commercial carpet tiles in Europe, too.
Tarkett has developed breakthrough technology at its Waalwijk facility and is now able to separate the two principal components of carpet tiles – yarn and backing, while retaining more than 95% yarn purity. This level of purity is vital in ensuring that the polyamide 6 (PA6) is transformed into regenerated ECONYL® nylon yarn.
Now, the partnership is going full circle, with Aquafil sourcing post-use PA6 yarn from Tarkett to create its regenerated ECONYL® yarn.

Figure 3.15 Econyl yarns
Econyl.com

SPECIAL TAKE BACK PROJECTS

An international network structured around recovering materials at end of use, based on partnerships with institutions, organisations, private and public associations and companies. This system allows Aquafil to collect quantities of waste for regeneration into ECONYL® yarn. Examples of this effort are represented by special take back projects in collaboration with different brands such as Napapijri, Speedo and Gucci.

The collaboration between Aquafil and Napapijri has allowed to create a completely circular apparel collection. The Circular Series is made with ECONYL® yarn and standard nylon and designed to be completely recycled because it is composed of a single material. In addition, thanks to a take-back program, it can be returned after two years of use and recycled into new ECONYL® yarn.

In 2018 Gucci launched its own recycling program to convert textile scraps into new ECONYL® yarn.

PRE-CONSUMER WASTE

Pre-consumer waste is waste coming from industrial processes such as plastic components, industrial waste and fabric scraps.

3.6.3 Re-fibra technology

The pioneering REFIBRA™ technology involves upcycling cotton scraps from pre-and-post consumer cotton textile waste. These cotton scraps are transformed into recycled pulp and a substantial proportion of 30 percent is added to the wood pulp. Out of these combined raw materials new virgin TENCEL™Lyocell fibers are produced to make fabrics and garments.
TENCEL™ follows the principles of a GOOD LOOP because its process consciously takes from nature and give back to nature creating a loop in the fashion supply chain - good for everyone, including consumers, brands, mills and the whole fashion community. (30)
This TENCEL™ the GOOD LOOP covers three innovative & industry leading approaches:

• TENCEL™X REFIBRA™ technology
• CARBON-ZERO TENCEL™fibers
• TENCEL™'s transparency (fiber ID)

Based on the same award-winning efficent closed loop production process as standard TENCEL™ Lyocell fiber, REFIBRA™ technology is Lenzing's first step to contribute to the circular economy in textile industry.
TENCEL™ fibers with REFIBRA™ technology are identifiable in yarn, fabrics and garments owing to the innovative special identification technology designed to confirm fiber origin. In turn, this improves supply chain transparency.

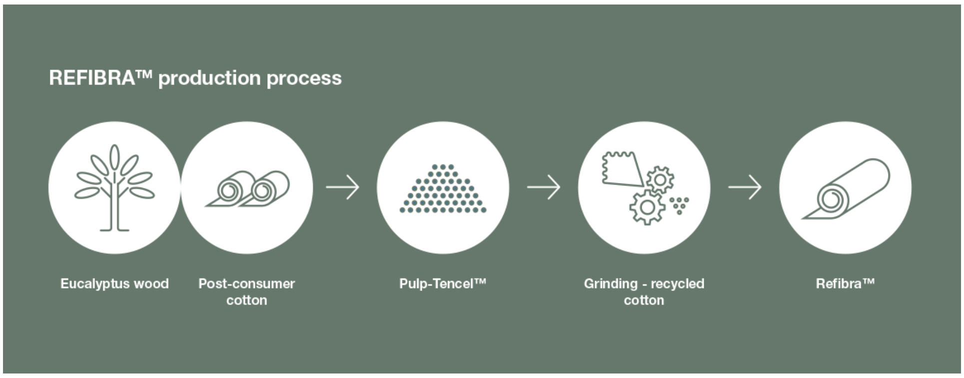
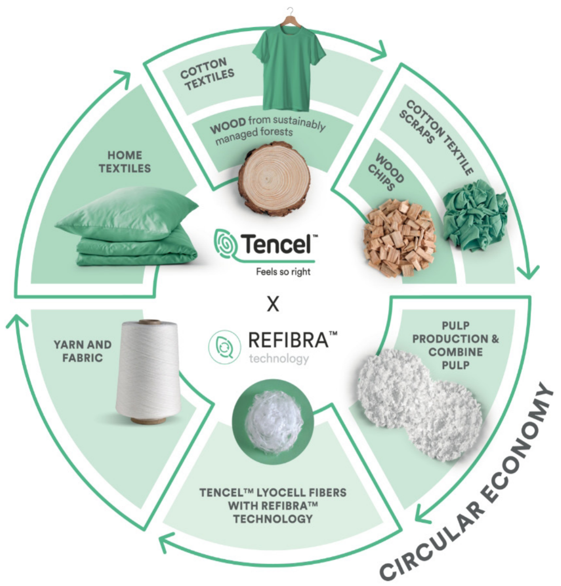


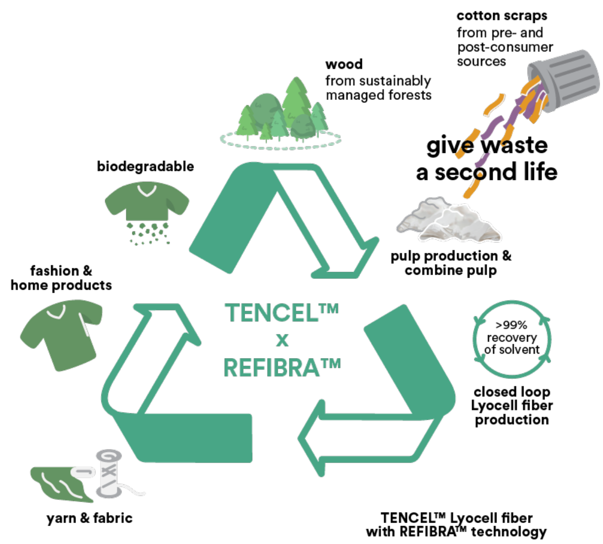
Figure 3.16 Re-fibra production process / Figure 3.17 Tencel x Re-Fibra production process
Textilesantanderina.com; Lenzing.com

Figure 3.18 Lenzing, Södra, and Riopele collaboation with TENCEL™ x REFIBRA™ lyocell fibers (news.europawire.eu)

ONCEMORE

The TENCEL™ Lyocell and Modal fibers help to maintain the environmental balance by being integrated into nature's cycle. The fibers originate from the renewable raw material wood, created by photosynthesis. The certified biobased fibers are manufactured using an environmentally responsible production process. The fibers are certified as compostable and biodegradable, and thus can fully revert back to nature.
The TENCEL™ Lyocell fibers have gained a commendable reputation for their environmentally responsible closed loop production process, which transforms wood pulp into cellulosic fibers with high resource efficency and low environmental impact. This solvent-spinning process recycles water and reuses the solvent at a recovery rate of more then 99%.
Consumers can have the assurance that their fashion choices are not contributing to an adverse impact on the environment.
Numerous Lenzing innovations have been integrated in the production of TENCEL™ Modal fibers. Lenzing strives to safeguard resources for future generations by the use of renewable energy and by the recovery process chemicals.





In the emerging circular economy of the future, nothing is treated as waste.
What is left over from one process becomes input to another, so keeping it circulating. REFIBRA™ technology gives a second life to pre- and post-consumer sources – which would otherwise be sent to landfills or incinerated – by upcycling it into brand new cellulosic fiber materials for clothing and home products.

Figure 3.19 Tencel x Refibra circular process / **Figure 3.20** Tencel Lyocell fiber with Re-fibra technology
Tencel.com

3.7 Results for the future of the field

TIME & COMPLEXITY
From what emerges from the analysis on biomaterials of this project and, in according with Biofabricate et al. (2020), Biofabricated materials, leveraging the tools of biotechnology, are both the most novel, but also the most technically challenging - requiring mastery of biological production with predictable, consistent quantities and qualities before even beginning further transformation into fibers or sheet materials.
Added to this is the expectation that, for the most part, they will "drop in" to existing textile and product manufacturing infrastructure - setting a high bar for first generation "challenger" materials. There is much new ground to be broken and so many technical hurdles to overcome along the way. Hence the longest timeline to go from concept to scaled commercial production: currently around 10-15 years would appear to be the norm. Those that have come to market thus far, e.g. "recombinant silk" from the likes of AMSilk and Spiber are both the result of over a decade of research, millions of USD$, and teams with experienced biotech founders (Biofabricate et al.,2020).
Although many brands have begun to approach this world, financial resources become a problem. Industry needs to cooperate (brands, investors, supply chain) to achively engineer the conditions for these innovators to collaborate.
The good news is that the last 5 years has seen an exponential growth of material innovation tackling biological alternatives to fossil fuel, plant and animal; dyes, chemicals, fibers, fabrics, and leather alternatives (Biofabricate et al., 2020).

EXPECTATIONS
These new technologies are not yet "silver bullets" however. Nature's materials; cotton, wool, silk, cashmere, leather etc are prized because they meet so many needs; comfort, durability, and transformative possibilities, all delivered at prices that reflect centuries of industrial efficency. High performing manmade synthetics, based on cheap fossil fuel, have also raised our expectations of material innovation to encompass properties beyond those offered by nature; super stretch, color saturation and fastness, performance finishes extreme durability and so forth (Biofabricate et al., 2020).
The challenge for innovators is in understanding deeply what the customer is looking for today and then how to walk towards that, acknowledging that the first generation of their product will likely not be the best; each iteration will bring improvements. The challenge for brands is how to walk with innovators on that journey, finding ways to support development so that technical gaps can be closed (or compromises found) in the short term in order to achieve greater success in the long term (Biofabricate et al., 2020).

AVAILABILITY & LONG TERM PROSPECTS
Availability is a real challenge for this sector. In developing new technologies, the first time they show up is often in severly limited quantities at a high cost. As the economy predicts, the price subsequently lowers and Biomaterials will sell at premium/high cost for the foreseeable future. Brands at the mass or lower end of the market will likely have to be more patient to access these material innovations for their customers.
The field of "Biomaterial" encompasses radically different technologies with vastly different times to market.
In according with Biofabricate et al.(2020), although they presents real complexities, this field represents the new era of material innovation with properties and impacts improving upon those we have today.

4.
Testing the field

4.1 Como textile district: the case study

This section presents an analysis of the Como textile sector from the point of view of sustainable evolution.
The Como textile district is taken into consideration because it is a point of reference, in Italy, in Europe and in the world for the production of all finished products linked to artisanal and industrial know-how.
The strengths of this sector are certainly creativity and continuous innovation. These elements are guaranteed by the figure of "converters", who have always been able to interpret tastes and fashions and to continuously innovate their products with a higher speed than that found in companies in the Far East.
The attention of entrepreneurs to the adoption of new production technologies is high and represents an added value although limited by the limited availability of financial resources to invest in research.
This point becomes fundamental in this analysis, as it places the companies that make up this sector in clear comparison with those analyzed in the previous section. The latter are smaller realities when compared to an entire supply chain and are completely focused on experimentation and research, making them more advanced in responding to the growing demand for innovative sustainable materials that fall within the perspective of a circular economy.
The Como supply chain is a reality based on the involvement of several companies in the creation of the finished product. The production process is made up of different phases, which, depending on the case, involve purging, dyeing, washing, and possible printing and finishing techniques. If to this is added the fact that, in many cases, it is still rooted in traditional schemes and that it addresses a much wider market than smaller companies that supply only one type of product, it becomes a difficult challenge to include an entire supply chain within a system that fully satisfies the principles of a circular economy.
In order to understand how the companies in this supply chain position themselves on the issue of sustainability and what is their approach towards new initiatives on the development of sustainable materials, some companies are examined by completing questionnaires on the subject.

4.2 Methodology

The initial desk research phase is followed by applying a case study methodology to narrow a broad scope of research into easily searchable topics. This methodology supports the researcher in dealing with such complexity by transforming the individual case into a functioning unit that can be investigated in its original context, thus encompassing many variables and qualities.
The case study methodology was choosen beacause it is appropriate when existing knowledge in the subject is insufficient (Yin 2003; 2008).
The purpose is to analyse the current positioning of sypplu chain processes and behaviours, in terms of sustainability advancement, biobased innovation and circular practices and initiatives.
This type of methodology offers pragmatic knowledge that while not generalisable permits the development of interpretation through case studies (Nixon and Blakley, 2012).
After the identification of the geographical area of Como (Lombardia), the research method uses numeric and quantifiable data to enable measurement and indipendent verification. The conclusions are based on objective and systematic observations and statistics, exposed in a grapical way.
This quantitative data analysis consists of different stages that was structured inspired to Allen, 2017:

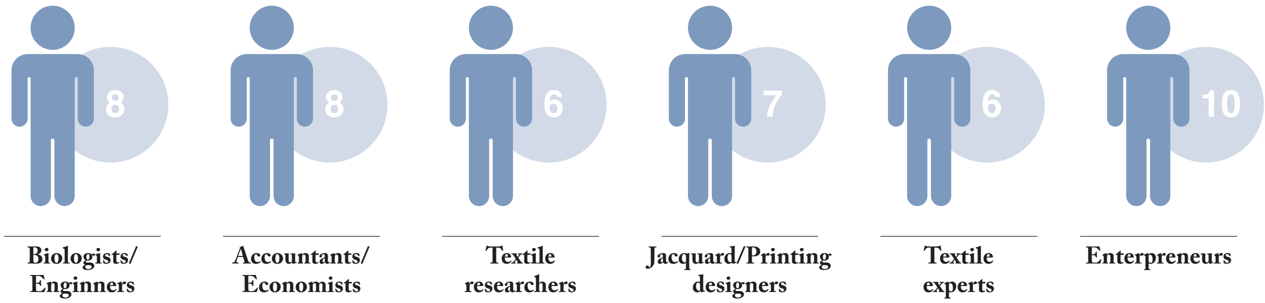
- Data preparation: the translation of raw data into readable files in order to have all of the data at the same level of completeness;
- Data validation: ensuring that the respondent has understood and replied correctly to all questions;
- Data editing: preventing any bias or incomplete answers. Missing data can be managed by the researcher by contacting the respondent or revisiting desk research to fill the unanswered questions;
- Data coding: categorising questions, assigning values and grouping responses;

Following this methodology, data is statistically analysed through descriptive tools (in this case percentage and range). After the 17 companies selected, 10 have agreed to participate in this project on condition that they remain anonymous for corporate reasons. The list is presented as follows.

LIST OF COMPANIES INTERVIEEWED

COUNTRY	CODE	SECTOR	BIG	MEDIUM	SMALL
Italy(Como)	A1	Textile Converter/ Printing			X
Italy(Como)	A2	Weaving		X	
Italy(Como)	A3	Weaving		X	
Italy(Como)	A4	Textile converter		X	
Italy(Como/Prato)	A5	Weaving		X	
Italy(Como)	A6	Weaving	X		
Italy(Como)	A7	Weaving	X		
Italy(Como)	A8	Dyeing/Finishing			X
Italy(Como)	A9	Finishing		X	
Italy(Como)	A10	Printing	X		

According to the methodology, the data is gathered through questionnaires to collect informations from a pool of respondents by asking open-ended questions. In drafting the questions, It is important to create a common meaning in the exchange of questions and answers which can guarantee that questions are asked in the simplest possible form while remaining faithful to the conceptual intentions of the research. There are 2 questionnaires drawn up (Appendix 1, Appendix 2), the structure of the questions is based on the same topics with variations depending on the reference sector of the company (e.g. if they are weaving or dyeing and finishing companies).
The main questions presented in the section are related to Appendix 1 but the schematization takes also into account of the answers of Appendix 2.
The questionnaires were sent and delivered via email, for privacy reasons the people interviewed are anonymous and it was only possible to verify their role within the company. In the following figure is presented the list of the figures interviewed.



The case study intervieews, in according to the first research of the teorethical frameword and to the personal experience of the author, follow several criteria in order to obtain a clear analysis of current sustainable system practices, new possibilities to explore and the limits faced by a market that works in a large scale.
For the purposes of this research, the following criteria are applied:

• **Current sustainable practices:** how the company is positioned in terms of applying sustainable practices and a circular economy system.
• **Innovative material production:** if the company produces sustainable materials, which can be either innovative or certified.
• **Partnership:** if the company is open to collaborative relationships to improve its sustainable performance.
• **Transparency and traceability:** how transparent the company considers itself in its production processes and the level of traceability of the materials it provides.
• **Possibilities and limits:** what are the possibilities for improvement on the practices in which the company knows it is deficient and what are the limits that do not allow it to go beyond.
• **Personal reflections:** what are the reflections on the theme of sustainability and circularity of the figures interviewed.

4.2.1 Current sustainable practices

From the point of view of sustainable innovation, does your company define itself as a reality aimed at researching new actions, solutions and initiatives aimed at improving the environmental impact during the production processes?

60%

- Photovoltaic systems
- Low energy frames
- Low energy illumination systems
- Plasma technologies
- Vacuum monatomic films
- Hot air regeneration of the frames
- Rationalization of raw materials
- Recycling textile waste

40%

- Personal actions

The first question asked to companies does not specifically concern sustainable innovation in terms of fabrics, but generic initiatives and actions undertaken to improve the environmental impact during production processes. What emerges is that 6 out of 10 companies are positive about the issue undertaking actions such as the installation of photovoltaic systems, replacement of old looms with low energy consumption ones, the introduction of new low consumption LED lighting systems, the recycling of textile waste by external companies, rationalization of raw materials, installation of hot air regeneration systems for frames which is filtered and reused for heating the company departments. In the specific case of tertiary companies that deal with finishing and printing techniques, the use of technologies with plasma and monoatomic vacuum films is highlighted.
On the other side, 4 companies answered in a negative way to the question. The latter are decidedly smaller realities that have fewer financial resources than the other six examined.
They claim that they have not taken any significant action in terms of sustainable innovation but that they only resort to personal actions aimed at reducing waste.
This part was schematized also making use of the answers to the question of the questionnaire n.5 (Appendix 1) and n.2 (Appendix 2).

4.2.2 Innovative material production

Does your company produce sustainable materials? If yes, are they innovative fabrics or made with certified yarns?

100% **CERTIFIED**

- GOTS
- OCS
- GRS
- RWS
- FSC
- BCI
- FOR TEXTILE
- REACH

10% **BIOBASED**

- SEAQUAL® YARN

Of the ten companies examined, all claim to make use of textile certifications. The latter, depending on the specific case, can certify the yarn that is used to create the fabric or the sustainability of the entire production process. Of the companies analysed, only two weaving mills belong to the FOR TEXTILE certification system, while all the tertiary companies that deal with finishing and printing techniques adhere to the REACH regulation. All ten companies are certified GOTS, FSC, OCS, GRS, RWS and BCI.
Only one company uses a yarn that is part of the biobased materials family, the SEAQUAL® YARN.
No selected company belongs to the program Cradle to Cradle Certified®.
The interviewees are asked to draw up a ranking from first to last place for the main fabrics for which sustainable alternatives are most in demand, with the first being the one with the highest demand. The primacy goes to polyester, immediately followed by cotton. Viscose ranks third, followed by nylon, silk and wool.
This part was schematized also making use of the answers to the question of the questionnaire n.3 (Appendix 2).

Which are the fabrics with the greatest demand for sustainable alternatives?

ALTERNATIVES DEMAND

1.Polyester

2.Cotton

3.Viscose

4.Nylon

5.Silk and wool

6.Other fibers

4.2.2.1 List of certifications

GOTS (Global Organic Textile Standard)
The Global Organic Textile Standard (GOTS) was developed by leading standard setters to define world-wide recognised requirements for organic textiles. From the harvesting of the raw materials, environmentally and socially responsible manufacturing to labelling, textiles certified to GOTS provide a credible assurance to the consumer.

FSC (Forest Stewardship Council)
As the world's most trusted sustainable forestry standard, FSC is a positive force for change that supports biodiversity, climate resilience, workers' and Indigenous Peoples' rights, and community livelihoods. But forests continue to come under pressure from deforestation, forest degradation, illegal logging, and the changing climate.

RWS (Responsible Wool Standard)
The Responsible Wool Standard (RWS) is a voluntary certification developed by Textile Exchange with contributions from farmers, animal welfare experts, land conservation experts, brands and retailers from all over the world. It mainly deals with animal welfare, but also with soil maintenance and preservation of the social aspect of production, especially in sheep farming.

GRS (Global Recycled Standard)
The Global Recycle Standard (GRS) was originally developed by Control Union Certifications in 2008 and ownership was passed to the Textile Exchange on 1 January 2011. The GRS is an international, voluntary, full product standard that sets requirements for third-party certification of recycled content, chain of custody, social and environmental practices and chemical restrictions.

OCS (Organic Content Standard)
The Organic Content Standard aims to increase organic agricultural production. It is a voluntary global standard that sets the criteria for third-party certification of organic materials and chain of custody.

BCI (Better Cotton Initiative)
Better Cotton Initiative (BCI), a global not-for-profit, is the world's largest cotton sustainability programme. BCI aims to transform cotton production worldwide, by addressing the negative impacts of cotton growing and processing.

FOR TEXTILE is a product and process certification system that derives from the evolution of the Seri.co brand. For Textile is based on a Disciplinary which aims to provide the maximum guarantees on the production process in compliance with the principles of quality, environment, health and safety, sustainability, social responsibility and chemical risk management on the textile product, both for technological and performance properties both for the eco-toxicological properties of the chemical product/formula/colorant and for the eco-toxicological properties.

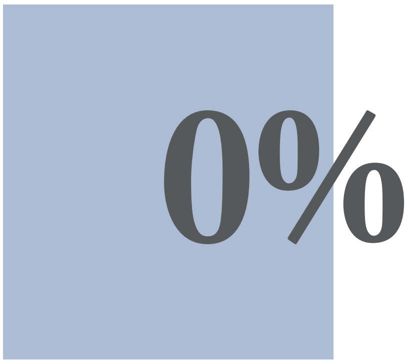
REACH
REACH is the EU regulation governing the manufacture and import of chemical substances. REACH is an acronym for the "registration, evaluation and authorization of chemicals" and has been in force in all EU Member States since June 1, 2007.

Cradle to Cradle Certified® is the leading multi-attribute standard used globally across industries by designers, brands and manufacturers for designing and making products that enable a healthy, equitable and sustainable future. For more than a decade, Cradle to Cradle Certified has been helping companies to innovate and optimize materials and products according to the world's most advanced science-based measures. The Cradle to Cradle Certified® Product Standard provides the framework to assess the safety, circularity and responsibility of materials and products across five categories of sustainability performance such as material health, product circularity, clean air&climate protection, water&soil stewardship and social fairness.
For each category, a product is awarded an accomplishment level (Basic, Bronze, Silver, Gold, or Platinum).
The lowest category achievement of a product also indicates its overall certification level. By providing certification based on rising levels of performance and mandating certification renewal every two years, the standard fosters continual development over time (Cradle to Cradle Products Innovation Institute, 2021).

SEAQUAL® YARN is a high quality 100% post-consumer recycled polyester yarn containing SEAQUAL® MARINE PLASTIC from SEAQUAL INITIATIVE. The yarn is almost identical in physical properties to virgin polyester and is available in a variety of sizes and finishes (both in continuous filament and staple fiber).
SEAQUAL® YARN is used in a multitude of applications including apparel and accessories, contract and automotive upholstery, home furnishings and technical textiles. It contains approximately 10% SEAQUAL® MARINE PLASTIC (from plastic marine litter), the remaining 90% is post-consumer PET from land sources.

4.2.3 Experimentation/Partnership

Has your company ever collaborated with other companies creating partnership aimed at improving sustainable performances?

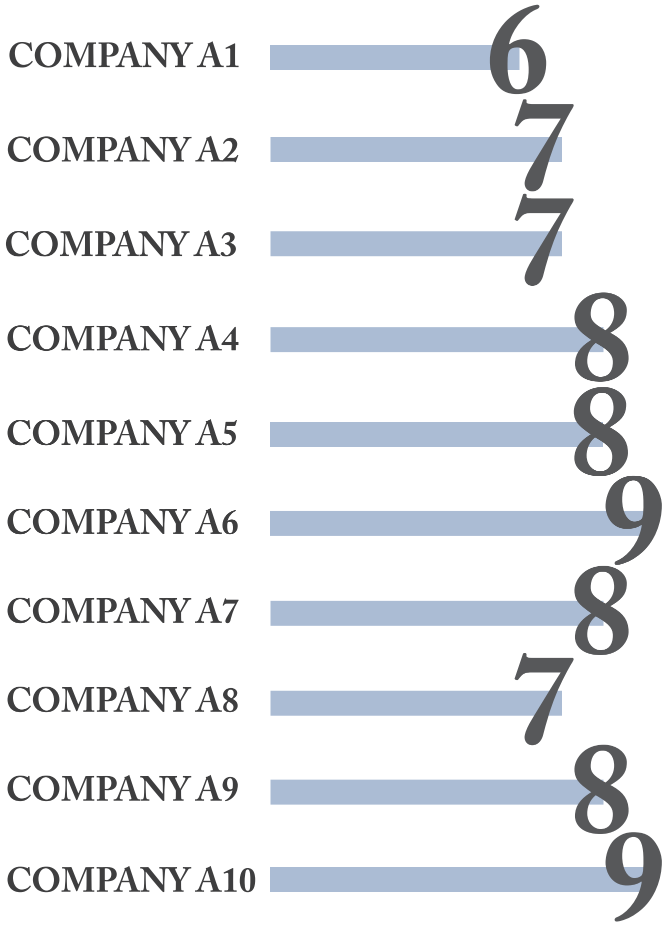


None of the companies examined proposes new experiments in order to create new fabrics that can be considered innovative. The answer that has united all the companies is the lack of economic resources that do not allow to have research teams that carry out research activities.
The answer was the same with regard to partnership relationships. None of the companies has ever started external collaboration relationships that could improve the degree of textile innovation.
These realities are very closed to external companies and are usually pushed towards advancement not thanks to themselves but, rather, by the requests that come from the client: the Brand.
If the brand asks, the supply chain answers.

4.2.4 Transparency & Traceability

**Transparency is a key factor in terms of sustainability. Where does your company stand in terms of traceability of materials? Is it possible to achieve a high degree of transparency or should external factors also be taken into account?
(i.e. who supplies the raw materials?)**

In response to this question, companies were asked to give themselves a score from 1 to 10 in terms of transparency e traceability of materials and to explain the reasons that led them to provide this score.



In general, all the companies examined are positioned positively in terms of transparency. Driven by the demand of the brands, they have to provide specific documentation in order to guarantee the traceability of materials. They must adhere to agreements and specifications such as REACH or FOR TEXTILE, with the purpose to guarantee parameters od sustainability and transparency.
This part was schematized also making use of the answers to the question of the questionnaire n.4 (Appendix 1) and n.4 (Appendix 2).

4.2.5 Possibilities & Limits/Personal reflections

Is the issue of 'sustainable innovation' still in experimental phase or is the Como textile sector seriously striving for change?
What are the factors that can encourage this transition and what are the limits of this sector?

100%

Striving for change

POSSIBILITIES

- Raise brand and consumer awareness
- More financial resources
- Speed up procurement processes

LIMITS

- Financial crisis in the sector
- Production times too slow
- Competition with Eastern countries

All the companies involved in this research state that the Como textile district has abandoned the experimental phase and is seriously and totally in step with the times in terms of sustainable innovation.
Expressing their own personal opinions all those who participated in the research highlight a lack of financial resources due to the economic crisis that the sector is facing after the pandemic period due to COVID-19.
Unfortunately, the latter has also slowed down the raw material procurement processes.
Another problem encountered is the competition with the countries of the Far East. These countries lack protection and controls on their manufacturing processes and are able to supply low-cost fabrics that meet the continuous demands of the Fast fasion.

4.3 Results

The application of the case study methodology shows acions and mindsets of some companies of Como's textile district. The study reveals that, in general, all stakeholders have a positive attitude towards the topic of sustainability.
Stongly driven by the demands of the brands, the suppliers have started to move towards new initiatives and circular practices. What emerged from the research carried out, is that there are companies that have made many steps forward compared to others. The gap is outlined between the larger companies, clearly superior from a sustainable point of view, and the smaller ones which, in this case, belonging to the category of converters. They remains aligned with linear economy schemes, in particular in researching new initiatives or solutions aimed to improving the environmental impact of production processes. They are stuck in simple personal actions aimed at reducing waste.
Among the companies most inclined to move towards a more sustainable system, common points stand out in the investment in renewable energy sources, in new machinery that reduces energy waste and in the use of new technologies on production processes such as printing, dyeing and finishing.
One of the key point of the research concerns progress not in terms of environmental impact, but of material innovation. What emerges from the research is that all companies produce or supply certified materials. Depending on the certification, the sustainability or circularity of the yarn used, of the production process or both is validated. Only one company, out of the ten selected, uses a biobased yarn. It is confirmed that the textile supply chain is not yet open to Biomaterials. According to the author's personal experience, most of the figures interviewed did not know what Biomaterials were.
From this specific part of the research it emerges that among all the fabrics, the ones for which sustainable alternatives are most in demand are polyester and cotton which, in fact, are those considered more 'unsustainable'.
This problem is linked to the fact that many of these companies are not open to collaborations with external companies or start-ups. In fact, the study did not reveal any partnership aimed to improve innovation practices.
In general, all the companies examined are positioned positively in terms of transparency. All claim to have to provide specific and official documentation to guarantee the products and chemical processes that validate their traceability. In order to work with many brands, companies must adhere to agreements and specifications that guarantee parameters of sustainability and transparency.
It is obvious that getting to be completely transparent is a difficult challenge. Many raw materials are imported and purchased from Eastern countries, being able to trace the materials up to that point is almost impossible, it is still far from full score.
Suffice it to consider that a 100% sustainable fabric when it is certified throughout its supply chain, from the yarn to the machinery, from the warehouses in which they are stored to how they are transported. Tracing the entire process is still almost a chimera today.
The last part of the case study methodolgy focuses on the personal reflections of the people intervieewed in terms of possibilities in encouraging the transition towards a "sustainable system" and the limits which prevent them from making progress. All the companies complain about the lack of financial resources, the slowness in the procurement of sustainable raw materials which, consequently, slow down the production processes and the deliveries of the finished products. Added to this is the problem of the costs of these materials which are clearly higher than conventional ones. All these factors, unfortunately, make it difficult to compete with Eastern countries which supply increasingly low-cost, qualitatively scarce materials without any control in terms of sustainability.
It is more than obvious that the change must start from the brand and the designers themselves. They are the ones who have to follow a circular economy system that starts from the conception phase. The production chain will follow them accordingly.

5.
Material-driven guidelines

5.1 Archetypal fibers: Cotton & Polyester

The previous chapters of this project analyzed the advancement of the textile supply chain in terms of sourcing, processing and end of use from an environmental impact point of view.
This chapter intends to take a step forward by analyzing the two archetypal fibers that dominate the market representing the two most 'unsustainable' realities in the fashion&textile scenario.
From the theoretical background and the interviews, proposed in previous chapters, wealth and sustainable alternatives have emerged which can replace these two conventional materials for building long-losting environmental and social quality through the design, production process and use of fashion and textile beyond ideas or expectations.
The alternatives proposed are not totally 'new' or futuristic ideas, they already exist to a greater or lesser extent in the fashon&textile reality today.
The research put them together into a holistic, multilayered and more sustainability-oriented vision for the sector. The conventional cotton and polyester and the relative alternatives are presented starting from the criteria identified by the research and listed below:

SOURCING The alternatives proposed are made from sustainable or biomass raw materials, proving more resource-efficent and culturally responsive practices from the start.

PROCESSING The production process involves more sustainable industrial practices in terms of yarn processing, fabric production (e.g. weaving or knitting) and finishing actions. The alternatives show a substantial reduction of GHGs emissions and water consumption.

END OF USE The sustainable alternatives, which can be certified solutions or biomaterials, present good example of a closed-loop system in according with the principles of a Circular economy because they are totally biodegradable in order to disappear at the end of their useful life or they can be reused in an other production process.

The decision to examine cotton and polyester stems from the tremendous confusion over the sustainability impacts of cultivating and extracting textile materials. Synthetic fibres are commonly seen as 'bad' and natural fibres are 'good'. This preconception is influenced by a complex set of factors including raw material renewability, biodegradability and stereotyped associations made with chemicals, factories and pollution. Of course, there is no dispute that producing synthetic fibres impacts on people and the environment, but natural fibres cultivation and processing also causes substantial impact.
Cultivating 1 kg of cotton, for example, draws on as much as 3800 litres of water. In comparison, producing 1kg of polyester uses little water, approximately 17 litres per kg of fibre. Polyester manufacture does, however, consume almost twice the energy needed to make the same amount of cotton. Thus, the key sustainability challenge in fibre production are different for different materials.
The process of recording and assessing impacts involves looking at resources consumed (energy, water, chemicals and land) and waste and emissions produced (to air, water and land).
Polyester and Cotton together accounted for almost 85 per cent of world fibre production; a percentage of the total that is increasing year-on-year. The implications of the dominance of material choices by two fibres is to concentrate impacts in specific agricoltural or manufacturing sectors, to increase ecological risk, to make the sector less resilient to changing global conditions in both business and the environment, and to reduce consumer choice.
Demand for polyester has doubled over the last 15 years and has now overtaken cotton as the most produced textile

Figure 5.1 Cotton plant
Sustainfashion.info

material. While volumes of natural fibres production have remained fairly constant for several years, cotton fibre production has recently been on the increase along with volumes of cellulosic fibre.
The alternatives proposed are: the organic cotton and the recycled cotton for the first conventional material;
the recycled polyester and the PLA for the second traditional fabric. These four possibilities aim to reprent fibres that can bring benefits by reducing pesticides, water use and our dependency on petrochemical products including oil.
It's important to clarify that the choice was also dictated by the fact that they are the most easily available options on the market, therefore they represent a more than real replacement.
In the following section they are explained in more detail.

5.2 Conventional cotton

Cotton is the most consumed natural fibre in textile and clothing industry.
Cotton crops are distributed around the world principally in dry areas where other commodities grow on with difficulties. China (26.4%), India (20.5%), USA (13.9%), Pakistan (8.5%), Brazil (6.3%), Uzbekistan (4.1%), Australia (3.8%), and Turkey (3.3%) are the main producers of cotton lint. The environmental impacts associated to cotton production and yarn spinning are heterogeneous and complex, even in numerous cases there is no data available in the literature.
This hike in productivity is widely attributed to the application of large quantities of fertilizers and pesticides to the cotton crop, the application is strongly correlated with a range of well-documented environmental impacts including: reduced soil fertility; loss of biodiversity; water pollution; pesticide-related problems including resistance; and severe health problems relating to exposure to acutely toxic pesticides. The pesticides applied to cotton (a generic term incorporating insecticides, herbicides and fungicides) are estimated to make up 11 per cent of global pesticides use. In cotton production, the use of insectticides dominates, making up 25 per cent of world consumption rates, with pyrethoids and organophosphates most widely used.
otton cultivation requires huge amounts of water, including green water, which arises from precipitation, but also blue water, from artificial irrigation, which is estimated as a 73% of the production. Actually, a 2.6% global water use is consumed in the production of cotton and it reduces freshwater reserves causing drought problems in the cultivation areas and a general damage of the water environment.
The quantities od water drawn down in the irrigation of the cotton crop vary according to agricultural practices and climate and can be up to 3800 litres per kg of cotton although it shoul be noted that approximately 50 per cent of land under cotton cultivation is not irrigated but rain fed and because water cannot be 'used up' (it is circulated in a natural cycle), problems associated with high levels of water use are linked more to changing access to water (through wells and infrastructure) and water contamination (by fertilizers and pesticides) which makes it unfit for use for other purposes.
The impacts of spinning and textile production, including weaving, cutting, and sewing, are noticeably elevated, considering the high amounts of electricity required, which considerably increases CO2 emissions and acidification potential. However, the environmental impact of the aforementioned steps is relatively low as compared with cotton dyeing, one of the most contaminant parts in the whole textile process. It involves the use of big amounts of energy, water, steam, and assorted chemicals like bleaching agents, dyes, wetting agents, soap, softener, and salts, in order to obtain the required colour. Moreover, high amounts of wastewater are generated in dyeing plants with deleterious effects to the environment, causing contamination of continental waters which is especially important concerning toxic dyes (Zhang et al., 2015).

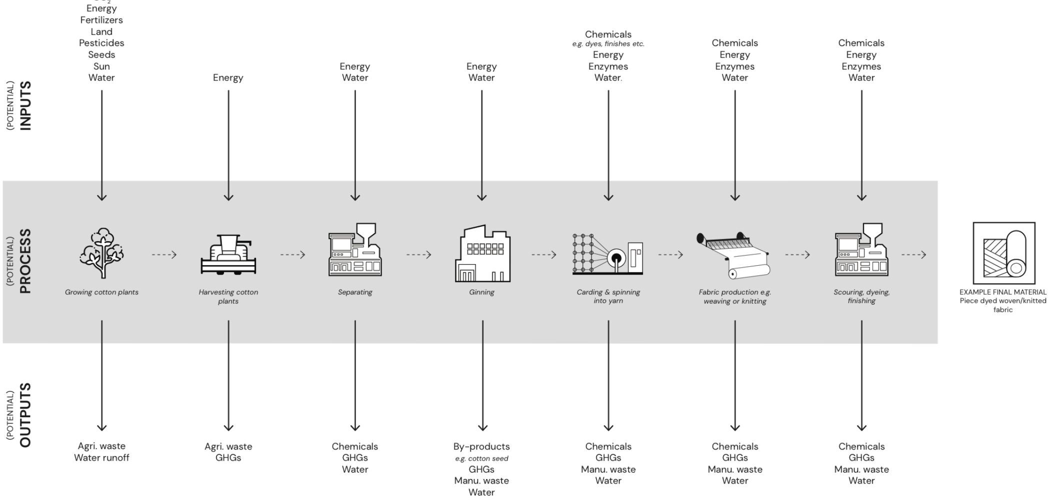


Figure 5.2 Conventional cotton example process
Biofabricate et al., 2020

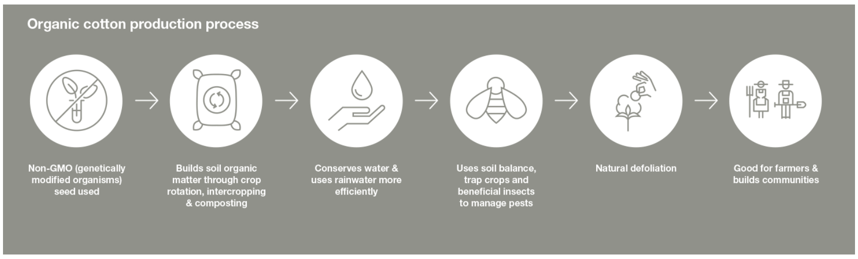
5.2.1 Possible alternative: Organic cotton

SOURCING
The greatest sustainability challenge for cotton cultivation lie in reducing pesticides, fertilizer and water use, and promoting better information and conditions for farmers. Cultivating cotton organically, that is in a system that does not use synthetic pesticides, fertilizers, growth regulators or defoliants, addresses many of these issues. In the organic system the use of synthetic pesticides and fertilizers is avoided as natural methods are used to control pests, weeds and diseas. Particular attention is paid to use of locally adapted varieties, the reduction of nutrient losses through wide crop rotation, and mechalical and manual weed control. Switching to organic production brings a major reduction in the toxicity profile for cotton (as minimal chemicals are used). Organic production also has strong social element and includes many Fair Trade and ethical production principles; as such it can be as more than a set of agricultural practices, but also as a tool for social change. Figure 5.3 explains the production process of this material.

PROCESSING
The industrial production process is based on the use of renewable energy sources reducing GHGs emissions and water consumption. Low environmental impact dyes and agents are used during the processes of dyeing, washing and finishing. The enire process is fully traceable.

END OF USE
The organic cotton is fully biodegradable and compostable, it is created for disappear at the end of its life cycle creating a good example of closing the loop in according with the principles of a circular economy.

The certification that certify the whole production process are:
• GOTS(Global Organic Textile Standard)
• OCS(Organic Content Standard)



ADVANTAGES
In comparison with traditional cotton, the use of the organic one can led to numerous benefits such as: substances harmful to the environment and human health are banned; the land is not exploited and abandoned, but enters the rotation regime; farmers are protected against forced labor, child labor and discrimination. Analyzing the two fabrics,theoretically there should be no difference, although to the touch it is evident: organic cotton is softer and more comfortable than traditional cotton, it is breathable and thermoregulator. Not being treated with aggressive chemicals such as bleach and formaldehyde, and being "respected" at every stage of production, organic cotton is comparable to medium quality cotton.

LIMITS
Among the many advantages there are also some disadvantages of organic cotton, which despite being one of the textile fibers more sustainable, it still shows limits. Among these limits is the higher production cost compared to standard cotton: it requires more time, skill and dexterity, in almost all stages of production. Then there is the certification of organic origin, which usually has a high cost. Elements that raise the selling price of organic clothing to the public. However, there is another disadvantage, which can not be easily solved: the yield of the organic cotton in quantitative terms it is lower than that of traditional cotton: organic cotton requires more arable land than standard cotton.

Figure 5.3 Organic cotton production process
Textilesantanderina.com

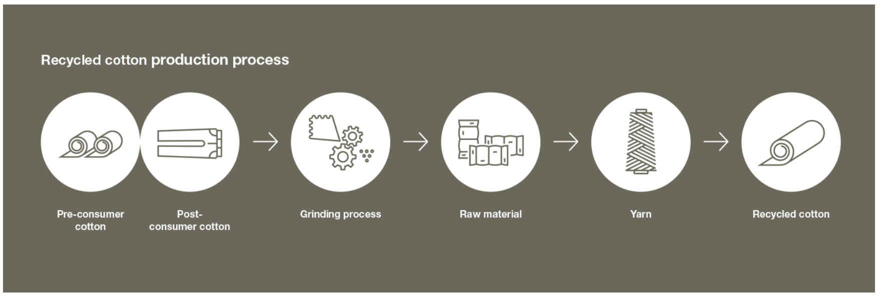
5.2.2 Possible alternative: Recycled cotton

SOURCING
Recycled cotton fabrics use pre and post consumer waste and less virgin cotton.
It reduces the negative impacts of cotton farming like water consumption, CO2 emissions, intensive land use, and gives a new life to textile waste.
Recycled cotton can be defined as cotton fabric converted into cotton fibre that can be reused in textile products. Cotton can be recycled from pre-consumer and post-consumer cotton waste: pre-consumer waste comes from any excess material arising from the production of yarn, fabrics and textile products; post-consumer waste comes from discarded textile products.

PROCESSING
Cotton waste is processed with stripping machines that break the yarns and fabric into smaller pieces before pulling them apart into fibre trough the grinding process.
The mix is carded several times in order to clean and mix the fibres before they are spun into new yarns and textiles. This process is explained in Figure 5.4.
The amount of energy, water and chemical products is definitively reduced in comparison of the traditional cotton.

END OF USE
By choosing recycled cotton it's possibile to reduce the side effects of cotton farming on the envirnoment, to avoid textile waste to be disposed in landfills or to be incinerated, and to increase circularity in textile industry. It is 100% biodegradable and recyclable.

In the case of recycled cotton the valid certification are:
• RCS(Recycled Claim Standard)
• GRS(Global Recycle Standard)



ADVANTAGES
In comparison with the traditional cotton, the use of recycled cotton can led to numerous benefits such as:
the recycling process can redirect many products that would otherwise end up in landfill; the amount of energy, water and dyes used is significantly reduced; the savings are obtained by offsetting the production of new materials, moreover, the common recycled cotton yarns come from textile scraps which are sorted by colour, therefore they are already dyed; savings on CO2 and GHGs emissions and fossil fuels are partially offset by using existing materials.
In terms of mechanical and phisical benefits this fibre is soft, thermoregulator, comfortable ansìd breathable.

LIMITS
Among the many advantages there are also some disadvantages related to this fibre.
The recycled cotton must be blended with other fibers to create a new strong and long-lasting yarn, so it cannot be recycled continuously.This aspect increases also the risk of contamination coming from the other fibres. Given the difficulty of production, the cost of recycled cotton is generally higher than virgin cotton.

Figure 5.4 Recycled cotton production process
Textilesantanderina.com

5.2.3 Table of comparison: Cotton

		CONVENTIONAL COTTON	ORGANIC COTTON	RECYCLED COTTON
PRODUCTION PROCESS	SOURCING	Fertilizers, Pesticides, insecticides	No GMO	Pre-post consumer waste
		Loss of Biodiversity	Natural defoliation	High quality recycled fibre
		Water consumption	Intercropping	No GMO plants
		Reducing soil fertility	Soil and fiber purity preservation	Renewable energy sources
		Chemical substances	Conserve water	Conserve water
		No ethical working conditions	Ethical working conditions	Ethical working conditions
	PROCESSING	GHGs emissions	No GHGs emissions	No GHGs emissions
		Energy and water consumption	Renewable energy sources	Renewable energy sources
		Use of chemicals	Certified sustainable process	Certified recycled process
		Toxic dyes	Natural dyes	Natural dyes
HAND/TOUCH		Quite soft	Soft	Soft
		Drapes well	Drapes well	Drapes well
		Compact	Compact	Compact
		Dry	Dry	Dry
PHISICAL/MECHANICAL PROPERTIES		Breathable	Breathable	Breathable
		Moisture resistent	Moisture resistent	Moisture resistent
		Not elastic	Non allergenic	Non allergenic
		Impact resistent	Thermoregulator	Thermoregulator
		Washable	Washable	Washable
		Strong	Strong and durable	Strong
		Comfortable	Comfortable	Comfortable
		Dry cleanable	Dry cleanable	Dry cleanable
		Absorbent	Absorbent	Absorbent
END OF LIFE		Inceneration	Biodegradable	Biodegradable
		Downcycling	Compostable	Recyclable
		Waste in landfills	No waste in landfills	No waste in landfills
		Waste used ad fertilizers	No inceneration	No inceneration

Figure 5.5 Table of comparison for cotton
Designed by the author

5.3 Conventional polyester

Polyester is a manufactured syntheric fabric. It is the most widely used fiber in the world.
It accounts for roughly half of the overall fiber market and around 80% of synthetics fiber, according to the Textile Exchange Preferred Fiber Materials Report 2017.
The term is generally referred to any fabric or textile which is made using polyester yarns or fibres. It is a shortened name for a synthetic, man-made polymer, which, as a specific material, is most commonly referred to as a type called polyethylene terephthalate (PET). It is made by mixing ethylene glycol and terephthalic acid. That all sounds extremely scientific, but, basically, polyester is a kind of plastic derived from petroleum. Petroleum is a non-renewable resource and the petrochemicals industry has complicated social and political implications. This fibre generally has significant negative environmental impact during production, use, and disposal.
In Figure 5.6 is explained the production process of this traditional synthetic fibre.
In general terms, water consumption of manufactured fibres is lower than for natural fibres but in terms of emissions (to air and water) arising from the production of polyester, these are seen to have a medium to high potential of causing environmental damage if discharged untreated including: heavy metal cobalt; manganese salts; sodium bromide; antimony oxide and titanium dioxide.
Recent studies show that during production facilities producing polyester without treating wastewater have a high probability of causing environmental damage through thr release of small pieces of plastic called microplastics with every wash. These microplastics are filling our water and air, and are being ingested by marine life and animals and even us. While the full extent and impact of these microplastics is not yet clear, it is clear that the problem is huge (microplastics have been found all around the world) and could have detrimental impacts to plant, animal, and human health.
Leaks or spills related to the extraction or transport of oil can also have detrimental effects on groundwater, oceans, and other water sources.
Another relevant problem related to this fibre is that it requires high amounts of energy to produce. The energy required to produce polyester and the greenhouse gas emitted (14.2 kg of CO 2 per kilogram produced) make it a high-impact process. In 2015, polyester produced for clothing emitted 282 billion kg of CO2 – nearly three times more than for cotton.
The mechanical and phisical properties of this fibre also confer many benefits such including durability, versatility, good sunlight resistance, light weight, resistance to wrinkles, resistance to stains, and quick drying time, making the overall impact lower than for fibers like cotton.
Unfortunatelly, among the most disadvantages it's not breathable and biodegradable and, in terms of circularity, it's very diffucult to trace the material making the entire process not transparent and traceable. It can remain in landfills up to 200 years placing it in the first places among the most polluting fibers in the world.

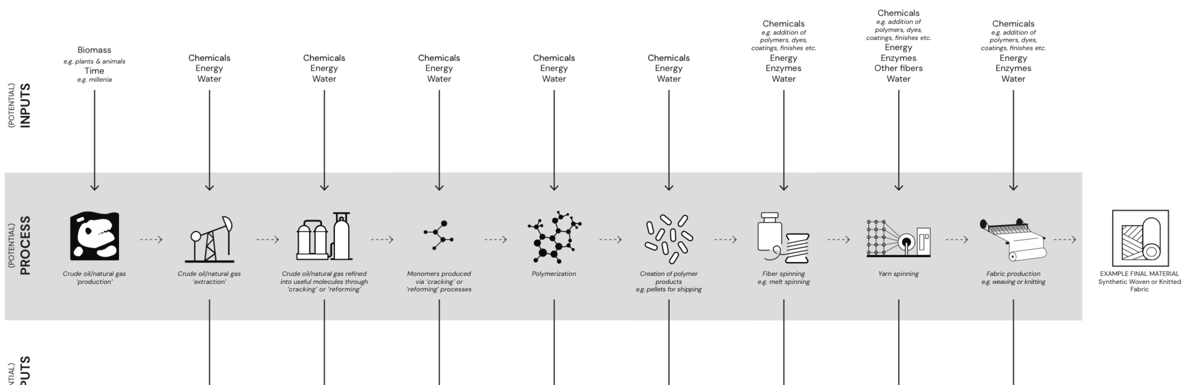


Figure 5.6 **Synthetic fibre example process**
Biofabricate et al., 2020

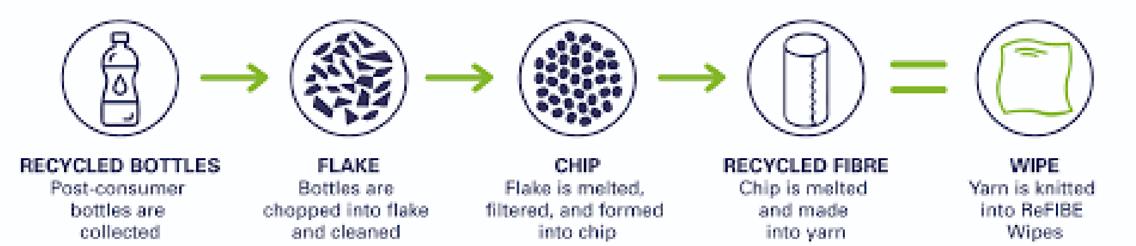
5.3.1 Possible alternative: Recycled polyester

SOURCING
Recycled polyester (rPET) is a synthetic textile fiber and is obtained by melting the plastic and trimming it into one new polyester fiber.
There is a lot of media attention towards recycled polyester made from plastic bottles or containers thrown away by consumers, but actually recycled polyester can come from both pre- and post-consumer plastics.
WRAP estimates that manufacturing recycled polyester reduces CO2 emissions by 32% compared to regular polyester, and when looking at life cycle assessments (LCAs), the recycled fabric scores significantly better than the virgin one. It can help reduce the extraction of crude oil and natural gas from Earth.

PROCESSING
The industrial production processes of rPet requires less energy which is supposed to be 50-60% than the production process of virgin polyester but it appears to be the same of the original one in terms of quality. Also the consumption of water, chemical and dyes are very less for rPET.
The other benefit of recycled polyester is the quality which is similar to the virgin polyester but the production process reduces 32% Carbon Dioxide(CO2) emission. The production process of rPet involves different stages: the collected PET bottles are sorted by color, they are sterilized, dried and crushed into small chips passing trough a grinder; the chips are then heated and dried to avoid any moisture. After that they are passed through a spinneret to form the filament of polyester fiber; the filaments are then strengthen and wounded up in spools; Need to give some texture on the filament is the next process which makes the fiber fluffy; then the filaments are dyed or colored; finally they are baled and made ready for weaving and knitting. The process is explained in Figure 5.7.

END OF USE
The recycled polyester processes reduce waste extending the life of landfill and reducing toxic emissions from inceneritors. It helps to promote nuothere recycling streams for polyester garments that are no longer wearable. According to the "Textile Exchange" , the rPET can be recycled again and again without hampering its quality.

The certification that verifies the process of the recycled polyester process is the GRS (Global Recycle Standard), that is applicable to products composed of at least 20% recycled fibres.



ADVANTAGES
In the case of rPET, the advantages it brings in comparison with the traditional fabric are, above all, from the point of view of reducing environmental impact, as expained in the previous points. If analyzing the mechanical and phisical properties, the fibre shows benefits including breathability, anti-microbial properties,
it is waterproof, soft, elastic and shrink resistence.

LIMITS
In comparison with the traditional polyester, the recycled one can led to numerous disadvantages such as: many of our garments are not made from polyester alone, but rather from a blend of polyester and other materials. In this case it is more difficult, if not impossible, to recycle them; also fabrics in 100% polyester they cannot be recycled forever; like virgin polyester recycled polyester also releases microplastics with each wash but in much smaller quantities.

Figure 5.7 Recycled polyester production process
Cleanroomtechnology.com

5.3.2 Possible alternative: PLA

SOURCING

The poly (lactic acid) PLA has been regarded as the most promising sustainable and biodegradable fiber to replace conventional polyethylene terephthalate (PET) polyester fiber in textile products.

PLA is a polymer with a 100% bio-based carbon content, it is a biopolymer that does not have a fossil-based counterpart. It has broadly similar properties as PET fiber, it's conventionally treted with the same dyes and chemicals as for PET fabrics in wet processing, but PLA has much lower glass transition temperature (55-60°C) and crystalline melting point than PET (165-180°C).

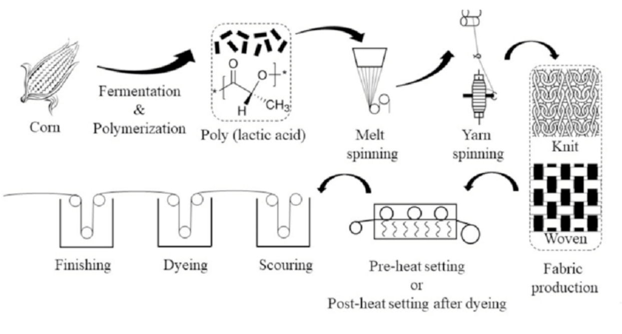
PLA is predominantly produced in ring-opening polymerization of lactides, used by NatureWorks in the USA, which is currently its most notable producer. During the production process corn-derived glucose is fermented into crude lactic acid by diverse bacteria; several continuous extraction and purification steps are applied to obtain an aqueous polymer-grade lactic acid. The acid is transformed into lactides by an open ring polymerization and pelletization by which PLA granulate is obtained. The final step provides the melt spinning of the granulate. Melt spinning is a thermo-mechanical, solvent-free process, possible only if the decomposition temperature of the polymer is above its melting point, which yields continuous or staple fiber. This process is explained in Figure 5.7 and it can equally be applied on PTT and PLA polymers.

PROCESSING

The most commonly used fabric-producing techniques for this fibre are kinitting and weaving. Like other synthetic fibre yarn, PLA staple fiber yarn and filaments could be knitted or woven into fabrics using currently existing knitting or weaving machines. Blended fabrics have been developed using blended yarn or combining PLA staple yarns or filaments with other yarns such as cotton, lyocell, rayon etc. The machine parameters for PLA fabric knitting and weaving are often set referring to PET fabrics, but the properties of PLA yarns and filaments should be considered, such as higher elongation, relatively lower strength and instability (becaming less elastic) after long-term storage in air. During these manufacturing processes, the production of this fibre results less impactful from an environmental point of view. These processes reduce the GHGs emissions and natural dyes and agents are used during the steps of dyeing, washing or finishing.

END OF USE

PLA has been considered as one of the solutions to alleviate the problems of plastic disposal. It is produced from renewable resources and is fully biodegradable and compostable at the end of its useful life. Furthermore, it is the only biobased and biodegradable polymer which can be large-scale melt-spun to textile fibres with the sufficent strength.



ADVANTAGES

PLA fibres has obvious advanages in textile application when compared with other fibres, in particular in terms of mechanical and phisical properties: PLA fibre has lower moisture regain and faster moisture transportation if compared to cellulosic fibres. The manufacturing process of rayon fibre, for example, generates toxic wastes that can cause environmental pollution, whereas the manufacturing process of PLA fibres is non toxic. In addition PLA fibres still have inkerent biological resistance, good anti-flame property and good UV resistance.

LIMITS

The PLA presents also some disadvantages including the fact that despite it can be dyed with the same dyes of PET fabrics, their color fastnessand shades are different. When PLA is blended to other fabric such as cotton or lyocell the scouring of dyeing and the reductive clearing after dyeing remain to be improved.

Figure 5.8 PLA production process
Muhammad Waseem Younas (ResearchGate.net)

5.3.3 Table of comparison: Polyester

		CONVENTIONAL POLYESTER	RECYCLED POLYESTER	BIO POLYESTER
PRODUCTION PROCESS	SOURCING	Petroleum-derived	Pre/Post consumer plastic	Bio-based carbon content
		CO2 emissions	Reduce CO2 emissions	Extraction&Purification
		Non-renewable resources	Reduce extraction of crude oil	Solvent-free process
		Microplastics	Chemical extraction	Thermo-mechanical process
		High energy consumption	Mechalical extraction	Reduce CO2 emissions
		Water and ocean pollution	Reduce microplastics	No fossil-based counterpart
	PROCESSING	GHGs emissions	No GHGs emissions	No GHGs emissions
		Energy and water consumption	Renewable energy sources	Non-toxic process
		Use of chemicals	Certified recycled process	Renewable energy sources
		Toxic dyes	Natural dyes	Natural dyes
HAND/TOUCH		Shiny	Soft	Soft
		Elastic	Elastic	Elastic
		Light weight	Light weight	Light weight
		Quite soft	Shiny	Shiny
PHISICAL/MECHANICAL PROPERTIES		Not breathable	Breathable	Breathable
		Durable	Moisture resistent	Moisture transmission
		Wrinkles resistent	Non allergenic	UV resistent
		UV resistent	Thermoregulator	Flame retardant
		Quick drying time	Quick drying time	Water repellent
		Stains resistent	Strong and durable	Strong and resistent
		Water repellent	Anti-microbial	Stains resistent
		Abrasion resistent	Shrink resistent	Shrink resistence
		Waterproof	Waterproof	Waterproof
END OF LIFE		Not biodegradable	Recyclable	Biodegradable
		Microplastics	Reduce microplastics	Compostable
		Waste in landfills	No waste in landfills	No waste in landfills
		Not compostable	No inceneration	No microplastics

Figure 5.9 Table of comparison for polyester
Designed by the author

5.4 Material-driven guidelines: Diagrams

Making an overview of all he sections analyzed in this project , the various points that have been examined are:

• The analysis of the textile supply chain from an 'unsustainable' point pf view and new and innovative sustainable practices which facilitate the passage from a linear to a circular economy (CHAPTER 1-2).
• The presentation of innovative applications that resides in Biomaterials, as advanced solutions in terms of sourcing, production process and end of life (CHAPTER 3).
• A qualitative research through interviews with various textile companies of Como's textile supply chain in order to understand its progress in terms of environmental impact and R&D (Research & Development) on new innovative and, above all, sustainable practices (CHAPTER 4).
• From the analysis of innovative start-ups in the world of Biomaterials and textile companies, which represent an antithesis in comparison with innovators, sustainable alternatives have emerged to the most impactful archetypal fibres on the market: cotton and polyester. The options proposed are presented on the criteria of sourcing, processing and end of use.

This last section brings together all the sections listed above and, on the basis of the proposed sustainable alternatives, it present material-driven diagrams useful for designers, users and workers of the sector giving them the opportunity to trial and develop citting-edge practices in terms of sourcing, processing and end of use of the two highlighted materials. Starting from the criteria listed above, the guidelines are structured as follows:

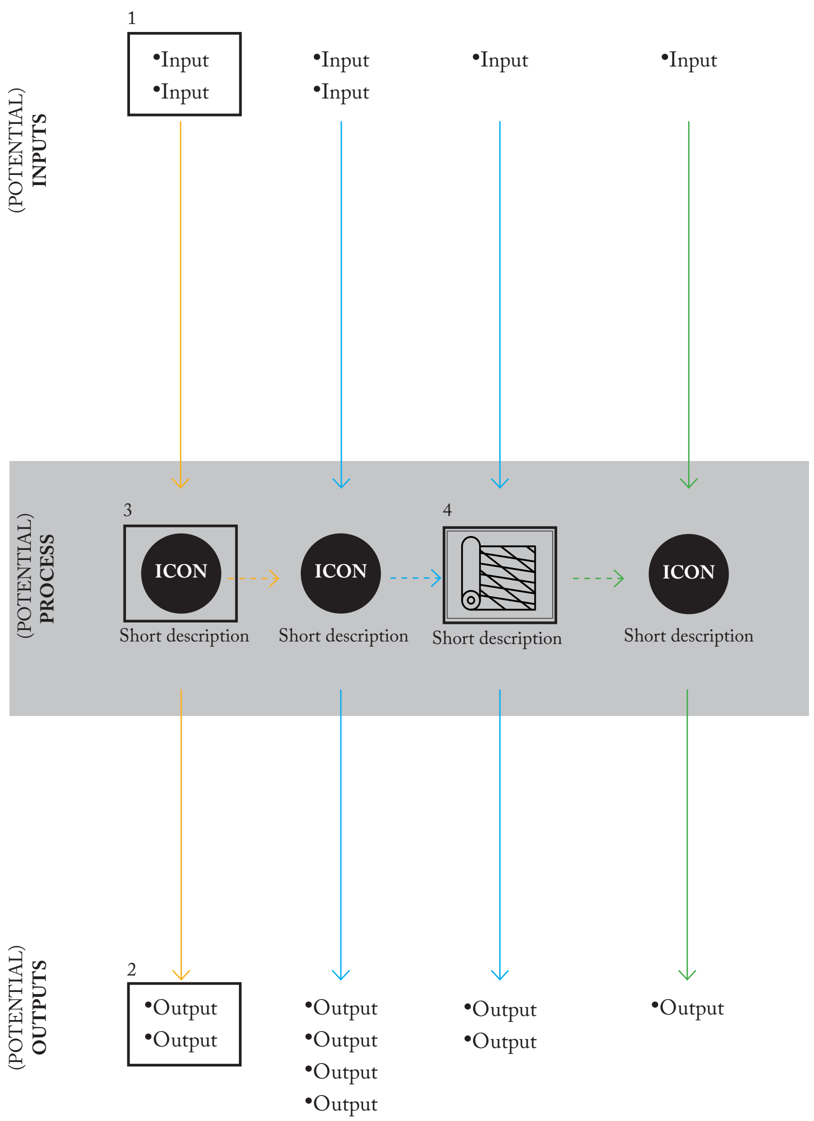
SOURCING The guidelines show the good practices of cotton and polyester from sustainable or biomass raw materials starting from potential inputs emerged during the research and potential outputs that present the benefits of such practices.

PROCESSING The guidelines present the industrial processes of cotton and polyester in terms of yarn processing , fabric production (e.g. weaving or kinitting) and finishing actions, analyzing them on the basis of potential inputs highlighted from interviews in CHAPTER 4. Potential outputs have emerged.

END OF USE In this last part, the guidelines propose potential practices to implement after the realization of the finished product. These practices involve the behaviour of designers and consumers in order to achieve a good model of 'Bioeconomy' that close the loop of the analyzed material.

The material-driven guidelines are built graphically adapting the materil production examples diagrams proposed by Biofabricate et al. (2020).
The intentions of the authors was to create illustrative diagrams that depicts the main types of 'biomaterial' production processes with more context.The goal is that by representing different key production stages it allows a further understanding that text alone would not provide. Their hope is that is additionally helpful to both brands and innovators alike. The diagrams serve to highlight what can be very different processes, inputs, outputs, feedstocks etc. They highlight elements such as where a feedstock is employed in a process; what it is, where it potentially comes from, and how it is used.
The diagrams proposed in this project use the general approach of the original ones proposing inputs and outputs that are extrapolated from the research process of the project. The steps of the production process are different and totally new parts are created, designed by the author, which go beyond the final step of the original diagrams constituted by the finished product.

It is important to note that is not possible to represent every single process step. The diagrams show a high level overview.
The material driven diagrams do not take into consideration the processes of making a garment (e.g. packaging) as the entire project focuses on all the processes prior to this phase and, in particular on the fibre and not on the garment.
The methodology used for the adaptation of the material-driven diagrams is presented below.
Material-driven guidelines are used broadly and in varying desgrees of detail to describe processes taken into consideration by large manufacturers and individual startups. The content of the diagrams in this project are created by reviewing and and reworking the conventional production processes of cotton and polyester, revisiting the process within a sustainable supply chain that follows the principles of a circular economy or that is part of a 'Bioeconomy' system. The elements that are included, in terms of INPUTS and OUTPUTS, come from the qualitative research developed in this work, from the theoretical background and from the interviews with the textile industries of the Como textile supply chain.
The diagrams proposed follow the 'Cradle to Cradle' process of material production based on the three criteria highlighted in the previous section: SOURCING, PROCESSING and END OF USE.
The structure of the diagrams is composed by three elements: PROCESS and INPUTS/OUTPUTS and it is indicative of the production process of cotton and polyester, not specific to one company's technology. Each step is represented with an icon. In addition to outlining the major process steps, the diagrams also list principal inputs and outputs: the inputs refer to the possible sustainable practices that can be adopted in that precise process step; the outputs focus on the benefits that can be brought by the application of these practices.



1	The list in this section of the diagram detail potential inputs into the different production steps. Each process present its own specific inputs. The list is indicative and based on the qualitative research of this project.
2	The list in this section of the diagram detail the potential outputs, in terms of benefits for environmental impact. As with inputs, the list is indicative.
3	The icons represent all the steps in a graphic way. Underneath each is a short descriptor of what each represent.
4	At the end of the processing step there is a graphic example of final product. This is defined as a material such as a fabric, not a final consumer product such as a garment.

LEGEND

SOURCING

PROCESSING

END OF USE

Figure 5.10 Material-driven guidelines diagram example
Designed by the author

5.4.1 Partnership/End of use

The material-driven guidlines address two relatively 'new' aspects: PARTNERSHIP and END OF USE, not intended only as the end of life of the material. In fact, this takes into consideration various inputs that involve both the designer and the consumer. This aspect takes into consideration the beahviour of these two figures in order to facilitate the transition towards a circular economy.
In this chapter these two 'new' aspects are explained in more detail.

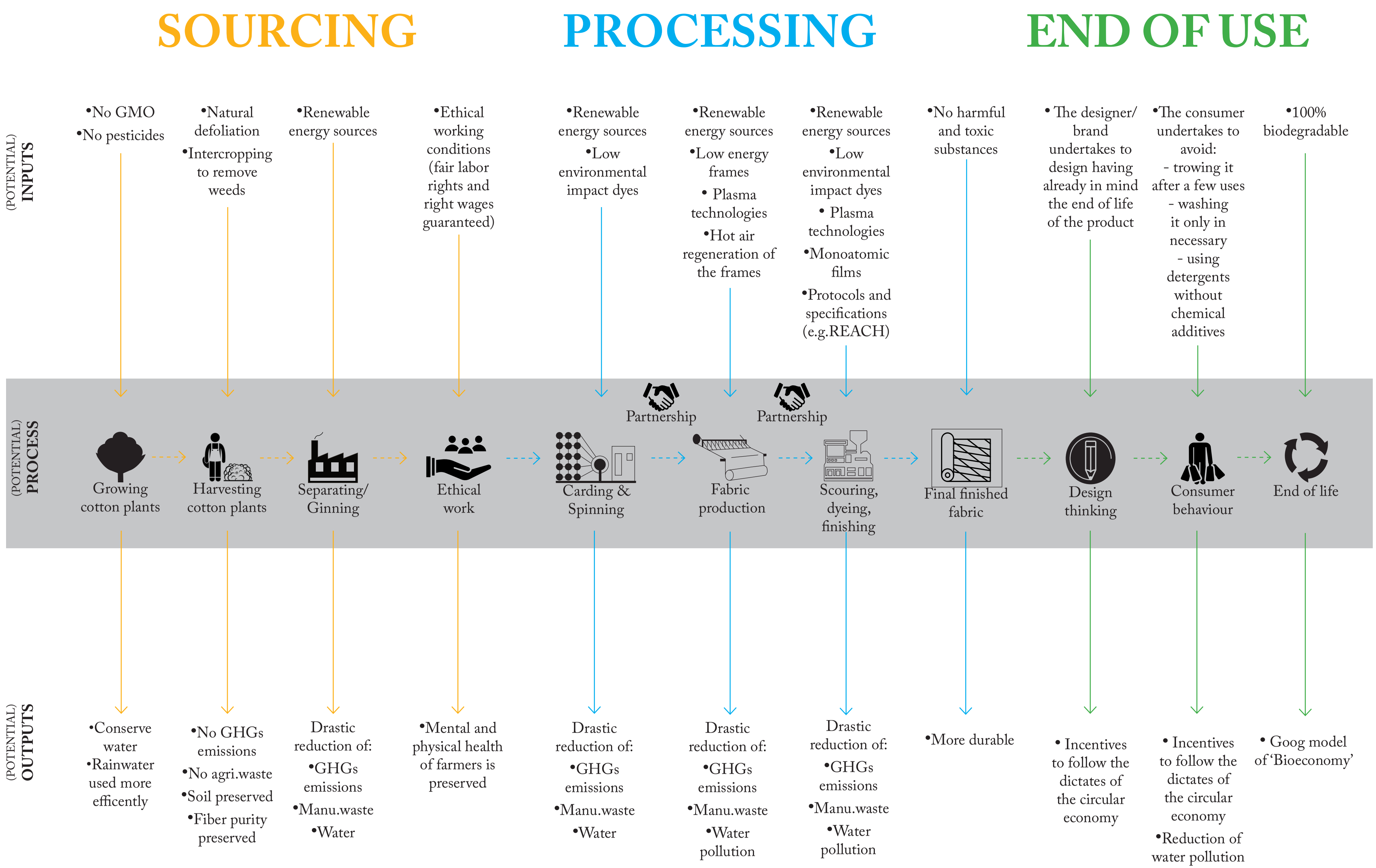
PARTNERSHIP

Partnership is a key point in the development of a sustainable textile production, for all the stakeholders of the textile supply chain. The collaboration between different companies, e.g. innovators and manufacturing industries, is an important step that can improve the performances of both parties in developing the better alternatives for a sustainable scenario.
For innovators that need to drop in to existing supply chains there can be specific challenges to scale. In order to understand a product's performance, an ingredient or material already needs to be developed to the point where it is ready both technically, and in the quantity required, to even run on a commercial line for the first time.
During the design phase many startups do not have sufficient means to test their product in all phases of scaling (Idea, Prototype, Validation, Production), choosing to partner strategically for support with tecnhnical development referring to external facilities who have the necessary facilities, e.g. yarn spinning, fabric weaving, coatings, finishing etc.
These decisions can help speed up development timelines, accelerate scale up, reduce capital expenditure and also negate the need to recruit and build in house expertise, which is both difficult and time consuming. The only challenge of partnership is to achieving an industry expected standards as a material innovation scales.
On the other hand, the collaboration is important also for the manufacturing industries. These realities, especially those of small or medium size, are lacking teams aimed at research, both because they are still tied to traditional schemes and for lack of financial resources. In this context partnership with startups and innovators is vital.
The collaboration can help these companies to grow from a technological point of view, to develop new initiatives with the support of qualified figures and to facilitate their transition towards more sustainable schemes.

END OF USE

In many ways the development of a new material is a series of choices and compromises. One choice will effect another, for example, some materials may need some kind of crosslinking in order to stabilise them and prevent degradation, but this same act of fixing material may affect its ability to degrade at the end of its life. There is a key aspect that need to be taken into consideration from the beginning: "*You need to think about end of life from the very start*" (Maurizio Montalti, Founder & Managing partner, Mogu).
In this context the first actor of this process appears: the designer. Its role is to think about the end of life of the product from the first phase of conception to facilitate the disposal processes; the second actor is the consumer, sensitized by the brand itself and society, it helps to implement behaviors aimed at improving the performance of the product's life. Going against the principles of fast fashion becomes the most important aspect in this phase, trying to apply the practices proposed by the circular economy schemes (recover, resuse and repair).
Thanks to the inputs coming from the spheres of these two actors, the end of use of the product fits perfectly into the dictates of a sustainable scenario, making the process of decomposition or reuse in other production cycles easier.

5.4.2 Cotton material-driven Diagram



Inputs and outputs keys

GMO	Genetically modified organism
GHGs	Greenhouse gases (carbon oxides and methane)

LEGEND

Possible partnership between companies e.g.innovative start-up and converters to improve existing solutions

Figure 5.11 Cotton material-driven Diagram
Designed by the author/Adapted from Biofabricate et al., 2020

5.4.3 Polyester material-driven Diagram

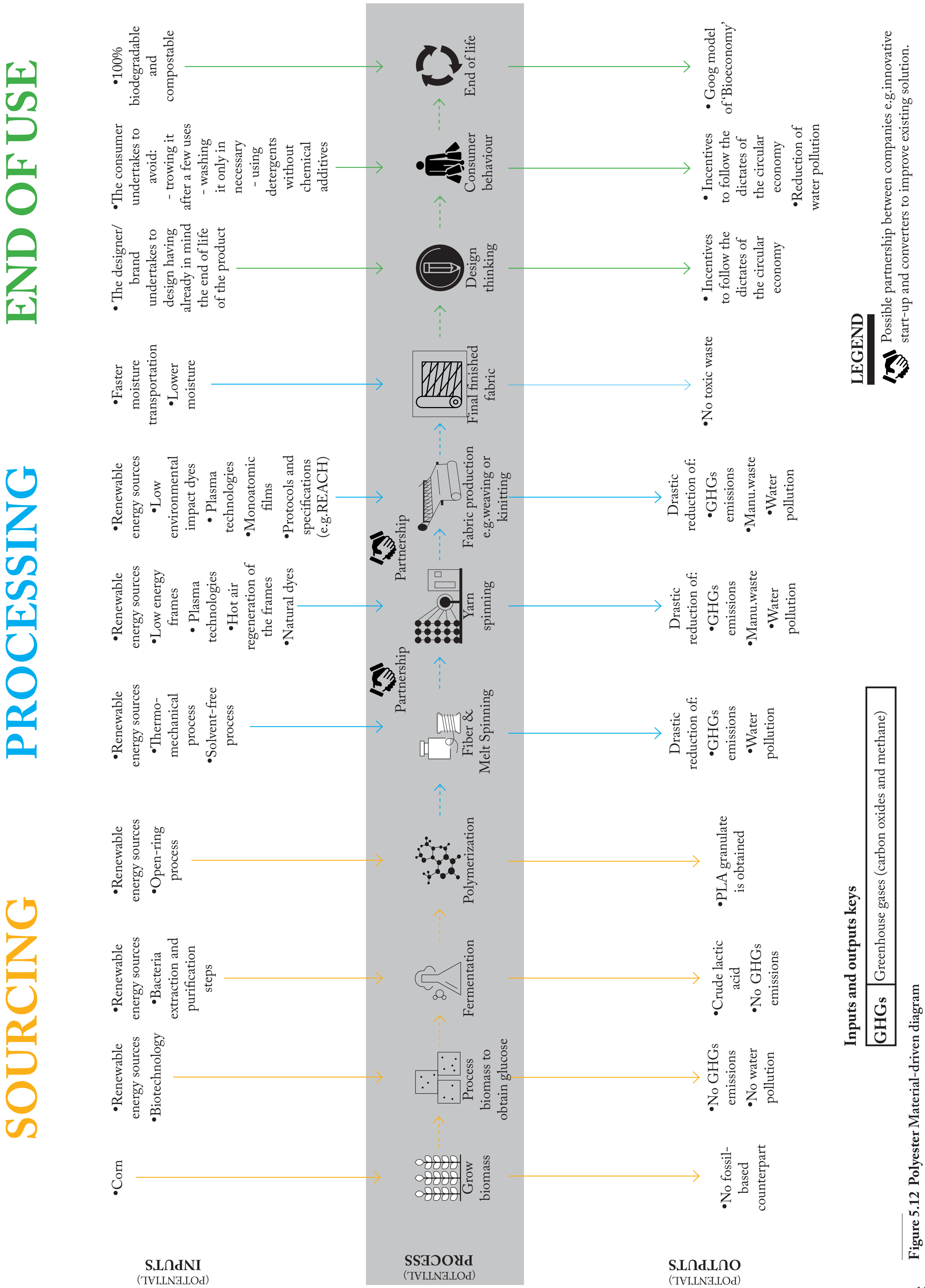


Figure 5.12 Polyester Material-driven diagram
Designed by the author/ Adapted from Biofabricate et al., 2020

5.5 Material-driven guidelines for designers

At this stage, designer plays an essential role in the transition to the sustainable textile industry, since they are the ones who generate new trends and thereby, the range of future products.
For this reason, it is fundamental that designers and large producing brands have a sustainable approach. Many designers integrate a sustainability approach to their products, whereby it is crucial to be informed about sustainability aspects such as knowing the origin of textile products and clothing at supporting the designers throught this process.
It is necessary a new mindset among designers in order to reach systemic change, but transition faces resistance and it takes time to emerge. It is not merely about rethinking the fundamentals on the supply side, but also about redesigning the business on demand side, e.g. in the form of the user experience and rethinking value creation. (Niinimaki et Hassi)
In this last section, guidelines for designers are proposed in order to help, support and facilitate them in order to create solutions that are invaluable for people, give businesses a competitive advantage, and are regenerative for our world. The design thinking proposed by these guidelines allows the designer to create sustainable, resilient, long-lasting value in the circular economy.
Guidelines help this figure to reframe its mindset, ask the right questions, take on projects, and start exploring the sustainable possibilities.
Starting from the statement of Maurizio Montalti "*You need to think about end of life from the very start*" the circular economy mindset looks much wider, to consider everyone who extracts, builds, uses, and disposes of things. As a designer, that includes building feedback loops into its work it is necessary knowing the life cycle of materials who use, collaborating with other industry stakeholders and considering unintended consequences.
It is important to clarify that the guidelines presented are generic as they are realized on the basis of the results emerging from the qualitative research designated in this work, in particular associated with the analyzed archetypal fibres of cotton and polyester, and the triangulation of three papers: The Circular Design Guide by Ellen McArthur Foundation (2017, 2018), the EU strategy for sustainable and circular textiles (2022) and Suzanne Lee's Handbook.
The guidelines are structured on the basis of the following steps:

1. MATERIAL SELECTION
The life cycle of any textile product begins by obtaining fibres, whether natural or synthetic.
They can be considered sustainable or innovative sources such as biomaterials, however it is necessary to know the origin of raw materials, their environmental performance and impact and if the fibre production follows the principles of a sustainable process, including ethical working conditions.
Material selection plays a fundamental role in designining for a circular economy. By choosing only safe and circular materials, it is possbile to ensure that materials are safer to both humans and environment, and the materials used to make them can be reused without causing contamination.

2. SUPPLY CHAIN INVOLVEMENT
After the fibres obtained, the following step is the one that involves the various industrial processes that concern the textile chain such as carding, spinning, winding and the next weaving, knitting, dyeing, washing and finishing. It is necessary to rely on certified companies that are aimed at a radical change towards sustainability. A fundamental role is played by partnership between stakeholders in order to improve sustainable performances. A key point is to create a relationship of trust between designer and suppliers about the production processes involving the selected materials.

3. LIFE CYCLE DESIGN
At this point, the designer plays a key role in 'Design for end of life': from the initial phase the designer must have in mind the end of life of the product. This step prevents the applications of circular practices and possibilities. The

circular designer's mindset looks much wider, to consider everyone who extracts, builds, uses, and disposes of things. The common practice pf a designer is to design 'finished' products. Now, he should think of everything he designs like software – products and services that can constantly evolve, based on the data he gets through feedback. Design is never done.

4. USE EFFICENCY
This step is based on the designer's knowledge of the physical and mechanical properties of the materials. The knowledge of these aspects, during the conception phase, increases the possibility of creating products that best meet the needs of the consumer.
Materials with best qualities encourage the user to lengthen the life cycle of the products they buy.

5. END OF LIFE
By following the guidelines of a sustainable and circular practice, the designer becomes the protagonist of a system that follows rules and principles based on the concept of circularity and 'Bioeconomy'. This way can closes the loop of selected material.
The materials that fall into this circle have characteristics that make them an integral part of zero-waste initiatives and practices.

MATERIAL-DRIVEN GUIDELINES FOR DESIGNERS

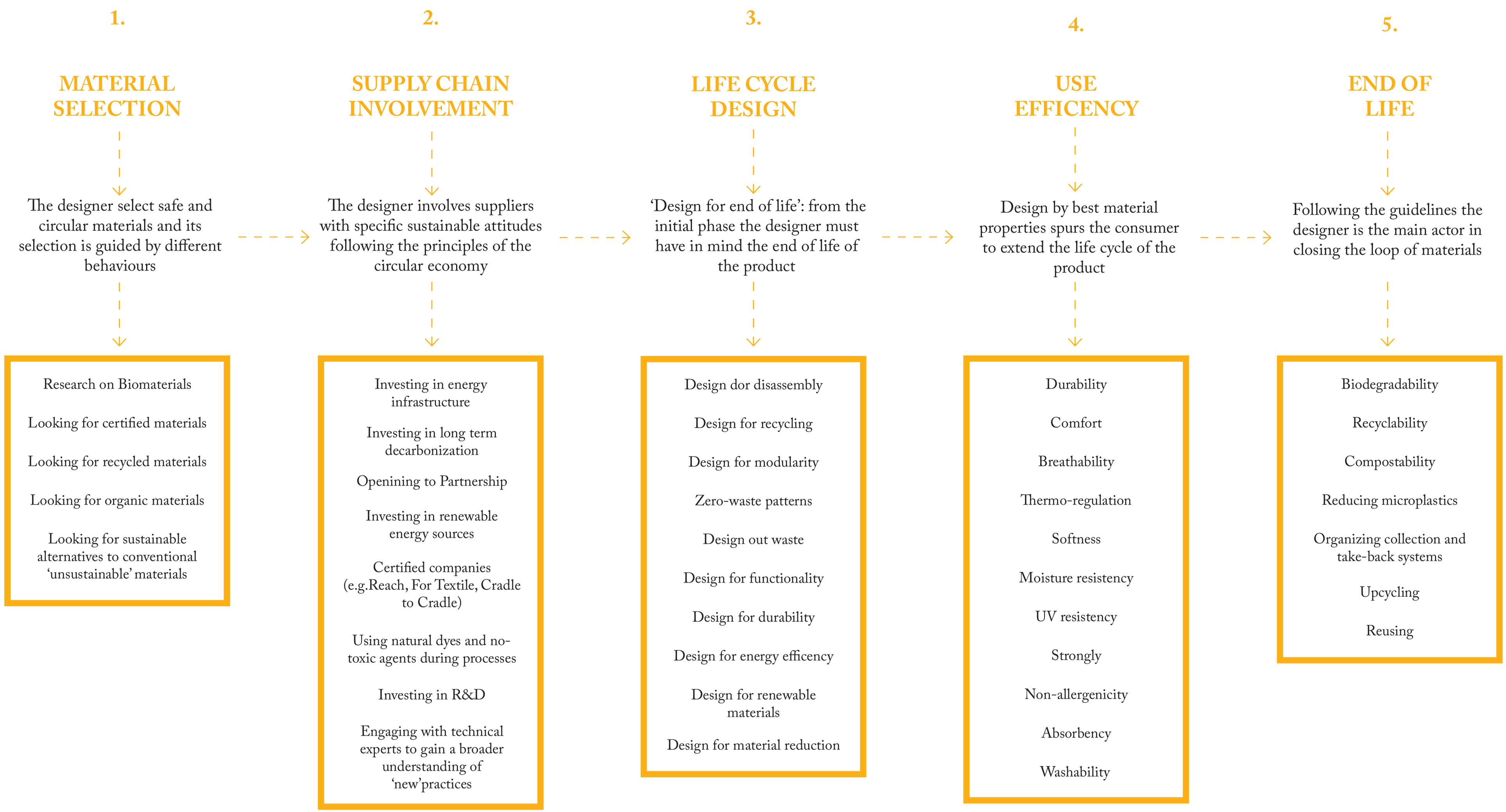


Figure 5.13 Material-driven guidelines for designers
Designed by the author

.Conclusion

This thesis focuses on an ecological dimension-oriented perspective based on the environmental impacts of processes and systems in the Fashion & Textile industry. The analysis of the environmental impact of this indusry is closely related to GHGs emissions, a key element that substantially contributed to the creation of a critical scenario.
This transformation process must start from the core and, consistent with the current state of the fashion system, must start at the material level, the most impactful. For this reason, the concept of "design thinking" establishes itself as a fundamental approach in the necessary transition from a linear to a circular economy in which the designer becames the main actor, implementing recycling concepts and alternative practices in order to protect resources, environment and people.
What emerges through these chapters is the potential of innovative practices and applications, which represent a step forward towards the future in terms of "decarbonization" for the for the industry: the Biomaterials.
They are effective circular and less impactful alternatives to conventional materials, considering the environmental impact of sourcing, processing and disposal. From the analysis of this fundamental section what emerges is that these new technologies are not "silver bullets" however. These radical new material innovation are constrained by the limitations imposed by research and development times and difficulties associated with obtaining grants or founding.
Although there has been exponential growth in the last five years of material innovation, availability and high cost are the real challenge for this sector and what clearly emerges is the cooperation between stakeholders (brands, investors, supply chain) as a key point to achievely engineer the conditions for these innovators to place their products on the market in the shortest possible time and with affordable costs.
The complexities that this sector interfaces with are clear but, nonotheless, this field represents the new era of material innovation with properties and impacts improving upon those we have today.
The issues facing this sector still make it an "experimental" field. This has made it necessary to analyze the other side of the industry coin: the textile supply chain, considered still newborn in circular economy practices. The qualitative analysis of ten companies in the Como textile district shows that suppliers have started to move towards new initiatives and circular practices, although there is a substantial gap between the larger companies with greater financial resources and the small ones which, often, in terms of circular progress, stop at mere personal actions.
From the qualitative analysis emerges a discrete effort on the sustainable improvement of the production processes and all the companies use certified materials.
Despite the progress, financial resources are scarce and do not make possible the investment in research and development necessary to offer truly innovative products. In terms of biomaterials, in fact, there is a general ignorance on the subject. Implementing partnership relationships could represent a beneficial solution for both parties.
From the in-depth data, two archetypal fibres have emerged as the most impactful from an 'unsustainable' point of view: Cotton and Polyester. Sustainable existing alternatives to these two conventional fibres are proposed, in order to present circular material-driven guidelines that take into consideration all the phases of the supply chain such as the sourcing, the processing and the end of use.
On the base of material-driven guidelines, this paper discusses a new mindset among designers in order to reach a systemic change in Fashion & Textile industry. Material-driven life cycle guidelines are proposed in order to help, support and facilitate these figure in creating and exploring new circular possibilities and solutions, aimed to implement sustainability, resilience and long-lasting value in the circular economy.
Designer plays an essential role in the transition to the sustainable textile industry, since they are the ones who generate new trends and thereby, the range of future products. For this reason, it is fundamental that designers and large producing brands have a sustainable approach. Guidelines help this figure to reframe its mindset, ask the right questions, take on projects, and start exploring the sustainable possibilities.
The question that arises at this point is whether it is really possible to achieve the highest standards of circular economy for this industry. The answer, from what can be seen in this thesis is positive only if the transformation process starts from the conception phase. It is the brands and designers who move this industry and, if the change starts from themselves, the textile supply chain will follow them accordingly. The fashion industry has the incredible potential to influence the consumer, to raise awareness of the issue of sustainability, coming to close a perfect circle that follows the paradigm of a circular economy until the end of the products' life.

.List of figures

.Bibliography

Aakko, Maarit, and Koskennurmi-Sivonen R. "Designing Sustainable Fashion: Possibilities and Challenges." *Research Journal of Textile and Apparel,* Vol. 17 No. 1, pp. 13-22 https://doi.org/10.1108/RJTA-17-01-2013-B002.

Allen, M. "The sage encyclopedia of communication research methods" Volumes 1-4, 2017 Thousand Oaks, CA: SAGE Publications, Inc.

Biofabricate, et al. "Understanding 'Bio' Material Innovations: A Primer for the Fashion Industry." Biofabricate, 2020. *Fashion for good*, fashionforgood.com/wp-content/uploads/2020/12/ Understanding-Bio-Material-Innovations-Report.pdf.

D'Itria, Erminia, and Colombi Chiara. "Biobased Innovation as a Fashion and Textile Design Must: A European Perspective." Design Department, Politecnico di Milano, 20123. *Sustainability,* 2022. Volume14(1), 570. https://doi.org/10.3390/su1401057.

Ellen MacArthur Foundation, and IDEO. "The circular design guide." *Ellenmacarthurfoundation.Org,* 2017, 2018. https://www.circulardesignguide.com/.

Ellen MacArthur Foundation. "Circularity indications. An approach to measuring circularity. Methodology", *Ellenmacarthurfoundation.Org*, 2019. http://www.ellenmacarthurfoundation.org/circularity-indicators/.

Ellen MacArthur Foundation. "Make Fashion Circular." *Ellenmacarthurfoundation.Org*, 2017. www.ellenmacarthurfoundation.org/our-work/activities/make-fashion-circular.

Esteve-Turrillas F.A., and de la Guardia, M. "Environmental impact of Recover cotton in textile industry." *Resources, Conservation and Recycling* Volume 116, January 2017. pp. 107-115. Journals & Books https://doi.org/10.1016/j.resconrec.2016.09.034.

Fashion seeds:Fashion Societal, Economic & Environmental Design-led Sustainability. "The Benchmarking report". *Education and research,* 2019. https://www.fashionseeds.org/_files/ugd/ed0694_72992639b4eb48899f6ee3b52ba392cf.pdf.

Fletcher, Kate. "Sustainable fashion and textiles: Design Journeys." Second Edition, New York, 2014 by Routledge.

Hur Eunsuk, and Cassidy Tom. "Perceptions and attitudes towards sustainable fashion design: challenges and opportunities for implementing sustainability in fashion." *International Journal of Fashion Design, Technology and Education* Volume 12, 2019. Pages 208-217. https://doi.org/10.1080/17543266.2019.1572789.

Jain, Toshit, et. al. “Investigation of environmental potentials on supply chain of textile and yarn industry using smart and sustainable life cycle assessment.” Management of Environmental Quality, 2022. *Emerald Insight* https://doi.org/10.1108/MEQ-03-2022-0062.

Kulczycki, Paulina. “Future of Sustainable Fashion | New Biofabrics & Biomaterials.” Sanvt, 26 Mar. 2021. sanvt.com/journal/the-future-of-sustainable-fashion-new-biofabrics- and-biomaterials.

Ley, Katrin, et al. “Unlocking the trillion dollar fashion decarbonisation opportunity: Existing and innovative solutions.” *Fashion For Good and Apparel Impact Institute*, 2021. https://apparelimpact.org/reports/unlocking-the-trillion-dollar-fashion-decarbonisation-opportunity-report/.

Luján-Ornelas, C., et. al. “A Life Cycle Thinking Approach to Analyse Sustainability in the Textile Industry: A Literature Review.” *Sustainability,* 2020. Volume 12(23), 10193. https://doi.org/10.3390/su122310193.

Miller, Sabbie A. “Natural fiber textile reinforced bio-based composites: Mechanical properties, creep, and environmental impacts.” *Journal of Cleaner Production* Volume 198, 10 October 2018. Pages 612-623 https://doi.org/10.1016/j.jclepro.2018.07.038.

Niinimäki, Kirsi, and Hassi, Lotta. “Emerging design strategies in sustainable production and consumption of textiles and clothing.” *Journal of Cleaner Production,* Volume 19, Issue 16, November 2011. Pages 1876-1883. https://doi.org/10.1016/j.jclepro.2011.04.020.

Niinimäki, K. et al. “Sustainable fashion in a circular economy.“ Aalto ARTS Books, Aalto University, School of Arts, Design and Architecture Department of Design, 2018. books.aalto.fi.

Niinimäki, K. et al. “Sustainable fashion: New approaches”. Aalto ARTS Books, Aalto University, School of Arts, Design and Architecture and the Baltic Fashion partnership, Helsinki, Finland, 2013. books.aalto.fi.

Niinimäki, K. et al. “The environmental price of Fast Fashion”. *Nature Reviews Earth & Environment,* 2020. https://doi.org/10.1038/s43017-020-0039-9

Provin, A. P., et al. “New materials for clothing: Rethinking possibilities through a sustainability approach - A review.” *Journal of Cleaner Production* Volume 282, 124444, 1 February 2021. https://doi.org/10.1016/j.jclepro.2020.124444.

Ribul, M., Lanot et al. “Mechanical, chemical, biological: Moving towards closed-loop bio-based recycling in a circular economy of sustainable textiles.” *Journal of Cleaner Production,* Volume 326, 1 December 2021. 129325. https://doi.org/10.1016/j.jclepro.2021.129325.

Syduzzaman, Md., et al. “Smart Textiles and Nano-Technology: A General Overview.” *Textile Science & Engineering,* Volume 5, Issue 1, 1000181, 2015. http://dx.doi.org/10.4172/2165-8064.1000181.

Teli, M. D. , et al. "Upcycling of textile materials." *Global Textile Congress, Bangkok*, 13-15 Feb, 2015. https://www.researchgate.net/publication/316922048_Upcycling_of_Textile_Materials.

Vural Gursal, I. et al. "Defining Circular Economy Principles for Biobased Products." Review. *https://www.mdpi.com/journal/sustainability Sustainability* 2022, 14, 12780. *https://doi.org/10.3390/su141912780.*

Yadav, M., and Agarwal M. "Biobased building materials for sustainable future: An overview." *Journals and books* Volume 43, Part 5, 2021. Pages 2895-2902 https://doi.org/10.1016/j.matpr.2021.01.165.

Yang, Y., et. al. "Poly(lactic acid) fibers, yarns and fabrics: Manufacturing, properties and applications." *Textile Research Journal,* Volume 91, Issue 13-14, 2020. https://doi.org/10.1177/0040517520984101.

Weiss, Martin, et al. "A Review of the Environmental Impacts of Biobased Materials" *Journal of Industrial economy* Volume16, Issues1, 2012. Pages S169-S181 Special Issue: *Meta-Analysis of Life Cycle Assessments* https://doi.org/10.1111/j.1530-9290.2012.00468.x.

Wren, Brianna. "Sustainable supply chain management in the fast fashion Industry: A comparative study of current efforts and best practices to address the climate crisis." *Cleaner Logistics and Supply Chain,* Volume 4 (2022) 100032 https://doi.org/10.1016/j.clscn.2022.100032.

Zaborowska M., and Bernat K. "The development of recycling methods for bio-based materials – A challenge in the implementation of a circular economy: A review." *Waste Management & Research,* Vol. 41(1) 68–80 2023. journals.sagepub.com/home/wmr https://doi.org/10.1177/0734242X221105432.

Zhang J., et al. "Review of carbon footprint assessment in textile industry" *Ecofeminism and Climate Change,* Vol. 1 No. 1, 2020 pp. 51-56. Emerald Publishing Limited https://doi.org/ 10.1108/efcc-03-2020-0006.

.Sitography

AmSilk. "Home." 2023. https://www.amsilk.com/amsilk/.

Application and Importance of Biotechnology in Textile Processing. "Biotechnology in textiles: Applications & Importance". 2021. https://textilelearner.net/biotextiles-application-and-importance/.

Art and designPhysical products Consumer goods and retail. "The Circular economy: design for disassembly". 2022. https://mailchimp.com/courier/article/design-for-disassembly/.

Cleanroom technology. "Going clean and green: A recycled polyester cleanroom wipe". 2020. https://www.cleanroomtechnology.com/news/article_page/Going_clean_and_green_A_recycled_polyester_cleanroom_wipe/170406.

Commissione Europea. "Strategia dell'UE per prodotti tessili sostenibili e circolari". 2022. https://environment.ec.europa.eu/strategy/textiles-strategy_it.

Econyl. "Old carpets destined for landfills". *Econyl.com* 2023. https://www.econyl.com/blog/old-carpets-destined-for-landfills/.

Econyl. "Fishing nets from aquaculture and fish industry and ghost nets". *Econyl.com* 2023. https://www.econyl.com/blog/fishing-nets-from-aquaculture-and-fish-industry-and-ghost-nets/.

Econyl. " Pre-consumer Waste". *Econyl.com* 2023. https://www.econyl.com/blog/pre-consumer-waste/.

Econyl. "Some see trash.Others see treasure". Discover the process behind the breakthrough material, To rescue, Tremake, To reimagine, to regenerate. *Econyl.com* 2023. https://www.econyl.com/the-process/.

Econyl. "Special Take Back Projects, Napapijri, Speedo e Gucci". *Econyl.com* 2023. https://www.econyl.com/blog/special-take-back-projects/.

Econyl. "The future is cicrcular". *Econyl.com* 2023. https://www.econyl.com/about-us/.

Ellen MacArthur Foundation. "Make Fashion Circular". *EllenmacArthurfoundation.Org*, 2017. www.ellenmacarthurfoundation.org/our-work/activities/make-fashion-circular.

Ellen MacArthur Foundation. "What is a circular economy?". *EllenMacArthurFoundation.org*, 2017. https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview.

Europawire, 2023. "Lenzing, Södra, and Riopele take sustainable fashion to the next level with TENCEL™ x REFIBRA™ lyocell fibers". https://news.europawire.eu/lenzing-sodra-and-riopele-take-sustainable-fashion-to-the-next-level-with-tencel-x-refibra-lyocell-fibers/eu-press-release/2023/02/14/10/47/10/110594/.

European Clothing Action Plan (ECAP). "Driving circular fashion and textiles: ECAP summary report". *ecap.eu.com,* 2019. https://wrap.org.uk/resources/report/driving-circular-fashion-and-textiles-ecap-summary-report

European Parliament. "Environmental impact of the textile and clothing industry: What consumers need to know". 2019. Briefing https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2019)633143.

Fashion For Good. "Textile Processing Guide". 2022. Available online: https://report fashionforgood.com/wp-content/uploads/2022/01/Textile-Processing-Guide.pdf.

Global Fahion Agenda. “Pulse of the Fashion Industry report, 2017”. *globalfashionagenda.org,* 2023. https://globalfashionagenda.org/product/pulse-of-the-fashion-industry-2017/.

Meadows(1999). “Leverage Points:Places to intervene in a system”. *Sustainability Institute.* Available from: http://drbalcom.pbworks.com/w/file/fetch/35173014/Leverage_Points.pdf.

MykoWorks. “How Reishi™ Could Bring Fashion Closer to Circularity”. 2023. https://www.mycoworks.com/how-reishi-could-bring-fashion-closer-to-circularity.

Orange Fiber. “Salvatore Ferragamo Capsule Collection 2017”. *Orangefiber.it*, 2023. https://orangefiber.it/ferragamo-capsule-collection/.

Orange Fiber. “TENCEL™ & Orange Fiber, 2021”. *Orangefiber.it*, 2023. https://orangefiber.it/process/.

Orange Fiber. “Who We Are.” *Orangefiber.it*, 2023. https://orangefiber.it/who-we-are/.

Redress design award. “Design for recyclability guide”. 2023. https://www.redressdesignaward.com/academy/resources/guide/design-for-recyclability.

Refibra. “What is REFIBRA™?”. *TextilSantanderina*, 2023. www. textilsantanderina.com/textile-solutions/refibra/.

Sciencefacts. “Types of renewable energy generation.” 2023. https://www.sciencefacts.net/ types-of-renewable-energy.html.

Science History Institute. “What nylon did for your legs, LYCRA will do for your figure!”. 2023. https://digital.sciencehistory.org/works/gq67jr53v.

Stockholm Environment Institute. “Transformational change through a circular economy, 2019”. *www.sei.org*, 2023. https://www.sei.org/publications/transformational-change-through-a-circular-economy/.

Sustainable Fashion: Everything you want to know about the sustainability of the textile and fashion industry, 2021. *sustainfashion.info*, 2023. https://sustainfashion.info/cotton-blends/.

Tencel. “Sustainability”. *Tencel.com*, 2023 https://www.tencel.com/sustainability.

TENCEL™ x REFIBRA™ technology. “The good loop”. *Tencel.com*, 2023. https://www.tencel.com/refibra.

Textile Exchange. “Preferred Fiber & Materials Market Report 2021.” *textileexchange.org*, 2023. https://textileexchange.org/app/uploads/2021/08/Textile-Exchange_Preferred-Fiber-and-Materials-Market-Report_2021.pdf.

The Great Recovery. “Four design models for Circular Economy”. 2023. http://www.greatrecovery.org.uk/resources/four-design-models-for-circular-economy/.

UN Environment Programme. “Sustainability and Circularity in the Textile Value Chain: Global Stocktaking”. 2020. https://wedocs.unep.org/handle/20.500.11822/34184.

Veja’s 2019. “The blindness around CO2 emissions.” project.veja-store.com, 2023. https://project.veja-store.com/en/single/emissions.

Klopman. “Tessuti con fibre TENCEL™ x REFIBRA™.” *Klopman.com*, 2022. https://www.klopman.com/it/greenwear/tessuti-con-fibre-tencel-x-refibra.

Appendix 1 - Questionnaire for weaving companies and converters

1. **From the point of view of sustainable innovation, can your company be defined as a reality aimed at researching new actions that can reduce the environmental impact during production processes?**

2. **Does your company produce sustainable materials? If yes, are they innovative fabrics or made with certified yarns?**

3. **Which are the fabrics with the greatest demand for sustainable alternatives?**

4. **Has your company ever been pressured by external clients to provide specific documentation or follow certain protocols regarding the degree of sustainability of the products you supply?**

5. **Has your company ever experimented with sustainable initiatives on the search for approaches to facilitate the waste disposal phases?**

6. Has your company ever collaborated with other companies creating partnership aimed at improving sustainable performances?

7. Transparency is a key factor in terms of sustainability. Where does your company stand in terms of traceability of materials? Is it possible to achieve a high degree of transparency or should external factors also be taken into account? (i.e. who supplies the raw materials?)

8. Is the issue of 'sustainable innovation' still in experimental phase or is the Como textile sector seriously striving for change?

9. What are the factors that can encourage this transition and what are the limits of this sector?

Appendix 2 - Questionnaire for dyeing/ finishing/printing companies

1. From the point of view of sustainable innovation and chemical safety, can your company be defined as a reality aimed at researching new actions that can reduce the environmental impact during production processes?

2. Many companies have undertaken to name the use of dangerous chemical substances using more restrictive parameters than those imposed by the European regulation. Has your company joined this initiative? If yes/no, did the choice depend on you or on external factors?

3. Does your company use dyes or agents with a low environmental impact? If they have certification?

4. Has your company ever been pressured by external clients to provide specific documentation or follow certain protocols regarding the degree of toxicity to chemicals during the production processes?

5. Has your company ever made use of self-diagnostic software (laboratory testing of wastewater or sludge) that helps monitor critical chemicals?

6. Has your company ever collaborated with other companies creating partnership aimed at improving sustainable performances?

7. Transparency is a key factor in terms of sustainability. Where does your company stand in terms of traceability of substances used during the production processes? Is it possible to achieve a high degree of transparency or should external factors also be taken into account? (i.e. who supplies the raw materials?)

8. Is the issue of 'sustainable innovation' still in experimental phase or is the Como textile sector seriously striving for change?

9. What are the factors that can encourage this transition and what are the limits of this sector?