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WILL YOUR CLOTHES OF TOMORROW BE MADE OF AGRO-FOOD RESIDUES?

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Abstract

Over the past decades, a new type of raw material for textile and fashion has seen the light of day: agricultural and food processing residues-based fibres and materials (AFPR). Straddling the food and fashion industry, these innovations appear to be an excellent solution for sustainable development achievement as they support the transition to a more circular system, where waste is valued as an input, while pressures on natural resources are reduced. As little research has been done on this topic, this paper aims to fill in the gaps by laying out the existing market and highlighting the potential that these fibres offer.

Keywords: food by-products, sustainable fashion, sustainable fibres, circular economy.

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I. Introduction

Every day, million tons of food is produced for human consumption all around the world. Associated to its production is the direct generation of by-products throughout the different levels of the food chain, most of which occur at the agricultural and food processing stages. These sources of unavoidable waste directly contribute to making the food industry responsible for 29% of global GHG emissions worldwide (Almond, Grooten et Petersen 2020), by being left to rot in the field, burned or sent to landfills. At the same time, the fashion industry is pointed out as one of the worst offenders in terms of environmental and social impacts. The UN Economic Commission for Europe (UNECE) estimates that it contributes to around 20% of global wastewater and 10% of global carbon emissions; more than all international flights and maritime shipping combined (UNECE 2018).

Agriculture and fashion have for long been intertwined; leather has been around for thousands of years and not as far as the 1960s 97% of textiles were made out of natural fibres, that is fibres that are either plant-based or animal-based (Business Wire 2018). However, the drastic increase of synthetic fibres over the last 50 years led to a decreased use of natural fibres in favour of petroleum-based fibres and material. This is true both for textiles and leather goods, which are increasingly replaced by synthetic leathers. However, technological advancements of the last decade combined with the push for circular economy started to forge new bonds between agriculture and fashion: by choosing and using agricultural waste as raw material inputs for garment manufacture, both industries positively contribute to the other. The recent technologies are also opening up opportunities for valorising food residues in the food processing industry.

Although studies support that fashion and agriculture are tightly linked and initial research on sustainable fibres supports the hypothesis that that AFPRs have a great potential for the textile industry (Chanana, Parmar et Sachdeva 2016), we identify a gap in the literature review associating the use of by-products in the clothing industry. Backing up the aforementioned

hypothesis, are the numerous innovators and companies which have developed processes to transform agriculture and food processing residues (AFPR) into fibre, yarn, fabrics and other materials such as bioplastics or alternative leathers. Fortified by this reality, this research, taking a business perspective, aims to fill in the gap by answering the following question: “Will your clothes of tomorrow be made of agricultural and food processing residues?". The objective is to assess whether or not these new inputs have the potential of replacing traditional fibres and materials in the short and the long run.

Circular economy as a guiding principle

The large availability of information brought by globalization as well as a growing momentum to halt climate change is pushing institutions and governments worldwide to act towards rethinking our economic model and industries to create a new one that ensures environmental, social and economic prosperity for all actors across the value chain. The Paris Agreement in 2015 has given a boost for businesses and governments to transform the way we produce and consume goods and services. Circular economy (CE), built around the principles of designing waste out of the system, keeping materials and products in use and regenerating natural systems, offers a tangible solution to achieve these goals. The Ellen MacArthur Foundation (EMF), focused on the promotion and development of CE gives us the following definition: "Looking beyond the current take-make-waste extractive industrial model, a circular economy aims to redefine growth, focusing on positive society-wide benefits. It entails gradually decoupling economic activity from the consumption of finite resources and designing waste out of the system. Underpinned by a transition to renewable energy sources, the circular model builds economic, natural, and social capital." (Ellen MacArthur Foundation s.d.) (Appendix 1).

Applied to food systems, circular economy promotes a system that improves rather than degrades natural environments, designs out food waste and loss and feeds healthy food to all. In other words, food is designed to cycle, so the by-products of one industry serve to the next;

redistribution surplus food where possible, while turning non-edible by-product parts into a value-added product (Ellen MacArthur Foundation s.d.). For fashion, circular economy means ensuring that products are made to be recycled, kept in use for longer and made from safe and recycled or renewable inputs.

II. Literature review: Understanding the problem on a global scale

Relevance to the food system

If edible food waste needs to be averted through prevention, reuse and redistribution, food systems remain a source of some unavoidable waste; by generating by-products. By-products, hereafter also referred to as residues, are defined as an incidental or secondary product made in the manufacture or synthesis of something else (Oxford Language). In the context of food systems, the generation of by-products occurs primarily at the agricultural and food processing stages.

In 2016, the FAO Food Loss Index (FLI), revealed that 14% of food was lost between postharvest and distribution stages of the food chain. It is to point out that this number includes both the edible and non-edible part of aliments, as separating edible from non-edible is operationally demanding and sometimes impossible to perform (FAO 2019). Furthermore, the Ellen MacArthur foundation reveals that only 2% of organic waste is valorised throughout our current food production and consumption system. In its report on cities and circular economy for food, the foundation highlights the under-utilized potential of food surplus and agri-food by-products and promotes the generation of high-value products derived from these waste streams (Appendix 2).

Agricultural by-products and loss:

Agriculture is a major contributor to climate change, with an estimated responsibility of 20% of CO2 emissions worldwide (McKinsey & Company 2020). In 2019, land use for food production represented 50% of habitable land, of which 77% were used for livestock and 23%

for crops destined to human consumption. As the population is expected to rise to 10,5 billion in 2050, the FAO forecasts a 40% to 54% increase in food production compared to 2012 thus increasing pressures on the agricultural sector: CO2 emissions, as well as a stronger competition on land availability between sectors, are projected to intensify (FAO 2018).

Agricultural by-products, usually referred to as agricultural waste, consist of plant and animal leftovers after the primary product is harvested (Appendix 3). They can take the form of liquid or solid waste. With growing food production levels, the generation of agricultural waste is forecasted to increase. Animal-based by-products have been used for centuries in the fashion industry to develop leather or blankets. However, these practices have been increasingly criticized over the past decade due to the conditions in which animals are raised, to the environmental costs of animal farming – water consumption, use of crops land to feed livestock etc, and to the chemicals used in the transformation process. In the past, most of agricultural plant-based by-products were usually left in the field to rot or burned, which can be hazardous for the environment and the surrounding inhabitants. As of today, it is estimated that only 10% are used as raw materials for other industries such as anaerobic digestion, automotive components or biocomposites and an increasing number of researches on the topic is taking place.

Food processing by-products:

It is common consensus amongst the scientific community and recognized organisations that the food processing industry is one of the greatest producers of by-product (Trigoa, et al. 2020). From meat and animal products, cereals and pulses to fruits and vegetables, food transformation generates large amounts of waste as a result of food transformation (Appendix 3). Previous researches have shown that this is particularly true in the vegetable and fruit industry (McCarthy, Kapetanaki et Wang 2019, Trigo, et al. 2020). Indeed, the vegetable and fruit processing industry produces by-products in various forms: peels, pomace, overripe and/or

damaged fruits and vegetables (Trigo, et al. 2020). These by-products represent a large stream of waste which is matched by a large potential for high value-added products and applications in several fields, including cosmetics, new food and more recently fashion and textile industry.

As food demand increases, better utilization of raw material needs to be implemented. Circular economy principles applied to these industries encourage the valorisation of agricultural and food processing by-products, by turning traditional waste streams into valuable inputs for other industries. This can not only reduce the need for virgin resources, reduce CO2 emissions linked to burned or discarded by-products but also sets food systems at the heart of a more sustainable ecosystem.

Relevance to the fashion industry

Often considered as the second most polluting industry in the world, the fashion industry has been under a lot of scrutinies over the past decades. Social and environmental scandals relayed all over the world, have been the catalyst of a growing interest in sustainable fashion. An increasing number of companies are pledging to sustainable practices, such as H&M group which incorporated sustainability as one of their core values or Adidas who committed to use 100% of recycled plastics by 2024 and to make recycling easy by design by 2030 (Segran 2020).

The current pandemic is expected to boost sustainable consumption behaviours, thus reinforcing the pressure on the industry to adopt more sustainable practices. Studies conducted over the past few months by the Boston Consulting Group (BGC), McKinsey & Company or the Institut Français de la Mode (IFM) all converge towards the same conclusion: if the consumer's current purchase behaviours aim stability – both in terms of frequency and amount spent, it would be critical for brands to stop their investment and commitment towards environmental and social sustainability. For the recovery, the environmental impact is expected to be at the forefront of customers' expectations and will be an increasingly important driver of

purchasing decisions in the long run (Martinez-Pardo, et al. 2020, Guinebault 2020, McKinsey and Global fashion agenda 2020).

Despite a recent awaking from fashion brands, current investments in sustainability solutions do not seem to counterbalance the negative impacts engendered by the speed of growth of the industry. The Pulse of the Fashion Industry 2019 report by BGC, the Global Fashion Agenda (GFA) and Sustainable Apparel Coalition (SAC) reveals that, despite slight improvement compared to 2018, companies' measurable progress decreased by a third between 2018 and 2019. With an industry expected to grow at 5% per annum until 2030, fashion risks to widen the gap between its 2030 objectives and the reality of its impacts. Consequently, the report calls for industry leaders to foster systemic change by putting more effort into overcoming technological and economic barriers for progress. Under the scope of circular economy, this means investing both in soft and hard tech solutions such as implementing new business models to keep garments in use – rental or second-hand systems, standalone innovation easily integrated into existing supply chains and complex technologies requiring intensive development. The development of new fibres and materials are integrated into these last two categories.

Relevance to the textile industry

Textiles are an inherent part of the fashion industry; production of raw material, spinning into fibres, weaving fabric and dyeing processes require tremendous amounts of water, energy and chemicals (Šajn 2019). The end-of-life of these fabrics also poses a problem: the Ellen MacArthur foundation estimates that less than 1% of all textiles are recycled into new textiles and that every second the equivalent of one garbage truck of garments is burned or landfilled (McCartney et MacArthur-Foundation 2017). The textile industry is growing in a highly competitive and fragmented market, with thousands of players located all around the world, Asia being its biggest producer (Mordor Intelligence 2019). Between 2018 and 2019, the global

fibre production increased from 107 to 111 million metric tons, of which less than 20% with a sustainability qualification (Truscott 2020).

The choice of fibre is one of the key contributors to the sustainability of the final fabric. They are divided into three main categories: natural fibres (plant-based or animal-based), synthetic fibres (petroleum-based: polyester, nylon, rayon…) and man-made cellulosic fibres (plant-based, usually come from tree pulp) (Appendix 4). As stated previously, over the past century the production of synthetic fibres has increased tremendously; from 3% in the 1960s, they represented in 2018 about 65% of the worldwide fibres production level (Business Wire 2018). Latest figures suggest that this trend is increasing with about 74% of worldwide textile fibre are synthetic fibres (Statista 2020). The ease and low cost of production are factors which drove this sharp increase of synthetic fibres.

As a direct consequence, the fashion industry is estimated to be responsible for half a million tons of microplastic ending up in the ocean every year: due to the washing of plastic-based textiles – e.g. polyester, nylon or acrylic (UNECE 2018). This issue is equally transposed to these fibres once recycled, as with every wash, microfibers still get washed away into the ocean. Furthermore, due to their petrochemical nature, they take a long time to decompose and can be hard to recycle (e.g. Nylon). However, synthetic materials are easy and cheaper to produce in big quantity, which explains their take over natural fibres during the last decades. Besides natural fibres are sometimes also pointed out for their negative environmental impact. The cultivation of natural fibres, due to intensive farming, monoculture and the use of pesticides, can be responsible for soil erosion, pollution and water contamination. The Higg Index, a self-assessment standard of environmental and social impact for fashion brands, classifies 7 out of the 10 worst textiles with the biggest impact as natural fibres while showcasing most of the best fabrics as being synthetic (Wicker 2020). However, this ranking requires from nuances; the Higg Index does to take into account in its assessment the recyclability of the fibre itself nor

does it include a factor about microfibres – due to a lack of widely accepted methodology for microfibres measurements (Higg.Index s.d.). Additionally, opposite to synthetic fibres, natural fibres come from a renewable source and usually support low-income rural farmers.

Nevertheless, these figures do point out to large improvement potential for natural fibres and highlight the issue related to the production of textiles used nowadays in the fashion industry, thus reinforcing the case for finding more sustainable materials.

III. Methodology:

The research project was organized and conducted in the following stages: 1. Determination of the objectives and scope of the research project, 2. Data search and collection: Literature review, online research and semi-structured interviews with relevant stakeholders, 3. Analysis of the obtained data, 4. Formulating conclusions.

Selection of databases and sources

The following literature databases were screened for information about the use of AFPR: Science Direct, Taylor & Francis and ResearchGate. The articles were screened based on recency (2000-2020) and a selection of keywords: “sustainable fibers / textiles”, “agricultural waste and fashion industry”, “sustainable fashion”, “fashion food waste”, “[name of by-product] fibre”, “sustainable fashion in [*name country*]”, “trends in sustainable fashion”.

Due to certain gaps, mainly due to the recency of AFPR-based fibres innovations, this information was completed with data from reports from trusted parties such as the Boston Consulting Group (BGC), McKinsey & Company, Food and Agricultural Organization (FAO) or the European Union (EU), as well as data collected from Non-Profits or Non-Governmental Organisations with expertise in the fashion & fibres sustainability field (e.g. Textile Exchange, Première Vision or Ellen MacArthur Foundation).

Refining the scope

Considering the time available and the answers received after preliminary contact, it was decided to focus the manufacturers' side and on the market opportunity for their materials. The selection of manufacturers was based on the following criteria: direct by-product from the food chain either at agricultural or food processing level, by-product traditionally undervalued and a potential source of pollution due to its destruction. In the search for innovative companies developing fibres and materials using AFP residues we thus excluded traditional uses of animal-based by-products such as cowhide, duck down and feathers, sheep wool and biobased synthetic fibres and yarn being created from plants and not its by-products. This also led us to leave out of scope vegetable dyes and tanning not using by-products from the food industry.

Interview realisation

A series of semi-structured interviews were conducted with 8 of 29 identified manufacturers. Each interview lasted between 30min and 1h with the aim to gain the following insights: Identification of new fibres and materials and their application in fashion, Exploration of the market potential, Identification of positive impacts and opportunities, Identification of limitations. To complement this data, 4 additional interviews were conducted with experts.

IV. Presentation of results

Fibres and materials from agricultural and food processing residues.

In order to better understand the market that AFPR can cover, the first need is to understand what are these materials, how can they be used by the fashion industry, who manufactures them and in which quantities can they be found.

Types and applications

As of 2020, six different types of AFPR fibres and materials have been identified (Appendix 5). Through the development of new technology and with scientific advancements, it is now possible to convert these waste streams into fibres or material which can, in turn, be transformed

into garments and accessories. These different types supply alternative fibres and materials with a wide variety of application to the leather goods and garment industry: clothes (outwear, sportswear…), buttons, bags, accessories (scarfs, belt), shoes, glasses... It highlights the possibility for AFPR fibres and materials to replace traditional ones for a great number of items.

Commercial availability

The development of these fibres started in the late 2000s, consequently, the number of manufacturers is still limited. Nevertheless, the past ten years have seen a strong increase in the number of players developing these materials and this trend is expected to continue growing as material awareness will grow, bringing new players to the market, but also as new technological advancements will enable to expand the number of waste streams used (Appendix 6).

As of 2020, a total of 28 manufacturers in 14 different countries were identified. Innovation is mostly driven by European firms with 18 manufacturers located in Europe. When it comes to operations Europe and Asia are the most represented continent, with 17 and 11 manufacturers respectively. Most of them innovate by making use of residues from the food processing industry and the greatest number of new AFPR fibres and materials innovation were conducted for leather and its alternatives (Appendix 7). This can be attributed to the raising concerns about animal welfare and the vegan movement, which have both pushed consumers to turn towards animal-free products. Other companies are working to develop new textiles and materials with waste from downstream stages of the food chain: S.café, Dyelicious, Biophilica make use of post-consumer waste to create fibre, dyes and leather respectively. Kaiku (dyes) and Fruitleather Rotterdam (alternative leather) operate at the distribution level by making use of food surplus, usually left to rot in the fields or refused by retailers as they do not correspond to traditional criteria (shape, calibre). The latter contribute to solving the issue of food waste, although in the circular economy all food surplus should first be redistributed for human

consumption. Nevertheless, if these companies are not analysed through the thesis' scope, their innovative use of downstream waste gives an insight into the many other existing possibilities.

Due to the recency of AFPR fibres and materials and lack of data, it is hard to estimate in which quantities most of these fibres and materials are present and used in the market today. However, it is possible to give an estimation of raw material availability, which can in turn provide a peek into the potential quantities available for fibre and material manufacture. Circular Systems, a material science company who has developed a natural fibre from crop residues, estimated that agricultural residues from hemp, banana tree, oilseed flax, rice straw, cane bagasse and pineapple leaves offered more than 250 million tons of fibre per year, which is equivalent to 2.5 times today's global fibre demand (Circular Systems s.d.). This number concerns solely fibre from specific agricultural residues: it does not capture the additional capacity from other agricultural residues nor food processing industry residues, which suggests that these waste streams have an even greater capacity. However, need is to remind that the possible quantity of material derived from waste also depends on the technology and processes developed by the manufacturer and that disclosure of this data is often marked as private in order to preserve competitive edge. Despite approximate knowledge of waste stream availability, this variable renders the estimation for potential coverage of new AFPR fibres and materials complicated. On the other hand, access to raw material is expected to be only limited by availability, as engaging in the selling of their agricultural or food processing residues provides the supplier with additional income while avoiding costs related to their destruction.

Is there a market for these fibres and materials?

If the creation of new products and services is powered by innovation, their economic viability is dependent on their adoption by the market. The analysis of market demand and readiness is hence essential to understand the potential for AFPR fibres and material development.

Brands

Fashion brands are under increasing pressure to integrate sustainability as a core pillar of their organizational strategy. As an inherent part of the fashion industry, textiles are building blocks of this sustainability shift. The commitment to more sustainable material is essential if the industry aims to reach its sustainability targets. As a matter of fact, 70% of the GHG emissions associated with the fashion industry come from upstream activities from raw material production to processing (McKinsey and Global fashion agenda 2020).

Brands are undertaking a shift to sustainability. In 2018, 89% of the brands participating in the Pulse of Fashion initiative declared that switching to more sustainable material was one of their key priority (Global Fashion Agenda 2018). To further support the transition to new fibres and materials, some big fashion groups such as H&M are C&A are investing through their foundation into the research and development of innovative fibres and material manufacturers. H&M's global change award has already supported companies such as Orange fibre, Circular Systems or Vegea (H&M foundation s.d.) while C&A's Laudes foundation has recently made a call for proposals on the viability of agricultural waste & residue as textile fibre feedstock (Laudes Foundation 2020). In practice, middle to upper range brands appeared to be the most common client of interviewed manufacturers, although lower appear to increasingly invest them as well. Names such as Hugo Boss or Salvator Ferragamo were cited, however, most of the brands ask for non-disclosure agreements which make it hard to identify them.

Through their "waste" nature, agricultural and food processing residues can directly contribute to the sustainability shift of brands. However, there are some barriers to the adoption of these new materials, which are discussed in the limitations of AFPR fibres and materials adoption.

Consumer

The awaking of consumers over the last decade, especially Gen Z and millennials, is driving sustainability in the fashion industry. McKinsey reports that 9 out 10 Gen Z consumer estimate

companies have a responsibility to address environmental and social issues (Amed, et al. 2019). Yet, if consumers are increasingly concerned with these issues, it appears that purchasing decisions are still led by non-sustainability related factors such as style, price, quality or size/fit (Kwok-pan, Huifeng et Woo 2019, Spinnova 2020). Research by Spinnova reveals that 49% of respondents (n=1572, Europe and USA) consider product feel and touch as a good indicator of the sustainability of a product which sheds light on the lack of education of consumers. However, market research conducted in Asia, the USA and Europe show that 30% of consumers consider the choice of material as a key consideration factor when making choices although little knowledge about material's impacts (Kwok-pan, Huifeng et Woo 2019, Spinnova 2020). Furthermore, the global pandemic is expected to have a direct impact on consumption behaviours. The IFM research suggests that consumers are going to put increased attention to materials' choice: 41,8% of participants (n=5000, Western Europe) declared that the choice of eco-friendly materials (recycled, organic, new fibres) was the most important factor driving their purchasing behaviour. Directly after eco-materials follows the importance of an environmentally-friendly production method (Guinebault 2020). The same study showed that 25% to 36% of respondents were willing to pay more for an eco-friendly item. Overall, research shows that consumers feel that COVID-19 could be the opportunity for fashion to rethink its industry: from sustainable sourcing, supply chain transparency to new business models and a stronger integration of circular economy principles (Martinez-Pardo, et al. 2020) (Guinebault 2020).

It is important to point out the differences between parts of the world. Most of the research found investigated fashion consumption behaviours in developed countries: Western Europe (France, Germany, Italy, UK, Northern Countries) and the United States of America. Attitudes towards sustainable fashion vary. For instance, in India, despite awareness about fashion environmental impacts, purchasing behaviours are mostly powered by lifestyle and engagement

in ethical and sustainable purchase is low (Rathinamoorthy 2019). Chinese consumers, on the other hand, are slowly turning towards sustainable fashion with research revealing that consumers are increasingly on the lookout for sustainable products. Nevertheless, this recent trend seems to be dominated by the aesthetic of sustainability rather than the environmental impact of the garment (Smith 2019).

Market analysis at a consumer-level reveals that the shift for sustainable fashion consumption is dominated by developed countries although Chinese consumers seem to be catching up on this trend. Strong stances on environmental issues generate a great potential for the adoption of sustainable fibres and materials. Nonetheless, some barriers still need to be overcome such as price and education towards what are sustainable fibres and materials.

Agricultural and food processing residues: what opportunities?

The great quantities in which agricultural and food processing residues are available not does only highlights the issue of waste associated to food systems but also reveals untapped streams which can be used as inputs for the textile for the fashion industry. In this part, we seek to highlight their potential benefits by identifying which problems do they contribute to solving and what additional benefits can they have. Few manufacturers have impact measurement, such as Life Cycle Analysis (LCA), in place, however, it was possible through interviews and online research to seize potential impacts expected from these materials.

What problems do they solve?

The impacts on the environment from the food and textile industries are many. Major impacts from the underutilization of residues from the food industry are related to their disposal: direct harmful effects are indeed associated with burning, dumping or sending this waste to landfills. These effects include methane and other gas emissions, wasted land space, pollution of soil, of surface water and groundwater (European Environment Agency 2013). The textile industry on the other hand is considered responsible for air and water pollution and intensive land use and

soil depletion. More specific to the leather industry, two main issues are pointed out: water pollution due to tanning processes and environmental costs of cattle farming. When crossed, we identify a few knots that the valorisation of AFP could help to sort out.

Air

With a combined 40% of CO2 emissions worldwide, the fashion and agriculture industry greatly contribute to air pollution which can be harmful not only for the environment but also for individuals. Through the reduction of residues sent to landfills or burnt, AFPR-based fibres and materials help to reduce CO2 emissions. A lifecycle assessment performed for Frumat, alternative semi-synthetic leather made out of apple peel waste, certified that their use of agro-food residues and green energy directly contribute to a 20%-25% reduction of CO2 emissions compared to traditional leather (Zargani 2020). Similarly, the life-cycle analysis of Green Whisper, who manufactures fibres and yarn out of banana stems, reduces by two the need for cotton in its final material which in turn decreases by three the amount of energy needed and halves the amount of CO2 emitted compared to the same amount of regular cotton yarn.

Water

Water is one of today's most precious resources and the effects of climate change are making it increasingly scarce. The World-Wide Fund for Nature (WWF) forecasts that by 2025, two-third of the population may face water shortage (WWF s.d.). Both the food and textile industries are very water demanding but they also directly contribute to the pollution of freshwaters; especially, due to their reliance on pesticides and chemicals throughout the different processes.

AFPRs provide a great alternative to reduce this reliance on chemicals for the fashion industry, for instance, as natural dyes. Dyes majorly contribute to fashion's negative impact: billion litres of waters are used every year for fabric dyeing, of which three quarters end up as non-drinkable water due to the release of toxic agents (Cole 2019). Through the use of agricultural residues, dyeing companies reduce the need for chemical agents in their dyeing process. Colorifix

completely replaced chemicals with agricultural by-products and manages to reduce by 10 the quantities of water and by 20% the energy use required in their dyeing process (Cole 2019). There are other applications for AFP residues to alleviate the need for chemicals, especially in the leather industry: in the tanning process. As of today, 90% of leather is chrome-tanned. This method has great negative consequences on the environment especially due to highly toxic wastewaters which are left untreated and thrown out in rivers (Pinnock 2019). Olivenleder, thanks to its wet green® tanning agent, is able to bring to the market a vegetable-tanned leather with minimal impact on the environment. The tanning agent is composed of solely 1 ingredient, a by-product from the olive industry: the leaves. The agent is also free of chemically synthetic reactive agent or metal (chrome-free process). Combined to its specific tanning process, the leather from Olivenleder significantly reduces the need for water and re-tanning agents compared to other chrome-free and vegetable tanning alternatives (Olivenleder 2020).

Furthermore, AFPR-based fibres and materials provide an alternative for the fashion industry free from microplastic release as opposed to other recycled textiles present on the market. For instance, Pinatex, with its 72% bio-based alternative leather from pineapple leaves, reduces greatly the amount of plastic in its final material while offering an animal-free product.

Soil depletion / Land pressures

Agriculture at large represents 50% of habitable land used. The intensified competition for land resulting from expected population growth highlights the urgent need for better land utilisation. As of today, pesticides contribute to the depletion of soils and cattle raising, whose by-products are used for leather, are very much land-intensive – 77% of habitable land is used for livestock raising and feeding. Natural fibres require dedicated crops which could be put to other uses.

Natural plant-based fibres and man-made cellulosic fibres (MMCF) are traditionally both derived from natural virgin resources, usually cotton and wood pulp, which are either reliant on dedicated crops or forests. Besides, both their productions raise environmental questions due to

their sourcing: cotton is known to use vast amounts of water and pesticides while MMCF are pointed out for their connection to deforestation and toxic chemical uses. If the recycling and sustainable sourcing of both fibres are on the rise, agricultural and food processing residues also offer an alternative which copes with these issues. First, by using residues, the need for dedicated land is deleted. Man-made cellulosic fibres from waste streams, such as citrus by-products or discarded milk, thus alleviates the pressure on forests. By making use of existing by-products from the food industry, they also reduce the need for dedicated land, energy and water used to grow virgin resources. With regards to leather, the environmental cost of cattle farming is one of the major problems pointed out. As a matter of fact, a 2009 report by Greenpeace concluded that the Amazon deforestation was fuelled by leather demand, as farmers burn the forest to make space for feedstock (Siegle 2019). Additionally, images about intensive cattle farming rose ethical questions with regards to animal welfare. Through the diversification of raw material, alternative leathers contribute to the reduction of the costs associated with cattle farming. Fish leather, which today represents less than 1% of the global leather production, allows to increase the livelihood of fish farmers while being less resource-intensive than cattle farming when ethically sourced. The vegan movement, concerned with animal welfare, is pushing for the development of animal-free leather; traditionally synthetic leather. Yet the latter does not offer a sustainable alternative due to its petrol composition. Partially plant-based leather such as Vegea, Pinatex, Fiscatech or Frumat supply the market with vegan alternatives to traditional synthetic leather and with a lower reliance on PU and PVC. Composed of 20% up to 70% of agricultural or food processing residues, these materials provide alternative options to consumers in search of animal-free products. As AFPR do not require more land use nor to cultivate plants that could be else used as food (which is often the case for natural dyes and vegetable tanning options), they present a great option for reducing pressure on land and non-renewable resources.

Additional impacts

Social and economic impacts

By valorising agricultural residues into high-value products, suppliers benefit from a dual positive impact: first, they benefit from a larger income and second, they avoid costs associated with their disposal. For instance, Kenya's fish leather company Victorians Food stated that fishermen now earn 30% more for each fish sold (Timmins 2019). Several manufacturers interviewed stated that fair wage and working conditions are fundamental pillars of their model.

By making use of existing waste streams from one industry as inputs for another, AFPR-based fibres and materials directly contribute to a thriving circular economy. The range of activities associated with their manufacture creates value throughout the two value chains: designing waste out of the food system while making clothes from safe and renewable inputs. Besides, the use of existing and unavoidable inputs from another industry allows to reduce the pressure on land availability, thus leaving more space for other economic generating activities. Income-generating activities associated to valorising usual waste streams, discarded and left to rot, are expected to offer job opportunities which were non-existing before.

Limitations to AFPR-based fibres and materials

The analysis of the opportunities brought by agricultural and food processing residues-based fibres and materials highlights great potential to reduce the impact of the fashion industry. On paper, brands and consumers show an increasing interest in these innovative materials. However, interviews and market analysis revealed that some barriers to adoption remain.

Material availability, quality and integration

Adopting a new raw material has several implications for brands: they need to make sure that quality delivered meets expected standards and is consistent, that the raw material can easily be integrated into existing processes and, when at scale, that the manufacturer can deliver a sufficient amount of material. These factors can create barriers to adoption from brands.

The innovative nature of agri-food residues-based textiles can lead to quality instability partly due to variation in the quality of raw material, especially when working with agricultural residues. To cope with this instability, some brands have developed a multi-supplier approach: collecting raw material from different regions and blending them all together to obtain overall stability in product manufacture. The overall performance of the final material also depends on the development stage of the material; a lot of investment is needed to push their development and performance. As stated previously, most of the innovations in textiles and material using agricultural and food processing residues occurred over the last decade, thus the majority of companies identified are still either in the pilot or acceleration stages (n=24) which implies that production quantities are limited. Through the interviews, it was possible to determine that some innovations are easier to scale as demand grows than others; the higher asset intensity and complexity, the longer to achieve development and commercial scale. Bio-based dyes, vegetable tanning or bioplastics have lower asset intensity and complexity, which make them easier to integrate into existing processes and bring to scale, while biobased fibres and yarns as well as alternative leather (fish-based and bio-sourced) fall onto the higher levels of asset intensity and complexity.

Large brands, benefit from strong R&D and bigger budgets which allow them to invest in innovation. Yet, the lack of knowledge of material functionalities and related uncertainty in terms of material integration into processes, quality stability as well as market reaction can negatively impact the material adoption. Additionally, big established brands require a large amount of textile supply to meet their demand, thus require from manufacturer large capacity. Despite large raw material availability, the current supply of sustainable textiles and materials from agri-food residues does not meet this demand. This can lead for brands just to create capsule collections but then be limited in further development. Young brands are less sensitive to the aforementioned points, as they integrate these new materials from the start into their

processes and require smaller quantities. However, they are equally concerned with quality stability and are more sensitive to the price of raw material.

Paradoxically, manufacturers need investments from brands so as to unlock their full capacity and reach commercial-scale; as a matter of fact, a lot of investment is needed to develop and perfect the fibre, yarn or material delivered to the market, and unless pushed from scale to industrial capacity, the development is hard to complete and the material performance lacks consistency. Overall, an estimated 20 to 30 billion US dollars is required to mobilise the scaling of technological innovation within the fashion industry (FFG & BCG 2020). To cope with this paradox, Robert Nicoll, co-founder of Chip[s]board, highlighted the need for “brave” brands, that is, brands which are taking this investment risk and working collaboratively with manufacturers to support their development for commercial scale.

Price

When asked about their current challenges, half of the manufacturers interviewed stated that education with regards to price was one of their challenges. Brands are interested in the materials yet want to keep the price either equivalent or cheaper than traditional fabrics, which makes it hard for these new players to compete. Some brands expect the price to be lower due to the "waste" nature of raw material, failing to take into account the processes, R&D and social commitments behind these raw materials. As a matter of fact, most of the manufacturers embrace the principles of circular economy, thus go beyond the sole waste valorisation purpose and aim to increase the livelihood of their whole ecosystem through fair wage and working conditions. The impact of COVID-19 is expected to have a direct impact on brands which will be focused on stability, thus reduce investments into new technologies over the upcoming couple of years. This could, in turn, slow down the technological development of new materials.

Besides, if consumers are turning back to natural fibres, the study performed by IFM and Première Vision which revealed that 25% to 36% of consumers were willing to pay more for

an eco-friendly item, implies that 64% to 75% are not. As Europe is one of the leading continents in terms of appeal for sustainable fashion, this figure is significative of the importance given to price. Additionally, research from KPMG highlighted the importance of price/quality ratio and style which entails that performance and looks of AFPR-based garments need to meet the market expectation. With increased initial costs of fabric and materials for brands, the final products' price for the consumer is also expected to increase which could create some resistance on the consumer's side.

Education

Overall, consumer market analysis showed that there are a growing concern and engagement from consumers with regards to materials present in their garments. Nonetheless, knowledge about sustainable fibres and materials appears to be relatively low: a study conducted in 2019 (n=5000, Western Europe and USA) highlights the lack of knowledge of consumers in terms of eco-materials: natural materials were majorly considered as the most sustainable fibres, even though some of these fibres have a negative impact on the environment. The same research also revealed that most of the respondent stated they never bought sustainable fashion items due to lack of knowledge about these products, and overall, 75% of respondents didn't feel they had enough information about sustainable fashion in general (IFM & Première Vision 2019). In-depth work needs to be performed to educate about sustainable fibres and materials and raise awareness about existing solutions on the market.

With an increasing number of sustainable fibres on the market (organic cotton, organic linen…), AFPR-based manufacturers also need to educate brands about the different properties and impact of their material. This is especially true due to the competitiveness level of traditional materials but also to better knowledge about "traditional" sustainable fibres such as organic cotton, which require less intensive investment as they do not represent new materials rather traditional fibres grown in better conditions. The lack of knowledge from brands is driven by

another key barrier for adoption: the lack of available data about AFPR-based fibres and materials environmental, social and economic impact.

Lack of available data

Today, most products sustainability is assessed through its life-cycle analysis (LCA). LCA is recognized as one of the most robust tools to provide insights for the system to accelerate towards more sustainable consumption and production patterns (UNEP 2016). However, available data about AFPR fibre and material development is still scarce. Out of the 8 manufacturers interviewed, only two had a LCA in place, of which the results of only one is made accessible upon request. Three others have in their plans to perform it in the future and another is currently developing it. Various reports on sustainable fibres concur with the lack of data as an impediment for sustainable fibres and materials development. As a matter of fact, need is to ensure that the whole transformation process is environmentally sound so that the benefits of using waste as an input is not counterbalanced by negative production impacts or generates issues in a different industry. In other words, it is capital to make sure that the positive change is systemic and does not create another problem somewhere else.

If we assume that most of the manufacturers start with a negative footprint since residues used are traditionally discarded, a set of other factors need to be considered: energy efficiency, water and chemical use, by-products generation, waste management efficiency or end-of-life management. To claim their sustainability, it is capital for manufacturers to perform LCA and to communicate their results transparently. Else, these claims can be questioned and it is feared that these new fibres and materials might be overlooked and undervalued compared to already established ones for which environmental impact data is made available (Sandin, et al. 2019). An additional important point within LCA is the longevity of the fibre and material: the longer its lifespan, the more reduced its impact on the environment. Consequently, material

performance is here again considered as a key element for wider AFP fibres and material adoption.

V. Conclusion, discussion and limitations to the thesis

Overall, agricultural and food processing residues as fibres or materials indicates a great potential to address the issue of food loss in the food industry while contributing to solving the problem of textiles raised by the fashion industry. Entering into a circular system, they directly contribute to shifting perceptions, transforming a traditional source of waste into a valuable resource. The few lifecycle analysis performed on these innovative textiles already point out towards positive impacts in terms of CO2 emissions, water and energy consumption. The increased livelihood of farmers through the valorisation of their waste and economic activities generated supports the fact that these fibres and material are not only environmentally sensitive but also socially and economically. The market assessment revealed that demand exists and is currently growing, mostly throughout Europe but also in China.

However, as of today, some limitations hinder the unlocking of their full potential. The lack of available data to assess lifecycle impact appears to be one of the most critical limitations as it leads to greater uncertainty for brands. Another key factor also relates to the uncertainty of adopting a new material, reliant on hard technological development, and their integration into existing processes of established big brands. This is capital as the latter are the ones which have the greatest financial capacity of investing into the scaling and improvement of AFPR fibres and material. Ultimately, greater production capacity and budget will drive the development of LCAs and help to lift the veil onto the entire environmental impact of AFPR-based fibres and materials. Final consumers will be essential contributors to the latter's development. By driving demand, they will push brands to offer more alternatives to current materials.

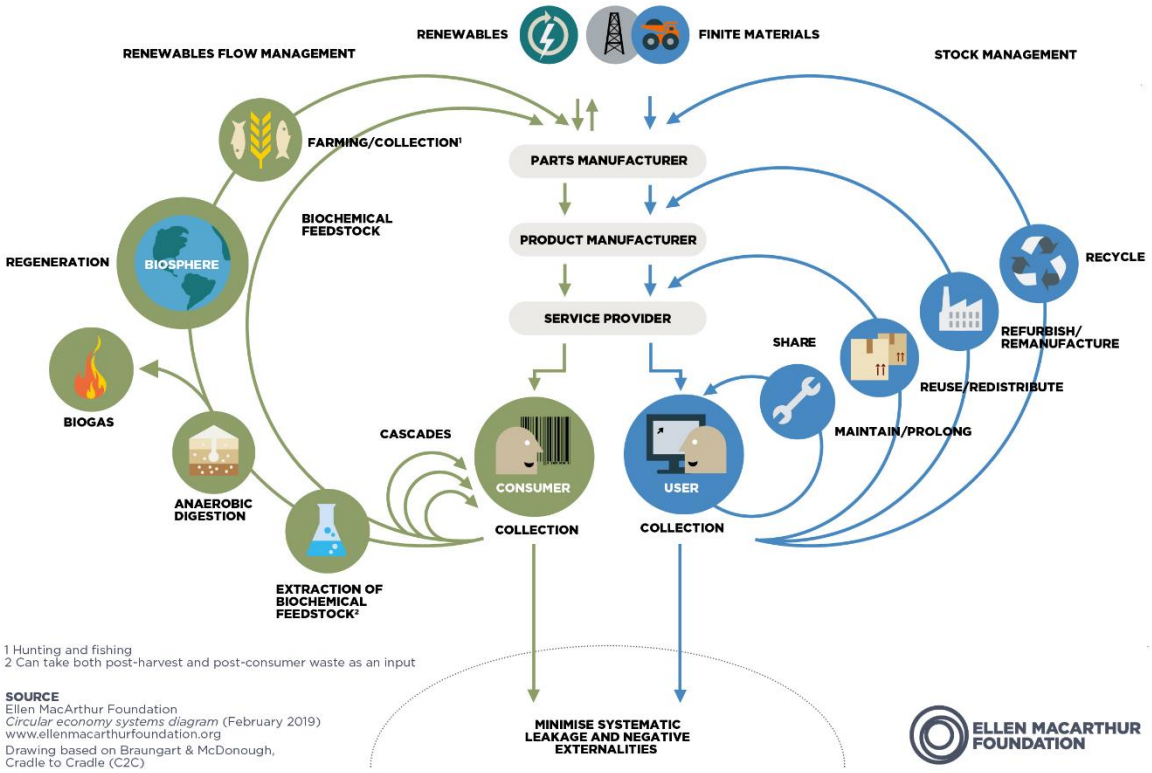
To unlock full potential, two key pillars have been identified: investments and education. For the market to firmly endorse these innovations, education is key and applies both for brands and consumers. Sustainable fashion desperately needs to be more known and understood if more individuals are to embrace it. With increased awareness and understanding of materials' impact, consumers hold all the cards to make better and educated choices when choosing their garments. Better knowledge with regards to material properties and integration will enable brands to reduce uncertainty related to the adoption of these new materials. With this market push, investments, which are necessary for materials to reach full scale and performance, are expected to naturally take place.

In conclusion, through their application to the textile industry, agricultural and food processing residues have the potential to directly contribute to reducing environmental impacts related to food and fashion industries, while creating value for society. Consequently, it is expected that these new fibres will increasingly replace traditional ones. However, the lack of perspective that the recency of these fibres entails and the little knowledge about sustainable fashion on the consumer side are considered to be the biggest impediments for their development.

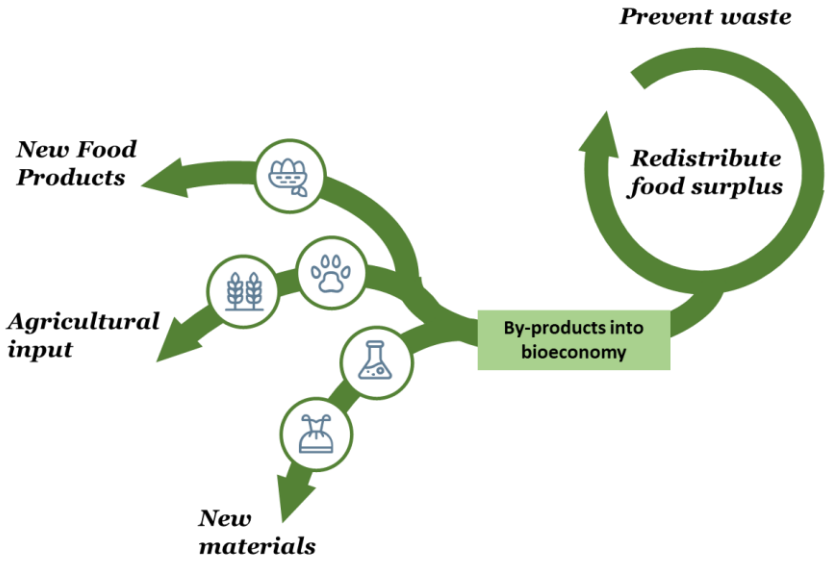
The outcome of the thesis was mostly limited by the availability of information as only 8 interviews were conducted and the recency of AFPR-based fibres and materials involves a lot of secrecy about the material and market demand. Additionally, as very few pieces of research had been done on these specific fibres and material, the information needed to be completed with articles. Nevertheless, the preliminary results provided by this thesis point out that the investigated fibres present significant business potential, set within the principles of circular economy. On the supply side, further scientific research needs to be conducted on the impact and technicalities of such fibres and materials while the demand side's research should investigate the gaps in consumer's knowledge about sustainable fashion, how to fill them and willingness to pay for clothes made out of agro-food residues.

Appendixes

Appendix 1: Circular Economy System Diagram by EMF



Appendix 2: Food by-products use in a circular food system. Inspired by Ellen MacArthur Foundation illustration



Appendix 3: Types and examples of by-products generated by the agricultural and food processing industries

Type of by-products	Examples
Plant-based	coconut (leaves, husk, water), corn (leaves and stalk), nuts (hull), rice (straw, stalks), sugarcane (leaves), coffee (hull and ground) and other vegetable and fruit waste (peel, pomace, kernel, overripe)
Animal-based	Cow (hide, manure, milk), sheep (wool), rabbits (skin, fur), duck and geese (down and feathers), fish (skin, head), mollusc (shell)

Appendix 4: Types and examples of traditional fibres

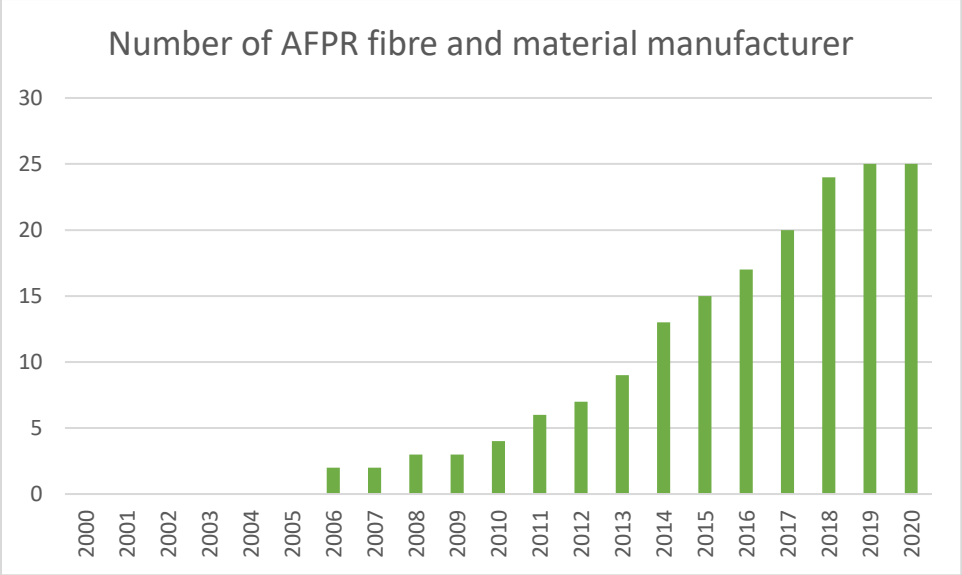
Natural fibres & material	Plant-based	Cotton, linen, hemp, jute, coir (coconut), flax
	Animal-based	Wool, silk, leather, down & feathers
Synthetic fibres (petroleum-based)		Polyester, polyamide
Man-made cellulosic fibres (wood-based)		Viscose, acetate, lyocell

Appendix 5: The different fibre and material types made from AFPR

Natural fibres	Natural fibres are hairlike raw materials derived from an animal or a plant which, once spun into yarn, can be converted into woven fabric. AFPR natural fibres include but are not limited to fibres derived from banana stems, rice straw and cane bagasse.
Man-Made cellulosic fibres (MMCF)	MMCF are fibres made with chemical compounds of the cellulose polymer. The fibres are traditionally derivatives of wood pulp but can also be derivatives of natural plant materials. AFPR MMCF derive cellulose out of the following sources: citrus industry, liquid industry, cow manure and dairy industry.
Leather & Alternatives	Leather is a material made from the skin of an animal through tanning; traditionally cowhides. Tanning process consists in turning the skin into leather by using tannin; usually chemicals. Natural tannins can be found in fruits and vegetables but they do not come as a by-product from agriculture and food processing industries. Yet, exceptions can be made e.g., tanning method with olive tree leaves. AFPR-based alternative to traditional leather includes: fish leather and biobased synthetic leather (a mix between residues and PU or PVC).
Dyes	Dyes are synthetic or natural substances used to colour yarn and fabric. Dyes made of residues from the agricultural and food processing level include: beetroot and almond shells.

Bioplastics	Bioplastics are plastics that can be either bio-sourced, biodegradable or both. Bio-sourced means they come from biomass while biodegradable stands for the fact that the material can be decomposed by microorganisms. Biodegradable bioplastics can come from fossil resources. AFPR bioplastic includes: potato peel.
Rubber	Rubber is an elastic polymeric substance made from the latex of a natural plant or made synthetically. AFPR-based rubber includes: oyster shells.

Appendix 6: Total number of manufacturers using AFP residues to create textile and materials per year.



To ease graph reading, the timeframe covers the last 20 years, however, one company, Atlantic leather, was created in 1994.

Appendix 7: Manufacturers' names based on fibre and material type and level of the food chain

	Agricultural residues	**Food Processing residues**
Natural Fibre	Circular Systems; Anandi Enterprises, Anis Enterprise, Essence Fibre, Green Whisper.	
Man-Made cellulosic fibres (MMCF)	Inspidere's Mestic®	Nanollose, Orange Fiber; QMilk, Duedilatte.
Leather & Alternatives	Pinatex, Fiscatech, Natural Fibre Welding; Wet green® OBE.	Ictyos, Atlantic Leather, Nanai, Nova Kaeru;

		Apple Peel Skin, Malai, Vegea, Frumat.
Dyes		Archroma, Food Textile Lab by Toyoshima, Colorifix;
Bioplastics		Chip[s]board
Rubber		Sooruz

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