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SUSTAINABLE FIBRES FOR TEXTILE INDUSTRY

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Abstract **–** Sustainable fibers are at the forefront of a global shift towards more environmentally conscious and responsible practices within the textile and fashion industries. These fibers are sourced and produced with the goal of minimizing their ecological impact, conserving resources, and promoting ethical labor practices. Sustainable fibres are generally examined in three categories; Natural fibers with high biodegradability, regenerated fibers such as Tencel and Modal and finally recyled fibers such as recycled pet and recycled poliamid which are derived from post-consumer waste reducing the need for virgin materials. This study has been conducted in order to give a brief summarization about the latest sustainable textile fibres and their advantages with the manner of sustainable textile production. Some textile companies that has just newly developed their branded sustainable fibre were also mentioned within the study to give special examples.

Keywords – Sustainable Textile, Natural Fibres, Regenerated Fibres, Recycled Fibres

I. INTRODUCTION

Sustainability has emerged as a paramount consideration in the textile industry, primarily due to its substantial energy consumption throughout the production process. The textile and clothing sector, with its intricate and extensive supply chain encompassing fibre formation, yarn production, fabric manufacturing, and apparel creation, is now firmly focused on advancing sustainability as a top priority.

Sustainability is becoming a prerequisite to the future of the fashion industry. A sustainable vision of the fashion industry relies on fibre, material and product-based innovations. Sustainable fibres not only contribute to solving the environmental burden, but also are becoming a new trend in the fashion market. Moreover, the focus of the fashion industry today is moving beyond the design aspects of products into functional and therapeutic features. While the term "sustainable fibre" still accentuates organic cotton or recycled polyester, most other innovations addressing sustainability together with desirable features are stuck in the niche. The journey towards sustainable fibers is seemingly challenging with many failures. However, exciting innovations are emerging fast, challenging the traditional ways of producing fibres. One such way is emulating nature (biomimicking) in fibre-to-fabric production. Biomimicking research in textile production is a rapidly growing area and its true potential in the development of entirely sustainable fibres has yet to be discovered through interdisciplinary research with an understanding of the holistic approach of nature in its formation of organisms. Nature provides excellent examples of complex functional systems, which are created through entirely sustainable processes. Most importantly, those natural systems leave no trace of waste at the end of their lives. Keeping nature's way in mind, this chapter pushes the concept of design to compost to address the challenges facing sustainable fashion [1,2].

The notion of sustainability holds universal significance across all industrial sectors, including the textiles and clothing industry, where it stands as a pivotal agenda. This industry, characterized by an extensive supply chain encompassing fibre formation, all the way through apparel production, comprises a series of interconnected stages. In the lifecycle of textile products, this protracted supply chain constitutes approximately half of the journey, leaving the remaining responsibility to consumers during the utilization and disposal phases. Consequently, it becomes imperative to assess and implement sustainability measures throughout this intricate supply chain, spanning every stage of a textile product's lifecycle.

II. ENVIRONMENTAL IMPACTS OF THE TEXTİLE INDUSTRY AND ITS ASSESSMENT THROUGH LİFE CYCLE ASSESSMENT

The textile industry has been cited as the most ecologically harmful industry in the world, whilst an argument said that water pollution is a major issue in China and that its textile industry, a large water user, has traditionally experienced wastewater problems. In some cases, wastewaters are discharged (largely untreated) into groundwater with extreme pH values and temperatures as well as high chemical loading. The following areas have the potential to make the life cycles of textiles and clothing unsustainable.

1. Use of toxic chemicals
2. Consumption of water
3. Consumption of energy
4. Generation of waste
5. Air emissions
6. Transportation
7. Packing materials

About 25 % of the global production of chemicals is used in the textile industry globally. As many as 2000 different chemicals are used in textile processing, especially in textile wet processing, and many of these are known to be harmful to human (and animal) health. Some of these chemicals evaporate, some are dissolved in treatment water which is discharged into the environment, and some are retained in the fabric. A list of the most commonly used chemicals, some of which are involved in fabric production, and linked to human health problems varying from annoying to profound, have been published by the National Institute for Environmental Health Sciences (part of the US Department of Health and Human Services)

Water ways such as rivers and lakes supply communities with vital resources, including drinking water, water for crop irrigation, and foods such as fish and shellfish. These waterways also serve as a support system for industrial activity, providing water for many manufacturing and cooling processes. However, such industrial activities can affect water quality and thereby jeopardise the other resources which rivers and lakes provide. Globally, water resources are being degraded by the increasing pressure of human activities. The textile and related industries are considered by some to be the second highest consumer and polluter of clean water next to agriculture. The textile services sector is an essential adjunct to the textile industry and is needed to manufacture, finish, market, and distribute the products. Water is used in various steps during the textile dyeing process both to convey the chemicals used during the step and to wash them out before the beginning of the next step [3].

More than six billion people inhabit our planet today (as of 2016) and they produce millions of tons of waste each day. It is almost unimaginable that textile waste is forecast to be the fastest growing waste category between 2005 and 2020. Most textile waste requires years to decay and takes up significant land space, directly threatening the wellbeing of organisms on the planet. Recently, the invention of fast-response systems promoting overabundance and disposability as well as increasing the demand for fast fashion has made the situation much worse. Consumers have started purchasing fashion clothing and throwing them away at a profligate rate and waste has accumulated. Most waste ends up in landfills without any kind of treatment. These materials hold compounds that release toxic chemicals or take unpredictably long times to break down. Only a fraction, a very small percentage, is recycled or remanufactured, although that is insufficient to offset the damage being done to the environment by the textile and fashion industry [4].

Fibre is the basic element of textiles. In nature, fibers are found in many forms: from nanoscale silk fibres produced in the cribellar glands of spiders to micro-scale cellulose fibers in wood. Most of these fibres fulfil a multitude of elementary functions of respective lifeforms. A closer look at the natural fibres found in animals and plants reveals that they are made up of polypeptides (proteins) and polysaccharides (cellulose and chitin) which are biodegradable making it easier for the lifecycles of these organisms to end up leaving no undesirable trace. However, the question is whether we take the maximum benefit of these properties into our textiles. The availability of a variety of natural and synthetic fibres today often leads to using fibre blends in the production of textiles. Moreover, some other functional properties are added to the textiles by mixing and coating many different materials. As a result the original identity of the fibre is hidden or lost in the process, which makes the product impossible or very difficult to recycle or compost [5].

Plants and trees also provide other excellent examples of bio-inspired fibrous structures. For example, Lenpur is a sustainable fibre introduced to the textile market with design to compost in mind. This fibre is made from white pine tree clippings. Only certain parts of the tree are collected in the clipping stage to produce a wood pulp, which is then treated in a rayon process to create Lenpur fibre. The fabric imparts excellent comfort and hand (feel) properties due to its softness, its absorption capacity and ability to release moisture (due to fibre morphology). Laboratory tests have shown that the absorption capacity of Lenpur fibre is 35 % higher than that of cotton and almost double that of viscose. Further, the fibre's ability to sustain a higher thermal range gives it an advantage over other cellulosic fibres as it keeps the wearer cooler in the summer and warmer in the winter. Lenpur fabric is used for performance garments and undergarments due to its exceptional human-friendly properties [6].

Polyester and other synthetic fibres have a lower water consumption during production compared to cotton. However, the energy demands involved in manufacturing synthetic fibres result in a higher carbon footprint. The main concerns with synthetic fibres revolve around their reliance on non-renewable resources and their non-biodegradability. Cotton and polyester currently dominate the industry, while emerging natural fibres like hemp, jute, and banana face difficulties in gaining market access. As the global population increases and oil prices fluctuate, it becomes challenging to meet fibre demand without causing further environmental harm. Nevertheless, finding alternative sources for fibre production is a genuine challenge. A growing trend is the production of compostable fibres, as using environmentally friendly fibres can significantly reduce the environmental impact of the textile and fashion industry. The fibre and yarn sector is an integral part of the textile and garment industries. To stay competitive, these industries are striving for continuous improvement and therefore are constantly looking for innovative solutions to meet the changing demands and industry standards. These standards are geared mainly towards sustainable solutions such as recycling, waste reduction, production efficiency and closed-loop production. With increasing involvement from governments, these standards now are becoming crucial for trade and businesses.

It is obvious that sustainability is a rising concern of brands, equipment and fabric manufacturers, and consumers. The industry is still very recycled-centric, which is clearly not enough. There has been a greater push for water savings, durability and waste management, as well as reduced emissions, water pollution, and carbon footprint [7,8].

III. SUSTAINABLE SOLUTIONS FOR TEXTILE INDUSTRY

The textile industry is one of the largest contributors to harmful environmental effects. According to the UN Partnership on Sustainable Fashion, it is responsible for approximately 10 percent of greenhouse gas emissions and 20 percent of wastewater production globally. As a result, the need for textile companies to alter their approach to manufacturing and production is drastically increasing. Across the board, companies are developing fibres and yarns as innovative solutions to address the need for more sustainable systems. There are two major sustainability initiatives exhibited by various companies — circular fashion and closed loop systems [9].

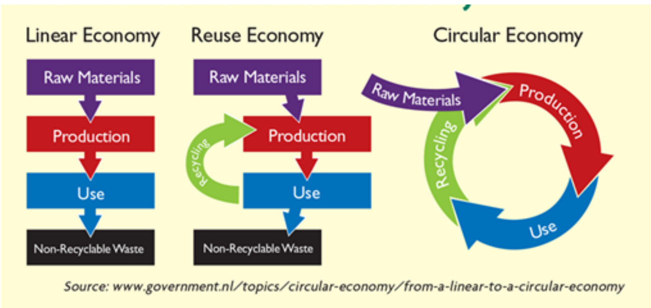

Fig. 1 From a linear to circular economy [10]

Circular Economy

The contemporary textile industry adheres to a linear economic framework characterized by a brief lifecycle: sourcing, production, and eventual disposal of textiles. Despite its speed, this economic structure proves highly ineffective, unsustainable, and harmful to the environment. Recently, the concept of the reuse economy has garnered significant attention as a response to this predicament. This approach enhances the linear process by repeatedly utilizing textiles. Nevertheless, this cycle eventually terminates when the item can no longer be repurposed or recycled, leading it to the land fill, mirroring the fate within a linear economy. This model of economy is termed a circular economy or circular fashion, an approach that not only extends a product's lifespan but also safeguards the environment concurrently. Within a circular fashion industry, all facets of the production process are oriented towards circularity, ethics, and overall environmental friendliness and sustainability. This entails recycling materials, employing biodegradable solutions, sourcing raw materials in an ethical manner, and adopting more efficient manufacturing and production methods [11].

Some companies underscored their commitment to circular fashion through the presentation of their initiatives, highlighting streamlined manufacturing and production approaches. These encompassed diminished emissions, waste, water usage, chemicals, and energy consumption. Simultaneously, they endeavored to identify methods for the biodegradation of post-consumer materials, with the aim of achieving a comprehensive closure of the loop.

There are some examples of these companies below mentioned:

Switzerland-based "Archroma" provides "safe, efficient, and enhanced textile chemical solutions, accordingto the company. Its chemicals are bluesign approved, GOTS certified, biobased, perfluorinated chemical (PFC) free, formaldehyde free and metal free. DBT Fibre, headquartered in Italy, championed sustainability in both its long and short staple spinning processes, driven by its commitment to enhancing environmental and social outcomes within a circular economy framework. Within its sustainable business model, the company's Eco Fiber Green Action Solutions initiative stood out. This involved the implementation of a photovoltaic system with a capacity exceeding 650 kilo Watts. This installation not only generates considerable carbon dioxide (CO_2) emission savings but also equates to a reduction of approximately 390 tons per year. Switzerland-based Clariant International Ltd. demonstrated its sustainability initiatives by introducing dope-dyed yarns that use 98-percent less energy and 99.9-percent less water compared to package-dyed yarns. In addition, the Clariant introduced new functional additive masterbatches such including fluorine-free hydrophobic and anti-soil masterbatches for polyester. Addressing the imperative for heightened environmental consciousness, Nylstar S.L., headquartered in Spain, presented its NATEO Sustainability Program. This program centers on endeavors aimed at achieving zero water pollution, fostering water conservation, and promoting recycling initiatives, all within the ambit of its Meryl® nylon brand. The Meryl NATEO nylon yarns not only offer an eco-conscious substitute for cotton but also provide solutions for recycling pathways. Meryl EcoDye yarns are dyed using a dope-dyeing method in which the color is added to the polymer dope before extrusion. This method provides excellent color fastness and colour take-up while eliminating the need for water during the dyeing process, according to the company. Beaulieu International Group, Belgium, introduced its Ultra Bond staple fiber that doesn't require latex or other binders when used in nonwoven applications. This product allows for a significant decrease in water consumption which results in a 93-percent reduction in energy use and reduces CO_2 emissions by more than 35 percent without the addition of any other agent.

Closed Loop Production

According to the latest data released by the U.S. Environmental Protection Agency (EPA), the United States witnessed the generation of 16.9 million tons of textiles in 2017. Regrettably, among this, a substantial 11.2 million tons of textile waste was disposed of in landfills, while a mere 2.6 tons underwent recycling. This waste not only exerts adverse effects on terrestrial environments but also plays a pivotal role in the proliferation of human-generated ocean pollution. Distressingly, the oceans are burdened with over 8 million metric tons of plastic waste each year. There are good examples of brands representing the closed loop production method. Seaqual™, a fiber from Spain-based Textil Santanderina S.A., stands out it its mission to reduce the amount of waste currently in the ocean and to reduce more waste from entering the ocean. Seaqual is a100-percent recycled marine plastic fiber, and the company partners with local fishermen to help collect the waste to produce the fiber. Textil Santanderina reports that for every kg of Seaqual fiber created, it removes 1 kg of trash from the ocean. Presenting a pioneering recycling innovation at ITMA, Infinited Fiber Co., headquartered in Finland, introduced a groundbreaking solution encompassing not only pre- and post-consumer textile waste but also incorporating cardboard scraps and agricultural residues. This ingenious process involves segregating the waste materials, converting them into liquid form, and subsequently spinning them into high-performance fibers. Remarkably, this approach empowers the company to curtail water consumption by 20,000 liters per kilogram of cotton and significantly diminish carbon dioxide (CO_2) emissions, thus contributing to a more sustainable textile production landscape.
Hailing from Turkey, Haksa Tekstil San Tic A.S. presents environmentally conscious knitted fabrics that employ recycled yarns sourced from pre-production textile waste. This innovative approach not only yields a distinctive product but also contributes to substantial conservation efforts. The company asserts that its creation results in the preservation of billions of liters of water, the conservation of thousands of tons of cotton fibre, and the prevention of thousands of tons of chemical pollutants from entering the environment. The recycled waste utilized encompasses diverse combinations of materials, including cotton, polyester, Unifi's Repreve®, acrylic, or wool . Germany-based Kelheim Fibres GmbH introduced specialty viscose fibers that are made using 100-percent cellulose. This allows the fibers to be completely biodegradable. Kelheim works with CanopyStyle to ensure it does not source wood from ancient or endangered forests.

IV. SUSTAINABILITY IN TURKEY

Sustainable development has gained significance since the 1990s and is deliberated upon with the underlying acknowledgment that growth entails not only economic but also ecological and social ramifications. The discussions underscore the significance of utilizing production resources such as raw materials, energy, and labour in alignment with societal and individual needs, while concurrently safeguarding the ecological balance for the system's perpetuation. To realize this objective, the United Nations has formulated sustainable development goals, mandating countries to revamp their production and consumption frameworks within the parameters of these goals. The translation of these sustainable development goals into the production sphere is closely intertwined with a nation's industrialization ambitions. Turkey's economic strategy, particularly since the 1980s, has primarily rested on export-driven industrialization endeavors. Within this context, the textile sector holds a pivotal role as one of the principal segments of the manufacturing industry. Import-reliance, a prevailing characteristic of the broader Turkish economy, also characterizes the textile sector. Despite the pursuit of sustainable development goals, the transition, particularly since the 1990s, towards technology-intensive polyester as a fundamental input in the textile sector has disrupted the input dynamic. Currently, Turkey's ability to vie in the global textile market hinges largely on augmenting polyester production. However, the technology-driven nature of polyester manufacturing poses challenges for Turkey's textile industry, which leans heavily towards labor-based operations. Furthermore, polyester, as a chemical industry derivative, entails elevated energy consumption and more intricate ecological waste management compared to natural fibers.

Our country “Turkey”, a nation that embarked on its industrialization journey belatedly, has nevertheless secured a substantial position in its economy, particularly within the realm of the manufacturing industry. The textile sector notably stands out as one of the prevailing forces in this manufacturing landscape. Given that Turkey adopted an export-centric industrialization strategy during the 1980s, the discussions revolving around green growth and sustainable development hold immense significance. Notably, a significant portion of the textile sector's output is directed towards EU member states. Turkey's industrialization path aligns closely with an export-oriented approach, making the discourse on sustainable green economic strategies a pivotal aspect of its trajectory, particularly in light of the European Green Deal (EGD). However, a noticeable shift in the sector's structural makeup, focused on material considerations, appears to run counter to the principles of the EGD, which strives to guide industries toward green and circular practices. The crux of the matter lies in whether Turkey, as it endeavors to transition from the production of low-value-added goods to high-value-added goods, possesses the means to effectuate this green transition in the immediate to mid-term.

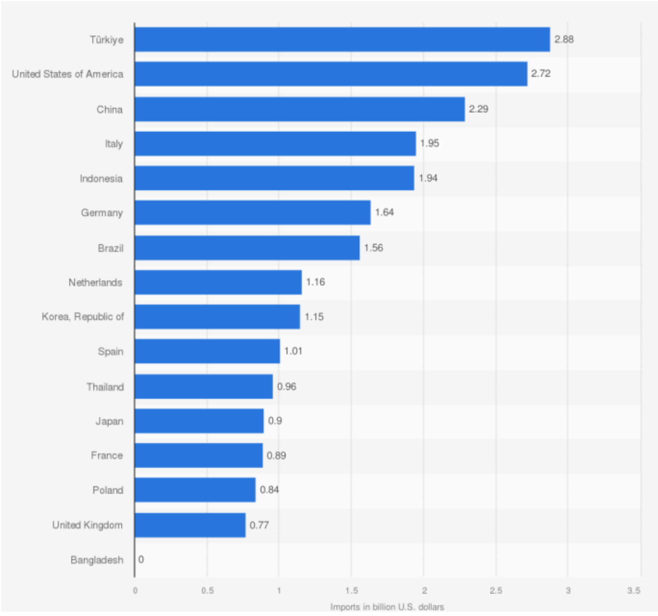

Fig. 2 From a linear to circular economy [13]

In the present day, the textile sector stands out as a primary domain of production that significantly contributes to ecological degradation due to the utilization of dyes in manufacturing, the incorporation of synthetic fibres like polyester, and the generation of production waste. This sector encompasses a spectrum of participants ranging from agricultural, natural, and chemical fibre producers to dye and chemical manufacturers, textile and apparel industries, intricate retail and service sectors, as well as extensive water usage and waste management systems. As production capabilities expanded, there emerged a departure from conventional manufacturing methods, leading to a proliferation of products and materials influenced by fashion trends. Consequently, global textile production of finished goods has attained substantial levels, establishing itself as a predominant industry in numerous developing and underdeveloped nations. However, the escalating production volume has concurrently escalated ecological detriment in the realms of manufacturing, consumption, and the circulation of goods.

Consequently, the imperative of establishing local, equitable, and environmentally conscious textile production has become increasingly evident, particularly when considering the ongoing global ecological challenges. Within this context, the pursuit of sustainability in the textile domain translates to endeavours encompassing the utilization of natural fibres such as linen and wool, promoting clean manufacturing practices, advocating for improved cotton cultivation techniques, endorsing reuse and recycling procedures. While recycling practices hold significance in the textile sector, they also present themselves as a distinct industry within the field. Promoting the augmented use of natural fibres, introducing finished products derived from recycled materials, prioritizing demand-driven production, and fostering local, ethical, and eco-friendly manufacturing to counterbalance the rapid pace of fashion's fast-fashion trend, all seem to constitute strategies capable of elevating sustainability within the textile industry.

The landscape of the textile sector has undergone significant transformations, particularly since the 1990s, with notable changes in its core materials. During this period, polyester, derived from petrochemicals, has surpassed cotton, the long-standing natural fiber of choice in the textile industry. The widespread adoption of polyester represents a shift towards a technologically advanced material with a chemical and industrial character. Polyester is produced from melted petroleum and involves complex manufacturing processes, enabling faster and more cost-effective production compared to natural fibres, which rely on natural growth cycles. However, recycling polyester remains a challenging and costly endeavour. While the ecological sustainability of polyester is subject to scrutiny, it's important to recognize that the production of natural fibers like cotton has also seen an increase in chemical usage over time. Beyond material production, the textile industry has evolved into one of the most chemical-intensive sectors globally, mainly due to dyeing and finishing processes. Currently, the textile sector relies on a vast array of over 8000 distinct chemicals, many of which have adverse effects on both human health and the environment, either directly or indirectly [14-18]. There are many ways for inserting the sustainability concept to the textile production stages. Utilizing sustainable fibres are one of the main methods. Sustainable fibres classification will be mentioned below considering their raw material.

V. SUSTAINABLE FIBERS

Utilizing sustainable fibres are one of the main methods for a sustainable textile production. Sustainable fibres may be classified to plant and animal based natural fibres, and recycled fibres. Naturally coloured cotton may be also investigated within the scope of sustainable textile fibres with a separate heading.

A. *Plant Based Sustainable Fibres*

Over the past decade, there has been a significant increase, approximately 13%, in the utilization of natural plant fibers like cotton, flax, hemp, jute, sisal, banana, bamboo, and similar materials in various industrial sectors such as leisure, automobile, medical, and building industries. These natural plant fibers offer numerous advantages compared to synthetic fibers, including abundance, low cost, renewability, eco-friendliness, low-density, high specific properties, non-abrasiveness, and biodegradability. Among them, cotton and linen, in particular, are highly favored for their ability to provide exceptional comfort in garments, making them extremely popular and widely employed in the apparel sector. Moreover, their lightweight nature, along with their impressive specific mechanical properties and other desirable attributes, has contributed to their increased annual consumption, which currently stands at *275 million kg.

Natural plant fibers are commonly acknowledged as being more environmentally friendly compared to synthetic fibers due to several reasons. Firstly, the growth of plants used for these fibers leads to the sequestration of CO_2 from the atmosphere, contributing to the mitigation of greenhouse gas emissions. Additionally, the cultivation of natural plant fibers requires less energy compared to the production of synthetic polymers and fibers, reducing the overall carbon footprint. Moreover, natural fibers are derived from renewable resources, whereas the production of synthetic fibers contributes to the depletion of natural resources. These factors highlight the environmental benefits associated with the use of natural plant fibers. The primary constituent of plant fibers is cellulose, which can be broken down by microorganisms through enzymatic hydrolysis, involving a multistage process that converts cellulose into glucose. As a result of these factors, natural plant fibers are generally regarded as having significantly lower environmental impacts and greater sustainability. However, it is important to note that the cultivation and processing of natural plant fibers may require increased water consumption, the potential use of synthetic fertilizers and pesticides, and the emission of greenhouse gases during certain stages of processing. These environmental aspects hold significant importance for these fibers and therefore warrant thorough investigation to gain a comprehensive understanding of their sustainability issues and to facilitate a proper comparison with the environmental impact of synthetic fibers.

Organic Cotton

"Organic Cotton" fibre can be defined as "more sustainable" than the conventional cotton" fibre which is an environmentally preferable product. The organic cotton proponents support the idea of "conventional cotton is not an environmentally responsibly produced crop". Since the conventional cotton production has a disadvantage of overuse or misuse of pesticide/crop protection products, it has adverse effects on the environment. Additionally, conventionally grown cotton fibre/fabrics/apparel has chemical residues on the cotton which may cause cancer and some other health related troubles. Organic cotton fibre is a "more sustainable" alternative to conventional cotton fibre, as it is an environmentally preferable product. Advocates of organic cotton emphasize that conventional cotton is not produced in an environmentally responsible manner. The overuse or misuse of pesticides and crop protection products in conventional cotton production has detrimental effects on the environment. Furthermore, conventionally grown cotton fibre, fabrics, and apparel may contain chemical residues that have been linked to potential health issues, including cancer and other health-related problems. The current production methodologies in both conventional and organic cotton share certain similarities while differing in other operational aspects. Adhering strictly to conventional methods renders the crop ineligible for organic certification. Undoubtedly, organic cotton production markedly reduces the consumption of synthesized chemical compounds, including fertilizers, insecticides, herbicides, growth regulators, and defoliants, which are exclusively employed in conventional cotton cultivation. Both organic and conventional cotton farming incorporate the practice of crop rotation. This rotational approach serves to mitigate weed issues that may arise from organic cultivation conditions. For the initiation of organic cotton production, it is imperative that synthetic chemicals used in conventional cotton farming, such as fertilizers, insecticides, herbicides, growth regulators, and defoliants, are refrained from in the field for a minimum of three years. Among the globally prevalent harvesting methods, hand picking takes precedence, and this practice remains consistent regardless of whether the cotton is organic or conventional. Employing a technique that removes only the fibre from the cotton boll, while keeping contaminants from both laborers and the field at bay, can result in a cleaner cotton yield. It is advisable to perform pre-harvest removal of green leaves, as a reduced leaf drop rate during harvesting not only slows down the process but also escalates ginning costs. Consequently, swift harvesting immediately after the bolls have opened is recommended [19,20].

Linen

The earliest Egyptian linen cloth dates from the Old Kingdom, but flax appears to have been grown for linen approximately 5000 years ago in the Early Dynastic period. In today's scenario, when we talk about flax fibre, it is well known as linen fashion as well as formal apparel for both males and females. Many leading manufacturers of linen-based products exist all over the world. Different blended linen products are linen/cotton (warp cotton, weft linen or warp cotton, weft cotton/linen blend yarn), linen-based/cotton (warp cotton, weft linen/jute, linen/ramie, linen-pineapple, or linen/silk waste, etc.), linen/synthetic (warp polyester/cotton or polyester/viscose blend, weft linen, linen/jute, or linen/cotton, etc.), etc. Apart from these, there is huge scope to develop many other blended materials from linen. Linen is a natural fibre which stems from the flax plant. It uses considerably fewer resources than cotton or polyester (such as water, energy, pesticides, insecticides, fertilizers). Flax can grow in poor soil which is not used for food production. In some cases, it can even rehabilitate polluted soil. Flax plants also have a high rate of carbon absorption. For these reasons, we consider linen to be a sustainable material, even when it is not organically grown [21]. Linen fibre material can absorb moisture quickly from body perspiration, and this provides cool and comfort in humid conditions. As far as the properties of the fibre are concerned, linen fibre material swells and thus improves the strength under wet conditions. This is one of the reasons linen/flax blend is normally preferred to spin under wet rather than dry conditions. As far as the international market is concerned, many pure/blended linen products are available such as ramie/linen for women for casual wear, linen blend trousers (50 % viscose, 35 % cotton, 15 % linen. The white label (65 % viscose, 25 % cotton, 10 % linen) by Joanna Hope, linen-mix trousers and shorts (55 % linen, 45 % cotton) by SOUTHBAY, single-breasted linen mix blazer (55 % linen, 45 % cotton; lining: polyester) by Williams and Brown: All of these are examples of lightweight fashion fabrics will keep you cool but stylish in the warm weather

Jute

Jute had the largest market share of all other plant-based fibres with around 50%.1 Similar to hemp, flax, and ramie, they are bast-fibres. Jute is used to make twine, ropes, matting, and packaging materials, as well as home textiles such as curtains and carpets. Numerous industries are currently directing their efforts towards innovating jute-diversified products tailored for both fashion and packaging of agricultural goods. Literature attests that jute, when adorned through suitable adaptations in spinning weaving, knitting, and nonwoven techniques, along with handloom fabrics, can yield a strikingly elegant appearance [22-25]. Consideration of fashion design elements has been seamlessly integrated at the fabric-manufacturing phase, and these principles have extended into garment creation with specially designed fabrics. Figure 3 and 4 showcase a jute-based fashion jacket and blazer, respectively.

Fig. 3 Jute-based fashion shawls

Fig. 4 Jute-based fashion jacket as winter garment and Jute-based fashion blazer [25]

Pineapple

Derived from the verdant leaves of pineapple plants, Pineapple Leaf Fiber (PALF) represents an unexplored natural resource typically regarded as an agricultural byproduct. PALF holds remarkable potential as a sustainable fashion textile, contributing to the realm of environmentally conscious attire. Characterized by its exceptional strength, luster, and creamy hue, PALF exhibits an intricacy and delicateness unparalleled among vegetal fibres . Each kilogram of leaves can yield approximately 15 to 18 pieces of silk-like fiber, approximately 60 cm in length, possessing a white, creamy, and lustrous appearance that readily absorbs dyes. The process of extracting these fibers entails scraping the leaves using tools like broken plates or coconut shells. A proficient scraper can yield fibres from over 500 leaves per day. After extraction, the fibres are washed, air-dried, waxed to eliminate tangles, and subsequently bound into yarns, ready for weaving into fabric. Primarily employed in crafting Barong Tagalog and formal wear, pineapple fabrics cater to scenarios demanding lightweight yet stiff and translucent textiles. At times, it is combined with silk or polyester to form a textile. The resultant fabric is lightweight, easy to maintain, and exudes an elegant demeanour akin to linen. Bestowed with the epithet of the "queen" of Philippine fabrics, Pineapple silk is a favoured choice among the country's elite. In the Philippines, fabric based on PALF is widely referred to as pina fabric. A diverse array of fashion products, both apparel and non-apparel, featuring PALF is readily available in the market. Figure 4 illustrates Filipino shirts, an emblematic national attire worn by individuals ranging from the Filipino president to newlyweds, crafted from piña, a variant of fabric derived from pineapple fibres. The inherent lustre of PALF ensures that even post-dyeing, the cloth maintains its luminosity, rendering the resulting garments even more captivating [26,27].

Stinging Nettles

The fabric provided from stinging nettles is entirely safe to wear and offers similar benefits to hemp, but without the legal complications associated with hemp production. Despite its protective exterior, the fibers found within the stinging nettle plant are remarkably well-suited for creating textiles. These fibers are pliable and have an ideal length for spinning into yarn. The final woven fabric closely resembles linen but possesses significantly greater strength. Interestingly, its strength even intensifies when exposed to moisture, making it perfect for structured garments. Furthermore, stinging nettle fabric blends harmoniously with other fibers, imparting softness and enhancing durability as needed. Doğan et al. (2008) [28] documented that across multiple Balkan nations, traditional handicrafts have embraced the utilization of stinging nettle stems and fibers. This fibrous nettle material, known as "Kopriva" in Bulgaria, has fostered sustainable advancements in the domains of cloth, sack, cord, and net manufacturing applications. In Romania, nettle, recognized as "Urzica," serves as a cotton substitute for fishing nets and paper production. Serbia labels it "Kopriva," attributing nettle fibre as a prominent component in the spinning industry, contributing to the creation of textile goods. Across this spectrum, diverse handicraft products emerge, encompassing items like doormats, flower vases, wall hangings, door chains, carpets, handbags, table mats, beach umbrellas, and lampshades. Nettle proves a versatile material for these creations, be it through fibres, yarns, fabrics, or their combinations. The profitability of these products is notably amplified due to their favourable cost-to-benefit ratio.

Hemp

Hemp is a “bast” fiber, which means that the fiber-producing part of the plant is made up of strands that run its length and surround the woody core of the stem. It grows quickly, is naturally resistant to many insect species, and needs little water to cultivate. It also has a deep root system, which helps to reduce soil loss and erosion, and is useful in many different crop rotations. In China, the leading producer of hemp, farmers rotate it with soybeans, tobacco, wheat, and corn. Hemp cultivation and processing often require significant amounts of fertilizer and machinery, both of which consume substantial amounts of water. Furthermore, due to its voluminous nature, the transportation of hemp to processing facilities can incur high costs and demand substantial energy. Obstacles to the broader integration of hemp also persist. Despite lacking psychoactive effects, hemp has faced unjust stigma due to its association with the cannabis family. Additionally, the primary processing methods for hemp were established in the early 1900s and are just beginning to undergo modernization and expansion to keep up with increasing demand [29]. Hemp fabrics possess antibacterial activity against a wide range of pathogenic bacteria. It has the best heat capacity ratio compared to all other fibres, so it keeps the wearer cooler in the summer and warm in the winter. It dyes well and does not discolour easily. It is also tough and is more resilient and longer lasting than cotton garments [30]. China accounts for more than 50 percent of the global hemp production and holds more than half of the over 600 international patents on hemp fibre and textile production. India and Romania have been producing finer hemp yarn using wet spinning processes. The majority of hemp processing is completed by cottonization — the process of removing the lignin that binds the hemp fibres and cuts the fibre to an average cotton length of about 1-1/8th inch to be spun and finished on already existing slightly modified cotton or wool processing equipment [31].

Rami Fibers

Ramie* (*Boehmeria nivea* (*L.*) *Gaud.- Beaup.*) is the name of the product of one or more species of the genus *Boelimeria*, a member of the order *Urticaceae* and nearly allied to the stinging nettle genus (*Urtica*), from which, however, it differs in the absence of stinging hairs. Some confusion has arisen in the use of the various terms *China-grass*, *ramie* and *rhea*. Two plants are concerned: one, *Boehmeria nivea*, China-grass, has been cultivated by the Chinese from very early times under the name Tschou-ma; the other, probably a variety of the same species (*Boehmeria nivea*, var. *tenacissima*) though sometimes regarded as a distinct species (*B. Tenacissima*), is the ramie (Malay zamf) of the Malay Islands and the rhea of Assam. Ramie (*Boehmeria nivea* (L.) Gaud., *Boehmeria nivea* var. *tenacissima*) is also commonly known as white ramie; green ramie is one of the groups referred to as the bast fibre crops. Ramie fiber shares a chemical classification with cellulosic materials like cotton and linen. Prominent ramie-producing nations encompass China, Taiwan, Korea, the Philippines, and Brazil. While until recently, ramie remained relatively obscure within the ready-to-wear market, it is progressively finding its place in an increasing number of garments. It is frequently combined with cotton and featured in woven and knit fabrics that span a range from those resembling fine linen to coarser canvas textures. Natural ligno cellulosic fibres can be used as a substitute to flax and silk. Rami is resistant to bacteria, mildew, and insect attack. Fiber is extremely absorbent and dyes fairly easy. Rami Increases in strength when wet and withstands high water temperatures during laundering. Having low elasticity, abrasion resistance and wrinkling easily are the main disadvantages of ramie [32].

Banana Fibre

The extraction of the natural fiber from the plant required certain care to avoid damage. In the present experiments, initially, the banana plant sections were cut from the main stem of the plant and then rolled lightly to remove the excess moisture. Impurities in the rolled fibres such as pigments, broken fibres, coating of cellulose, etc,… were removed manually by means of a comb, and then the fibres were cleaned and dried. This mechanical and manual extraction of banana fibres was tedious, time-consuming, and caused damage to the fibre. Consequently, this type of technique cannot be recommended for industrial applications. A special machine was designed and developed for the extraction of banana fibres in a mechanically automated manner. It consisted mainly of two horizontal beams whereby a carriage with an attached and specially designed comb, could move back and forth. The fibre extraction using this technique could be performed simply by placing a cleaned part of the banana stem on the fixed platform of the machine and clamped at the ends by jaws. This eliminated relative movement of the stem and avoided premature breakage of the fibres. This was followed by cleaning and drying of the fibres in a chamber at 20^{o}C for three hours. These fibres were then labelled and ready for lamination process. After extraction of fibre, weaving is done in the looms as per normal process like any other material. The processes for making yarn from banana fibres vary from region to region. Most popular methods among these are those followed in Japan and Nepal.

The cultivation of banana for clothing and other household use in Japan dates back to the 13th century. In the Japanese method of making banana fiber, the care is taken right from the stage of plant cultivation. The leaves and shoots of the banana plant are pruned periodically to ensure their softness. The harvested shoots are first boiled in lye to prepare the fibers for making the yarn. These banana shoots give away fibers having varying degrees of softness. This further results in yarns and textiles with differing qualities that can be used for specific purposes. The outermost fibres of the shoots are the coarsest ones. They are, therefore, more suitable for making such home furnishings as tablecloths. The softest part is the innermost part that gives soft fibres which are widely used for making kimono and kamishimo, the traditional Japanese apparels. The banana cloth-making process is a lengthy one and all the steps are performed by hand.

Fig.5 Banana fibre extraction in Japan

In Nepal, the focus is on harvesting the trunk of the banana plant rather than its shoots. Afterward, small sections of these trunks undergo a gentle softening procedure to facilitate the mechanical extraction of fibres. Subsequently, these fibres are subjected to bleaching and drying processes. The resultant fibre shares a visual resemblance with silk, and it has gained popularity under the name of banana silk fibre yarn. This fibre is then meticulously refined, processed, and formed into skeins, primarily by Nepalese women. The harvesting process involves selecting only the mature bark or the outer layers of the banana plant that are in the process of natural decay. These harvested materials are soaked in water to accelerate the natural breakdown. Once the chlorophyll dissolves, the remaining components are the cellulose fibres. These fibres are then extruded into pulp to make them suitable for spinning into yarn. The resulting yarn is subjected to manual dyeing techniques. Notably, they possess a luxurious texture akin to silk, making them highly valuable for crafting premium-quality rugs. The creation of these traditional rugs involves intricate hand-knotting methods, a craft predominantly carried out by Nepalese women [33,34].

Fig 6. Banana fibre extraction in Nepal

Coffee-beans

Fabric made using discarded coffee grounds is one example of an interesting textile innovation. Two companies are offering such products. "Nat-2™, a sneaker brand headquartered in Germany, has recently unveiled an innovative sneaker infused with the fragrance of repurposed coffee grounds. These sneakers incorporate a varying amount of up to 50 percent recycled coffee grounds, depending on the specific style, resulting in a refined and velvety texture, as indicated by the company. The selection of coffee utilized is contingent upon sustainable availability. Singtex Industrial Co. Ltd., based in Taiwan, employs coffee grounds in the production of their S.Café® yarn. Through a patented yarn manufacturing process, the functional performance capacity of the coffee grounds is optimized. Singtex's technology amalgamates processed coffee grounds with polymer to create masterbatches prior to being spun into yarn. The company asserts that the yarn boasts exceptional inherent qualities, including natural anti-odor properties, ultraviolet protection, and remarkably swift drying times—up to 200 percent faster than cotton drying times [35].

Lotus Flower

Lotus flower fiber from the root of the lotus plant has been used for centuries to produce rare fabrics used in hand-spun scarves. The process, in which the stems of the lotus are cut and twisted to expose the fibers, is however time-consuming. The process produces a luxurious fabric that feels like a combination of silk and raw linen. Lotus fabric has unique properties — it is naturally soft, light, breathable and antibacterial. Cambodia-based Samatoa Lotus Textiles reports the Lotus plant is believed to have healing abilities, and wearing a fabric made using the fibers lotus fibers may have healing effects curing the wearer of headaches, heart ailments, asthma and lung issues [36].

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B. *Recycled Fibers for Sustainability*

Waste management system enables collection, categorization, reduction, recycling, and reuse of waste. At present, countries' intensive efforts on waste management are striking. Waste management, which has an important place among environmental protection policies, should prevent the rapid depletion of natural resources and minimize the potential risks of the wastes to the environment and human health. Recycling is one of the major applied techniques for sustainable textile production where waste management is applied. Different man-made and cellulose based fibres may be produced with recycling.

Recycled Polyester

Polyethylene terephthalate (PET) showcases its versatility through a broad spectrum of applications. Its utility spans across diverse sectors including clothing, acoustic panels, sportswear, agricultural nets, nonwovens, sheets and films, straps, engineering resins, food and beverage bottles, packaging materials, and reinforcement in building construction, among others. Notably, PET of bottle grade quality is commonly chosen for water and beverage packaging due to its trifecta of advantages: lightweight nature, cost-effectiveness, and its inherent resistance to microorganisms and light. In fact, water, soft drink, and beverage bottles constitute a substantial 83–84% of the global demand for PET resin.

While PET's presence has been widespread, it inevitably generates a substantial amount of waste. Although PET is harmless to human health and the environment directly, its classification as potentially harmful arises from its sizeable volume within waste streams and its resistance to atmospheric and biological agents. Due to its sluggish biodegradation, PET waste poses a removal challenge. Two viable solutions emerge: incineration and recycling. However, the burning method introduces toxic emissions and environmental contamination, rendering it less favourable. Recycling PET bottles emerges as a favourable alternative, conserving natural resources, addressing landfill issues, mitigating greenhouse gas emissions, and fostering economic growth. Recycling stands as the optimal approach to curbing PET waste. Economically beneficial, it reduces both energy and raw material costs, particularly advantageous in fibre production. Two distinct forms of PET bottle recycling emerge: closed loop and open loop recycling. Closed loop, or bottle-to-bottle, entails reusing post-consumer waste within the same system. Open loop recycling, on the other hand, incorporates recycled material into different product systems, like bottle-to-fiber recycling [37-43].


(https://bit.ly/31K789P)

Fig. 7 Products made with recycled polyester

Recycled Nylon

Similar to recycled polyester, recycled nylon offers comparable advantages: it effectively redirects waste from landfills, while its production consumes significantly fewer resources compared to newly manufactured nylon, encompassing reductions in water, energy, and fossil fuel usage. A substantial portion of recycled nylon originates from discarded fishing nets, serving as a valuable strategy to alleviate ocean pollution. Additionally, recycled nylon derives from sources like nylon carpets, stockings, and other materials. Although the cost of recycling nylon remains higher than producing new nylon, its numerous environmental benefits make it a compelling choice [44].

Recycled Man-Made Cellulosic Fibers

Lyocell is a manufacturing process of rayon which is much more eco-friendly than its relatives modal and viscose. Lyocell is made in a closed-loop system that recycles almost all of the chemicals used. "Lyocell" is the generic name of the manufacturing process and fiber. Tencel® is the brand name of the lyocell commercialized by the company Lenzing AG. Tencel® is made from eucalyptus from PEFC certified forests. Eucalyptus trees grow quickly without the use of pesticides, fertilizers or irrigation.

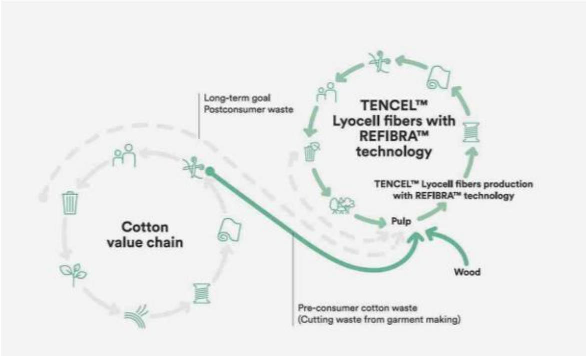

Fig. 8 Tencel ™ fibers with Refibra™ technology [45]

The pioneering REFIBRA™ technology involves upcycling cotton scraps from garment production. These cotton scraps are transformed into cotton pulp. A substantial proportion of this – up to one third – is added to wood pulp, and the combined raw material is transformed to produce new virgin TENCEL™ Lyocell fibres to make fabrics and garments. 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. Lenzing Tencel ™ fibers with Refibra™ technology is the first lyocell fiber made with reclaimed materials offered on a commercial scale. Refibra™ was launched in spring 2017. While it was initially made with 20% pre-consumer cotton residues, the percentage increased to 30% in 2019. A special lot production including 5% post consumer waste and 25% pre-consumer waste started and will become the standart product in the near future. Lenzing's and Södra's joint goal is to process 25 thousands tonnes of textile waste per year by year 2025.

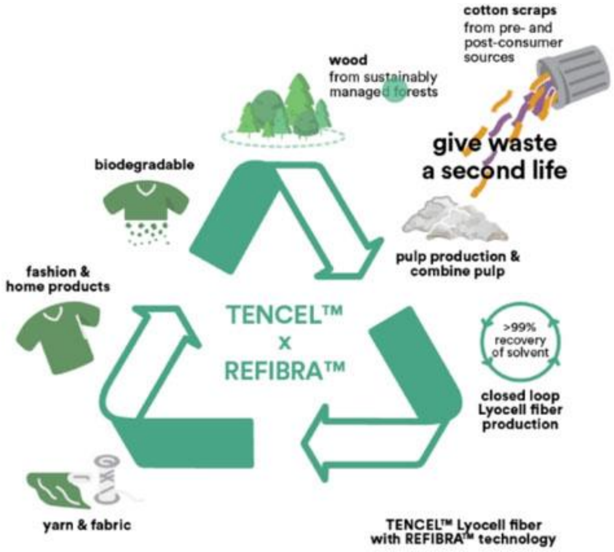

Fig.9 Tencel ™ fibers with Refibra™ technology [45]

Cupro

Cupro is an artificial cellulose fiber made from Linter Cotton (or Cotton wastes). In order to obtain the ready to weave yarn, the extracted cellulose is soaked in a bath of a chemical solution called “cuprammonium”, hence the Cupro Name. All the process is made in closed-loop. The large quantities of water and chemicals used in the production of Cupro are therefore constantly reused until they are completely exhausted. The chemicals used are free of toxic or dangerous compounds for health and the environment. Cupro is also biodegradable, so it considers a good eco-friendly alternative to viscose [46].

Recycled Wool

Recycling wool is very important for meeting the demand for quality protein fibers which eliminates the environmental impact factor. Accounting 1% of textile fibers, wool fibres unfortunately fail to meet the demand due to limitation of land and water sources. Sheep farming for wool production consumes valuable resources as it involves clearing land and cutting down trees to provide animal grazing space which results in negative environmental impacts such as soil salinity , erosion and a decline in biodiversity. Addittional hughe amount of water consumption is required for the wool process which includes the sheep raisement and wool fibre cleaning

Fig 10. Recycled wool production

Recycling 'waste' clothing offers numerous environmental benefits. It eliminates the need for practices that harm animals and reduces the demand for the production of new, natural fibres. This results in a significant carbon footprint reduction, saving nearly 11 kg of CO_2 per kilogram of wool yarn or 6 kg of CO_2 per wool sweater. Moreover, repurposing existing colourful clothing eliminates the environmentally damaging processes of toxic dyeing and washing, while conserving over 500 Liters of water per kilogram of yarn. Additionally, recycling clothing reduces transportation requirements since the raw materials originate from our own households, enhancing the transparency of the production process [47]

C. Naturally Colored Cotton

Processing of fibres into textile materials requires the usage of extensive water, energy, chemical and other related resources. Dyeing processes may cause environmental pollution due to its chemical dyestuff and dyeing process auxiliary usage. There are some new considerable efforts for reducing the ecological hazard and waste generated during textile processing or developing sustainable and green materials. One of these promising approaches is to promote the usage of naturally colored cotton fiber usage and its production. As the world is moving towards to the pollution-free organic textiles and products, the naturally colored cotton fiber is going to be the next buzz word in the textile market [47].

Naturally colored cotton's (NACOC) origin is South and Central America where it has been cultivated for about 200 years. Native peoples in the former American lands have used these wild cottons for weaving and hand spinning for centuries. The brown and green cotton varieties available in today's cotton market originate from various strains of the Gossypium hirsutum species. These cotton seeds are found in seed banks worldwide. The pigmentation that gives cotton its color occurs after the cotton ball opens, owing to the presence of pigments intertwined with cellulose. This coloration is a genetically inherited trait, resulting in different shades of green and brown for colored cotton varieties. When cotton bolls open, the colors develop naturally under the sun. Initially, cotton fiber is white, but within a week, it assumes its original color based on its genetic makeup. The specific shades of naturally colored cotton may vary depending on factors like the season, location, climate, and soil type .

It's worth noting that naturally colored cotton has shorter staple length, lower staple strength, and finer diameter compared to regular upland cotton, leading to lower fiber yields and limited use in commercial textile applications. However, growing environmental concerns and the preferences of conscientious consumers have spurred interest in using naturally colored cotton in the textile and apparel sector. In Turkey, there are small-scale efforts to cultivate and produce naturally colored cotton fiber. While not very common, these fibres are occasionally used in textile products like blankets, displaying eco-friendly and healthy natural colors ranging from yellow to brown and green, influenced by the crop's growing conditions, seed types, and inherent genetic traits .

Notably, naturally colored cotton exhibits high resistance to insects and diseases, making it a suitable choice for organic cultivation without the need for pesticides or herbicides. It's important to mention that while naturally colored cotton is not always cultivated using organic methods, it can serve as an environmentally friendly raw material for ecological fabrics when grown following ecologically sound practices [48-60]

Fig 11. White cotton and naturally colored cotton fiber examples

D. *Bio-Based and Biodegradable Fibers*

Biosourced materials represent an important commitment to the environment and to reduce the dependence on fossil fuels.

PLA (Poly lactic acid)

Polylactic Acid, commonly known as PLA, is a biodegradable and bioactive thermoplastic polymer. PLA is derived from renewable resources, primarily corn starch or sugarcane, making it an environmentally friendly alternative to traditional petroleum-based plastics. One of its remarkable features is its biodegradability, as PLA can naturally break down into non-toxic components in composting conditions. PLA is also versatile and finds applications in various industries, including packaging, 3D printing, biomedical devices, and textiles. It exhibits good mechanical properties, such as strength and stiffness, while offering the flexibility to be processed through methods like extrusion, injection molding, and fiber spinning. PLA's eco-friendly nature and versatility make it a promising material in the quest for more sustainable and environmentally responsible plastic solutions.

Cargill Dow Polymers (CDP) produces PLA in the United States by transforming corn starch into lactic acid, followed by the polymerization process. Unlike alternative synthetic fibre materials derived from plant sources, such as cellulosic, PLA stands out as an excellent candidate for melt spinning into fibres. Unlike the solvent-spinning method necessary for synthetic cellulosic fibres, melt spinning enables the creation of PLA fibres with reduced financial and environmental expenses while providing the capacity to generate fibres with a broader spectrum of properties [61,62]

When initially encountering PLA, it may be tempting to observe that its polymerization involves the condensation of an acid with an alcohol, resulting in the formation of a polyester. It's natural to assume that because PLA is classified as a polyester, it would exhibit behaviours similar to PET, a polymer commonly referred to as "polyester." Certainly, both polymers require pre-drying before melting to prevent hydrolysis, and they both readily yield fibres through melt extrusion. Moreover, fibres from both polymers can be drawn (stretched) to enhance their tensile strength. However, beyond these shared characteristics, PLA and PET exhibit differences. Some of these distinctions stem from PLA's plant-based origin in contrast to PET's mineral source. Yet, substantial variations in processing and properties result from dissimilarities in the respective polymer structures. To begin with, PET belongs to the aromatic polyester family, featuring a benzene ring in each repeating unit. In contrast, PLA is classified as an aliphatic polyester, characterized by relatively small pendant methyl groups that impede rotation and hinder easy access to the oxygen atoms in the ester linkage. Secondly, PET chains are typically linear in structure, whereas PLA molecules tend to adopt a helical configuration. These distinctions make it possible for higher purity grades of PLA to crystallize much more readily and, in our estimation, to a greater extent than PET. Consequently, this leads to significantly different processing requirements for manufacturers of PLA fibres. While these distinctions occasionally pose challenges, they more often offer a heightened level of control over the ultimate properties of the fibres, including strength, shrinkage, and bulk [61,62]

Biofeel® PLA

Biofeel® PLA is a continuous filament yarn made with polylactic resin (polylactic acid), synthetized from non-GMO vegetable raw materials, 100% biodegradable and compostable [63]

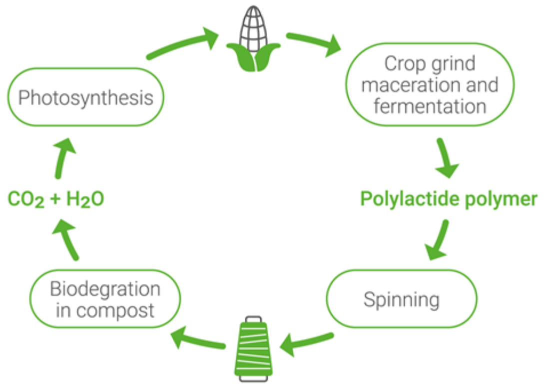

Fig 12. Biofeel® PLA production [63]

VI. CONCLUSION

Sustainability can be described as the ability of natural systems to function, maintain biodiversity, and generate everything necessary to preserve harmony with the environment. In the realm of textile science, natural plant fibres stand out as sustainable raw materials. Ensuring sustainable existence for humanity involves sustaining agricultural and ecological productivity despite various challenges. Currently, our planet's ecosystems are strained by the overproduction and disposal of plastics, prompting a critical examination of the potential offered by natural plant fibres for textiles.

All natural plant fibres possess the attributes of biodegradability and sustainability. While most man-made fibres will eventually degrade, their decomposition period is considerably longer, and the degradation process can have detrimental effects on soil, water, and, consequently, the broader environment. Against the backdrop of global warming, climate change, a growing environmental awareness, and evolving legislative regulations, there is a renewed interest in natural fibres. Many plants, fruits, and seeds are now either rediscovered or newly harnessed for the development of innovative fabrics that have the potential to contribute to environmental healing.

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