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COLLECTION OF GOOD PRACTICES ON CIRCULAR ECONOMY OF FIBROUS COMPOSITES

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1. TECHNICAL TEXTILES AND FIBROUS COMPOSITES

New materials and technologies in the field of textiles are the key innovations that can meet a variety of societal challenges. In recent decades, there has been an exponential increase in the use of textile materials in engineering and in the production of composite materials. Technical textiles represent a multi-disciplinary field with numerous end use applications.

1.1. TECHNICAL TEXTILE

Technical textiles are defined as textile materials and products manufactured primarily for their technical and performance properties rather than their aesthetic or decorative characteristics. They are an input to other industries such as the automotive, medical devices, and agro-food sectors. Technological advancements, increase in end-use applications, cost-effectiveness, durability, user-friendliness, and eco-friendliness of technical textiles have led to the upsurge of its demand in the global market.

The differences between technical textiles and the conventional textiles industry [1]:

-Technical textiles are favored for their extremely precise performance quality, and consequently, they are more expensive than conventional textile.

-Technical textile producers must use accepted testing techniques to gain customers' trust concerning standard specifications.

-Technical textiles are for a certain sector of a market that requires more flexible production schedules and smaller manufacturing spells.

-Technical textiles producers usually have to be prepared to spend on research and development.

The areas of application for technical textiles are heavily fragmented and include end markets such as agriculture, building and construction, geotextiles and civil engineering, industrial textiles, hygiene and medical, transportation packaging, personal and property protection, and sports.

Technical textiles have been classified according to the field of application, as follows:[2]

- Agrotech: agriculture, horticulture, and fishing. Textiles employed in agriculture such as erosion and crop protection, layer separation in fields, sunlight screening, windshield packaging for storing grass, and anti birds nets. Light-weight spun-bonded fleeces are nowadays used for a variety of products, such as shading, weed suppression, and thermal insulator. Agriculture is also an essential consumer of high-performance textile merchandise from other end-user segments such as Geo-Tech textiles for land reclamation and drainage, Pro-Tech garments for workers who must handle sprays

[1] Aldalbahi, A., El-Naggar, M. E., El-Newehy, M. H., Rahaman, M., Hatshan, M. R., & Khattab, T. A. (2021). Effects of Technical Textiles and Synthetic Nanofibers on Environmental Pollution. *Polymers*, *13*(1), 155. https://doi.org/10.3390/polym13010155

[2] https://techtextil.messefrankfurt.com/frankfurt/en/profile.html

and hazardous tools, and Mobil-Tech textiles for tractors and lorries, conveyor belts, hoses, filtration systems and reinforced composites for building silos, tanks, and pipes.

• Build tech: constructions and buildings. These are employed in construction including concrete reinforcement, frontispiece, interior architectures, sewer and pipes, linings, noise and heat insulation, fire and waterproof, air conditioning, house-wrap, wall reinforcement, aesthetic, and sun-protective products. Another use is for safety nets, lift and tension ropes, and flexible shutters for curing concrete or for different kinds of temporary constructions, such as awnings, marquees, and tents. Double-walled spacer textiles can be filled with appropriate materials to afford sound and/or thermal insulators. Glass-reinforced composites involve septic tanks, wall panels, and sanitary fittings.

• Cloth tech: technical components for footwear and clothing. Cloth-Tech is high-performance textiles for clothing purposes, particularly for smooth finishing procedures where the cloth is treated under pressure and high temperature. This class of technical textiles involves yarns, fibers, and textiles employed as technical elements in the production of clothes, such as waddings, interlinings, sewing threads, and insulators. Some of the most recent and highly complicated advances have seen the inclusion of temperature phase-changing materials into those insulating merchandise to offer an extra level of control and resistant character to sudden extreme changes in hot or cold temperature.

• Geotech: geotextiles and civil engineering. Geotextiles are characterized by superior strength, durability, low moisture absorption, and thickness. Geotextiles are used in supporting embankments, bridges, and drainage systems, while permeable Geo-Tech has been employed for soil reinforcement, erosion control, and filters.

• Home tech: household textiles, furnishings, and upholstered furniture industry. High-performance home textiles (Home-Tech) are used for internal decoration, furniture, carpeting, floor and wall cover, sun-shielding, and fire retardant.

• Indutech: products and solutions for filtration, purification, mechanical engineering, chemical industry, and many other industrial applications. Specific products under Indutech include filters, wipes, felts, and three-dimensional (3-D) textile products. The textile includes ropes, which occupy the prime position in the market and are used in shipping, ports, oil rigs, and defense areas.

• MedTech: hygiene and medicine. Textiles that find hygiene and medical applications are termed high-performance medical textiles. The main applications include surgical gowns, drapes, wound care products, diapers, sutures, sanitary napkins, and sterile packaging.

• Mobiltech: cars, transport, railways, and aircraft. Mobil-Tech textiles are generally employed in the manufacturing of railways, automobiles, heavy trucks, ships, aircraft, and spacecraft. They are used as a truck and car trunk covers, airbags, parachutes, timing belts, boats, engine noise insulation, higher-end tires, seat covers, safety belts, air filters, and air balloons. Technical transportation textile goods range from rugs, seats, tires, seat and timing belts, and safety airbags, to reinforced composites for automotive and aircraft, including wings and engine machinery contents.

• Oekotech: environmental protection. Oeko-Tech textiles have been used for safety purposes and environmental protection, such as air and water filtration systems, erosion defenders, oil spill management, floor sealing, and waste handling.

• Packtech: packing. Pack-Tech textiles are used for packaging, storing silos, containers, tents, and clothes covering.

• Protech: personal and property protection. Technical protective clothing has been used for additional protection values against hazards such as high-temperature insulation particularly for fire-fighters, radiation in nuclear reactors, electric arc flash discharge, molten metal impacts, metal sparks in welding, and highly acid/alkaline environments, bullet impact, and astronaut's kit. The protection of functional textiles involves safety against stabs, explosives, fire, foul weathering, cuts, temperature (hot or cold), high voltage, abrasion, and dangerous dust and tiny particles, as well as chemical, biological and nuclear hazards.

• Sporttech: sports and recreation. These were designed for shoes, cycling, summer and winter sports, angling, sail and fly sports, climbing, and sports equipment. Examples of uses: synthetic grass employed in textile surfaces, carbon fiber reinforced composites for fishing rods, racquet, and cycle frames as well as a golf club and balloons, parachutes, paragliders, and sailcloths.

There are a variety of yarns have been applied for high-performance textiles, including natural as well as man-made yarns depending on the end product.

Special characteristics can be obtained by different yarns to afford particular functional requirements of technical textiles according to the end-use application, such as packaging, medical agriculture, protection, filtration, and geotextiles. Natural fibers are characterized by high modulus/strength and moisture intake as well as low elasticity and elongation. Regenerated cellulosic fibers possess low modulus/strength and elasticity as well as high elongation and moisture intake. Synthetic fibers, such as polyamide, polypropylene, and polyester, possess high modulus/strength and elongation with an acceptable elasticity and comparatively low moisture intake. Natural fibers can be divided into the plant, animal, and geological origins. Plant fibers possess excellent engineering characteristics, while animal fibers possess a lower modulus/strength as well as higher elongation than plant fibers. Geological fibers are costly, brittle, and lack strength and flexibility.

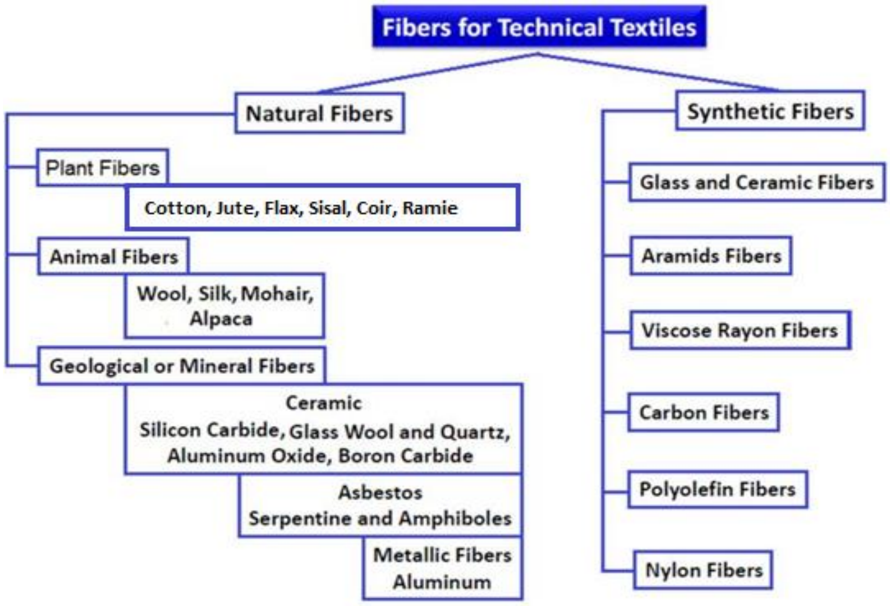

Fig. 1: *General classification of fiber-based technical textiles into synthetic and natural fibers*

Source: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7794755/ Effects of Technical Textiles and Synthetic Nanofibers on Environmental Pollution

1.1.1. Natural fibers

Are used for the production of technical textiles, are divided into the plant, animal, and geological origins.

a. **Plant fibers**: cotton, jute, flax, sisal, coir, and ramie.

Cotton fibers are natural hollow fibers; they are soft, cool, known as breathable fibers, and absorbent. Cotton fibers can hold water 24–27 times their weight. They are strong, dye absorbent, and can stand up against abrasion wear and high temperature. Since cotton wrinkles, mixing it with polyester or applying some permanent finish gives the proper properties to cotton garments. Cotton fibers are often blended with other fibers such as nylon, linen, wool, and polyester, to achieve the best properties of each fiber.[3]

Jute fibers are classified as natural multifilament fibers, which are characterized by being durable, strong, and easy to manufacture/dispose of. Jute fibers are biodegradable and recyclable materials, i.e., environmentally friendly materials. Jute fibers have good insulating properties for both thermal and acoustic energies with moderate moisture regain and no skin irritations. Woven jute textiles were originally used as geotextiles. Jute geotextiles have been found useful for control of surface soil erosion, construction of embankments on weak soil as well as strengthening road pavement and surface for separation, drainage, and temporary reinforcement. As a filter, it can be used for the revetment of the river and canal banks. Jute yarns have been employed for producing sacks of flexible packaging.[4] [5]

Flax fibers are originally derived from the bast or skin of the stem of the flax plant.
Flax fiber is soft, lustrous, and flexible, two-fold stronger than cotton fiber but less elastic and five-fold stronger than that wool. Flax fiber is hollow and capable to absorb water up to 12% of its weight. Flax has been long used as a source of textile fibers. Lately, it has also been used to meet technical applications such as packaging, automotive industry, asbestos replacement, panel boards, insulation

[3] S.A. Hosseini Ravandi, M. Valizadeh, 2 - Properties of fibers and fabrics that contribute to human comfort, Editor(s): Guowen Song, In Woodhead Publishing Series in Textiles, Improving Comfort in Clothing, Woodhead Publishing, 2011, Pages 61-78,

[4] Utpalendu Datta (2007) Application of Jute Geotextiles, Journal of Natural Fibers, 4:3, 67-82, DOI: 10.1300/J395v04n03_05

[5] Fonseca C.S., Silva M.F., Mendes R.F., Hein P.R.G., Zangiacomo A.L., Savastano H., Jr., Tonoli G.H.D. Jute fibers and micro/nanofibrils as reinforcement in extruded fiber-cement composites. Constr. Build. Mater. 2019;211:517–527

and reinforcements for plastics and concrete, and geotextile. Flax yarns have been considered environmentally friendly yarns with the ability to replace glass fibers in engineering composites. [6] [7] [8]

Sisal fiber is a vegetable fiber having specific strength and stiffness that compare well with those of glass fiber. [9] The physical and mechanical behaviors of sisal fiber depend on their source, age, and location, as also their fiber diameter, experimental temperature, gauge length, and strain rate. Sisal fiber is a potential reinforcement for polymer composites. Beyond its traditional applications (ropes, carpets, mats, etc.), sisal fiber has potential applications in the aircraft and automobile sectors. [10]

Coir fiber is the natural fiber extracted from the husk of the coconut. The coir fiber is the thickest and most resistant of all commercial natural fibers. It is used in upholstery padding, sacking, and horticulture. Coir is often used in gardening and landscaping projects, for making fishing nets, nets for shellfish harvesting and marine rope for boats, in construction for drainage applications, and different types of household items. Coir fiber treated with 2% alkali was used to reinforce polyester composites and the fruit shell can be used as another form of reinforcement in the composites sector.[11]

Ramie fibers. The ramie plant produces fibers from the bark which are used for textile raw materials. The fiber produced from the ramie plant is very strong compared to all fiber-based plants, even more than double the fiber of cotton. Ramie fiber has several advantages, namely the texture is smooth, long, and strong, which is very good and important for natural fibers. Apart from that, ramie fiber also has other advantages such as resistance to bacteria and higher tensile strength under hygroscopic conditions. Ramie fiber which has a high enough strength is more widely used as technical textiles or functional textiles, such as geotextiles, military textiles, medical textiles, and others. Another use is the manufacture of ramie textile-based composites.[12]

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[6] Seghini M.C., Touchard F., Sarasini F., Chocinski-Arnault L., Tirillò J., Bracciale M.P., Zvonek M., Cech V. Effects of oxygen and tetravinylsilane plasma treatments on mechanical and interfacial properties of flax yarns in thermoset matrix composites. Cellulose. 2020;27:511–530.

[7] Deng, Y., and Tian, Y. 2015. "Assessing the Environmental Impact of Flax Fibre Reinforced Polymer Composite from a Consequential Life Cycle Assessment Perspective." Sustainability-Basel 7 (9): 11462–83. https://doi.org/10.3390/su70911462.

[8] Yan, L., Chouw, N., and Jayaraman, K. 2014. "Flax Fibre and Its Composites – A Review." Compos Part B-Eng 56 (January): 296–317. https://doi.org/10.1016/j.compositesb.2013.08.014.

[9] Johannes Karl Fink, Chapter 1 - Unsaturated Polyester Resins, Editor(s): Johannes Karl Fink, In Plastics Design Library, Reactive Polymers Fundamentals and Applications (Second Edition), William Andrew Publishing, 2013, Pages 1-48.

[10] J. Naveen, M. Jawaid, P. Amuthakkannan, M. Chandrasekar, 21 - Mechanical and physical properties of sisal and hybrid sisal fiber-reinforced polymer composites, Editor(s): Mohammad Jawaid, Mohamed Thariq, Naheed Saba, In Woodhead Publishing Series in Composites Science and Engineering, Mechanical and Physical Testing of Biocomposites, Fibre-Reinforced Composites and Hybrid Composites, Woodhead Publishing, 2019, Pages 427-440.

[11] L.C. Hao, S.M. Sapuan, M.R. Hassan, R.M. Sheltami, 2 - Natural fiber reinforced vinyl polymer composites, Editor(s): S.M. Sapuan, H. Ismail, E.S. Zainudin, In Woodhead Publishing Series in Composites Science and Engineering, Natural Fibre Reinforced Vinyl Ester and Vinyl Polymer Composites, Woodhead Publishing, 2018, Pages 27-70, ISBN 9780081021606, https://doi.org/10.1016/B978-0-08-102160-6.00002-0

[12] Sudirman Habibie, Nandang Suhendra, Budiman Adi Setiawan, Muhammad Hamzah, Nuning Aisah, Diah Ayu Fitriani, Riesma Tasomara, Mahendra Anggaravidya, Prospect of Ramie Fiber Development in Indonesia and Manufacturing of Ramie Fiber Textile-based Composites for Industrial Needs, an Overview, *International Journal of Composite Materials*, Vol. 11 No. 3, 2021, pp. 43-53. doi: 10.5923/j.cmaterials.20211103.01.

b. **Animal fibers** - silk, wool, mohair, and alpaca.

Wool is the most complex and versatile of all textile fibers. Due to its very special and unique properties, it is being widely used for conventional applications such as carpets, rugs, shawls suitings, knitwear, etc. Now, its increasingly being used in technical applications. The wool is used to make special clothing and sports equipment but also protective equipment. Performance of wool in terms of its resiliency and thermal are applied in furnishings, upholstery, and industrial uses. Wool can be recommended to use in medical and geotextile.[13]

c. **Geological or mineral fibers** are obtained from mineral sources. Mineral fibers can be metallic such as aluminum; asbestos such as serpentine and amphiboles; or ceramic such as glass wool and quartz, silicon carbide, aluminum oxide, and boron carbide[14]

1.1.2. Synthetic Fibers

Synthetic fibers are man-made fibers developed to improve the properties of natural fibers. Synthetic fibers are obtained via an extrusion process of polymers prepared by reacting to certain monomers through a process called polymerization. Synthetic fibers used for the production of technical textiles are divided into glass and ceramic fibers, aramid fibers, viscose rayon fibers, carbon fibers, polyolefin fibers, and nylon fibers.

a. Glass and Ceramic Fibers

Glass has been used as an inexpensive insulator as well as reinforcement of comparatively low-performance plastics. It is now broadly used for various high-performance glass-reinforced composite purposes such as sealing, rubber reinforcement, filters, Pro-Tech clothing, packaging, and the automotive industry to replace metal body parts and components. The use of ceramic fibers in composite applications is taking attraction/attention for the last decades. From the point of view of industrial implementation, ceramic-fiber-reinforced composites are utilized in many different commercial products such as aircraft engine components (turbine combustors, compressors, and exhaust nozzles), automotive and gas turbine elements, aerospace missiles, heat exchangers, hot gas filters, rocket nozzles, gasket, and wrapping insulations.[15]

b. Aramid Fibers

Aramid fiber was the first organic fiber used as reinforcement in advanced composites with high enough tensile modulus and strength. They have much better mechanical properties than steel

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[13] Ramchandra Sawant[1*], Aniket Bhute[2], Mayur Basuk[3], Wool in technical textiles, https://www.textiletoday.com.bd/wool-in-technical-textiles/
[14] Demott G., Marolt B., Ducarme D. Manufacturing of Continuous Mineral Fibers. Application 15/546,277. U.S. Patent. 2018 Jan 25
[15] Emre Yalamaç, Mucahit Sutcu, Suat Bahar Basturk,9 - Ceramic fibers, Editor(s): M. Özgür Seydibeyoğlu, Amar K. Mohanty, Manjusri Misra, In Woodhead Publishing Series in Composites Science and Engineering, Fiber Technology for Fiber-Reinforced Composites, Woodhead Publishing, 2017, Pages 187-207, ISBN 9780081018712, https://doi.org/10.1016/B978-0-08-101871-2.00009-6.

and glass fibers on an equal weight basis. Aramid fibers are inherently heat- and flame-resistant, which maintain these properties at high temperatures. Aramid fibers have been used extensively in body armor, vehicle armor, military helmets, protective gloves, and fireproof suits for firefighters. Aramid fibers are often used in composites in a broad spectrum of industrial, aerospace, military, and civilian applications.[16] [17]

c. Viscose Rayon Fibers

Viscose rayon is a cellulosic fibre, which is manufactured by regeneration. It is neither a synthetic fibre nor natural fibres fully because it is obtained from naturally occurring polymers. Viscose rayon fibers had significance in tires and other mechanical rubber products, such as conveyors, safety belts, and hoses. Additional characteristics of viscose, such as heat resistance and high absorbance are favorable factors for use in disposable clean and hygienic applications, upholstery, and bedspreads.[18]

d. Carbon Fibers

Carbon fibers can be categorized into two groups: carbon fibers made by carbonizing precursor fibers and carbon fibers synthesized directly from a hydrocarbon gas, such as methane. In recent decades, carbon fibres have found wide application in commercial and civilian aircraft, recreational, industrial, and transportation markets. Carbon fibre is a unique combination of strength, and lightweight, these qualities make it fit to be used in applications where strength, lightweight, and good shelf life are the basic requirements. They also can be used on occasions where high temperature, chemical inertness, and high damping are important. It is used in the field of aerospace, nuclear, transportation, and general engineering. Various components like bearings, gears, cams, fan blades, and automobile bodies employ carbon fibre. Others include decoration in automotive, marine, general aviation interiors, general entertainment, musical instruments, and after-market transportation products. [19]

e. Polyolefin Fibers

Polyolefin fibres have good tensile properties, good abrasion resistance, and excellent resistance to chemicals, mildew, micro-organisms, and insects. These make them very suitable for a variety of applications such as packaging, carpet backing, and furniture linings. [20]

f. Nylon Fibers

[16] Mustafa Ertekin, 7 - Aramid fibers, Editor(s): M. Özgür Seydibeyoğlu, Amar K. Mohanty, Manjusri Misra, In Woodhead Publishing Series in Composites Science and Engineering, Fiber Technology for Fiber-Reinforced Composites, Woodhead Publishing, 2017, Pages 153-167, ISBN 9780081018712, https://doi.org/10.1016/B978-0-08-101871-2.00007-2.

[17] R.A. Ash, 9 - Vehicle armor, Editor(s): Ashok Bhatnagar, In Woodhead Publishing Series in Composites Science and Engineering, Lightweight Ballistic Composites (Second Edition), Woodhead Publishing, 2016, Pages 285-309, ISBN 9780081004067, https://doi.org/10.1016/B978-0-08-100406-7.00009-X.

[18] https://www.technicaltextile.net/articles/important-fibres-of-technical-textile-2538

[19]

[20] Mabrouk Ouederni,Chapter 10 - Polymers in textiles, Editor(s): Mariam Al Ali AlMaadeed, Deepalekshmi Ponnamma, Marcelo A. Carignano, Polymer Science and Innovative Applications, Elsevier, 2020, Pages 331-363, ISBN 9780128168080, https://doi.org/10.1016/B978-0-12-816808-0.00010-X.

Nylon Fibers afford high-quality elasticity and uniformity, abrasion and moisture resistance, and high strength. In technical textiles, nylon fibres are widely used for a number of the following applications: in carpet fibres, because of resilience and excellent aberration resistance, parachute fabrics, safety belts in cars, hoses, and lightweight canvas for luggage are exclusively made from nylon filaments, tyres for trucks and airplanes are made from nylon tyre cords, ropes, and cordages, fishing nets, sailcloth, ribbons for printers, bolting cloths, sutures, and toothbrush bristles.[21]

g. Polyester Fibers

Polyester fibers are strong and very elastic. They have high abrasion and wrinkle resistance. and less flame resistance, when ignited they can melt. Compared to plant-based fibers, synthetic polyester fibers have better tear, water, and environmental resistance. Knitted or woven fabrics made from polyester thread or yarn are widely used in home furnishings: blankets, bed sheets, comforters, carpets, cushioning and insulating in pillows, upholstery padding and upholstered furniture. Industrial polyester fibers, yarns and ropes are used in tire reinforcements, safety belts, tapes, fabrics for conveyor belts, and in plastic reinforcements with high-energy absorption. [22]

h. Acrylic fiber has high resistance to UV degradation, and to damage from mould, mildew and micro-organisms. The structure allows the acrylic fibers to develop woollike bulk and resiliency. These fibers are used as precursors for the manufacture of carbon and graphite fibers. Acrylic fabric is one of the least breathable forms of textiles and it is widely used in heat-retention applications: athletic equipment, tracksuits, hoodies, athletic pants. Also, the fibers can be used in fake-fur products, upholstery fabrics, anti-bacterial socks,

I. Elastane, known as Lycra or Spandex is made up of polyurethane. It is a lightweight, synthetic fibre used to make stretchable clothing. It is scratch resistant, strong, durable and it has a higher retractive force than rubber. Elastane is used in all areas where a high degree of permanent elasticity is required: intights, sportswear, swimwear, corsetry, and in wovenand knitted fabrics[23].

1.2. TEXTILE COMPOSITES

Textile composites represent a class of advanced materials, which are reinforced with textile preforms for structural or load-bearing applications. The properties of a composite are superior to the properties of the individual components. Reinforcement is the main load-bearing component and is responsible for the strength and stiffness of the composite material.[24]

Textile composites are composed of textile reinforcements combined with a binding matrix (usually polymeric). This describes a large family of materials used for load-bearing applications within several industrial sectors. The term textile is used here to describe an interlaced structure consisting

[21] B.L. Deopura, N.V. Padaki, Chapter 5 - Synthetic Textile Fibres: Polyamide, Polyester and Aramid Fibres, Editor(s): Rose Sinclair, In Woodhead Publishing Series in Textiles, Textiles and Fashion, Woodhead Publishing, 2015, Pages 97-114, ISBN 9781845699314, https://doi.org/10.1016/B978-1-84569-931-4.00005-2.
[22] https://polymerdatabase.com/Fibers/Polyester.html
[23] M.Senthilkumar, N, Anbumani, J. Hayavadana, (2011). Elastane fabrics – A tool for stretch applications in sports, Indian Journal of Fibre & Textile Research, Vol. 36, September 2011, pp. 300-307
[24] https://www.intechopen.com/chapters/55424

of yarns, although it also applies to fibres, filaments, and yarns, and most products derived from them.[25]

Textile composites encompass a wide variety of textile structures, which include braids, weaves, knitting, and nonwoven fabrics. Examples of the wide variety of textile structures that can be implemented in the design of advanced composite structures are shown in figure 2.[26]

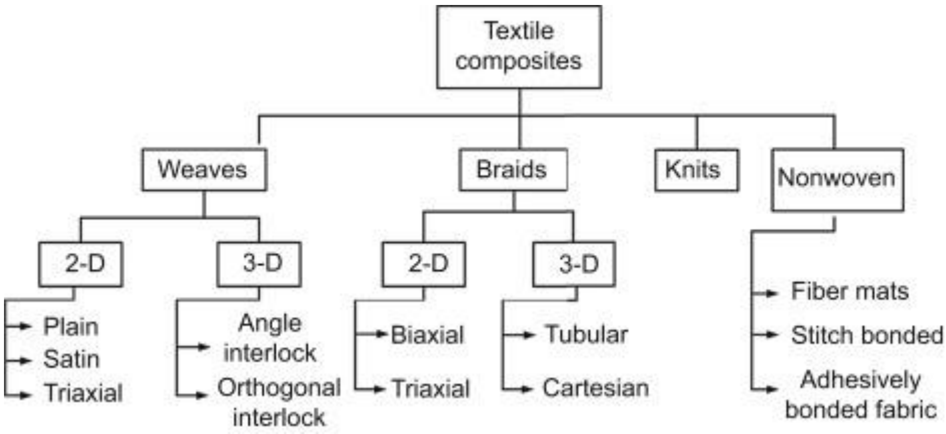


Fig. 2: *Examples of textile structures used in the manufacturing of advanced composite structures*

Source - https://www.sciencedirect.com/science/article/pii/B9780081003695000052

Textile-reinforced composites consist of a textile form as the reinforcement phase and usually a polymer for the matrix phase. 2D or 3D woven fabrics, knitted fabrics, braids, and nonwovens can be used as textile materials. Each of these textile forms has its fiber architecture and combination of properties such as strength, stiffness, flexibility, and toughness which are translated to composite performance to a certain extent. Different textile architectures offer enormous potential for designing composite properties. [27]

Composite materials can be classified into two categories: Thermoplastic Composites and Thermo-set Composites.

- Thermoplastic Composites folosesc resin-like polyester, HDPE, etc. They are lesser used as high-tech materials due to their higher viscosity which causes problems during their penetration into the reinforcement. Their manufacturing required equipment that can withstand high temperatures and pressure which increases the manufacturing cost. But they have some advantages too. For example, they are not toxic and can be recycled.[28]

[25] https://www.sciencedirect.com/science/article/pii/B9781855737440500181
[26] https://www.sciencedirect.com/topics/materials-science/textile-composite
[27] https://www.intechopen.com/chapters/55424
[28] https://www.fibre2fashion.com/industry-article/4503/classification-and-applications-of-textile-composite-materials-part-1

- In Thermo-set Composites polymers like epoxy, unsaturated polyester, and vinyl-ester are used as the resin. They are the most used type of composites materials in automotive, naval, aeronautical, and aerospace applications. They are preferred over thermoplastic resin due to their lesser viscosity (normally lesser of the order of 103 times than thermoplastics) which helps them to penetrate in reinforcement easily even at room temperature. Moulding equipment used is relatively cheaper as there is no need to rise to very high temperatures and pressure. They have the disadvantages of being toxic, non-recyclable, and lesser availability for penetration time once polymerization starts.[29]

Textile composites are used typically because of their high strength-to-weight and stiffness-to-weight ratios.[30]

One of the fundamental advantages of composite materials is that they can be designed to acquire a wide variety of properties by changing the type and proportions of constituent materials, their directions, process parameters, etc. Composites additionally have high mechanical properties with a low weight which makes them ideal materials for automotive and aerospace applications. High fatigue resistance, toughness, thermal conductivity, and corrosion resistance are other of the composite's advantages. The principal impediment of composites is the high processing costs which limit their wide-scale utilization.[31]

Because of these properties, composite textiles find a wide range of use. Target application areas for textile composites are primarily within the aerospace, marine, defence, land transportation, construction, and power generation sectors. Fiber-reinforced composite materials have gained popularity (despite their generally high cost) in high-performance products that need to be lightweight, yet strong enough to take harsh loading conditions such as aerospace components (tails, wings, fuselages, propellers), boat and scull hulls, bicycle frames and racing car bodies.

Several structures for the Airbus A380 passenger aircraft, the world's largest passenger airliner, rely on textile composites, including the six-meter diameter dome-shaped pressure bulkhead and wing trailing edge panels, both manufactured by resin film infusion (RFI) with carbon non-crimp fabrics, wing stiffeners and spars made by RTM, the vertical tailplane spar by vacuum infusion (VI), and thermoplastic composite (glass/poly (phenylene sulfide)) wing leading edges.[32]

Other application areas include construction. Some potential advantages are the reduction of weight of construction, the (mass) production of complex form components, possible overall cost reductions thanks to industrialized off-site manufacturing processes, reduction in construction time, and production of multifunctional components. For example, composite bridges offer significant cost savings for installation due to their low weight. Membrane structures, such as that used for the critically acclaimed (in architectural terms) Millennium Dome at Greenwich, UK, are also a form of

[29] https://www.fibre2fashion.com/industry-article/4503/classification-and-applications-of-textile-composite-materials-part-1
[30] https://www.sciencedirect.com/science/article/pii/B9781855737440500089?via%3Dihub
[31] https://www.intechopen.com/chapters/55424
[32] https://www.sciencedirect.com/science/article/pii/B9781855737440500181

textile composite.[33] In addition, from an architectural point of view, textile composites offer a variety of appearances: translucency, color, surface texture, finish quality, etc.[34]

Numerous automotive applications exist, primarily for niche or high-performance vehicles but also in impact structures such as woven glass/polypropylene bumper beams.[35] Carbon composite is a key material in today's launch vehicles and heat shields for the re-entry phase of spacecraft. Furthermore, disk brake systems of airplanes and racing cars are using carbon/carbon material, and the composite material with carbon fibres and silicon carbide matrix has been introduced in luxury vehicles and sports cars.[36]

Probably the largest components produced are for off-shore wind power generation, with turbine blades of up to 60 meters in length being produced using (typically) non-crimp glass or carbon fabric reinforcements impregnated via vacuum infusion.[37]

Another area of applicability of textile composites is in sports. For example, they are used to make baseball bats (a combination of wood with E-glass (or graphite) fiber-reinforced composite results in an optimal combination of ball speed control and shock absorbance) or at the realization of modern skis that combine composites with metal and natural (and other) materials.[38]

Splinting materials for the repair of broken bones are not only the largest medical market for textile reinforced composites but the oldest. Several textile materials can be used to reinforce natural tissues as well as replace them. Textile surgical implants, such as suture threads, have been in use for many generations and over the past 40 years, there has been extensive use of polyester woven and knitted tubes in the replacement of arteries. More recently, however, textile structures have been developed that will act as a scaffold for natural tissue re-growth, the textile remaining within the body for the rest of the patient's life and forming a living textile-reinforced composite. [39]

Other uses include fishing rods, storage tanks, swimming pool panels, etc.

1.2.1. STATISTICAL DATA

The textile and clothing sector is an important part of the European manufacturing industry, playing a crucial role in the economy and social well-being in many regions of Europe. According to data from 2019, there are 160,000 companies in the industry employing 1.5 million people and generating a turnover of €162 billion. The sector in the EU is based on small businesses. Companies with less than 50 employees account for more than 90% of the workforce and produce almost 60% of the value-added.[40]

[33] https://www.sciencedirect.com/science/article/pii/B9781855737440500181
[34] https://www.sciencedirect.com/science/article/pii/B9781855737440500120
[35] https://www.sciencedirect.com/science/article/pii/B9781855737440500181
[36] https://www.textileschool.com/amp/4474/textile-composite-materials/2/
[37] Long, A. C. (Ed.). (2005). Design and manufacture of textile composites. Elsevier.
[37] https://www.sciencedirect.com/science/article/pii/B9781855737440500181
[38] https://www.sciencedirect.com/science/article/pii/B9781855737440500144
[39] https://www.sciencedirect.com/science/article/pii/B9781855737440500132
[40] https://ec.europa.eu/growth/sectors/fashion/textiles-and-clothing-industries/textiles-and-clothing-eu_en

Technical textiles have an important place in this industry. Technical textiles have seen an upward trend globally in recent years due to improving economic conditions. Technical textiles have been defined as "textiles, fibres, materials and support materials meeting technical rather than aesthetic criteria". They are an input to other industries such as the automotive, medical devices, and agro-food sectors. Technological advancements, increase in end-use applications, cost-effectiveness, durability, user-friendliness, and eco-friendliness of technical textiles have led to the upsurge of its demand in the global market. The technical textile industry is one of the fastest-growing industries in the world. It is a highly innovative and versatile industry, serving a wide range of end markets with less competition and higher added value compared to conventional textiles. These attributes have led many countries to shift their textile industry from conventional to technical.[41] The technical textiles industry is commonly regarded as a top value-added growth industry, where Europe has a strong market position and prominent know-how potential. It is, however, immensely fragmented, comprising a large number of the European SMEs that are specialized in a specific product/market niche (e.g.ballistic protection) or technology (e.g. non-crimp fabric manufacturing).

In the EU27 the technical textiles industry represents around 30% of the total turnover in textiles and it accounts for a growing share (28%) of total textile production (see Figure ...). The sub-sector of technical textiles is one of the most dynamic, accounting for a growing share in the EU Textile production.[42] The growing demand for technical textiles is based on applications in various industries such as healthcare, agriculture, construction, sportswear, automotive, etc.

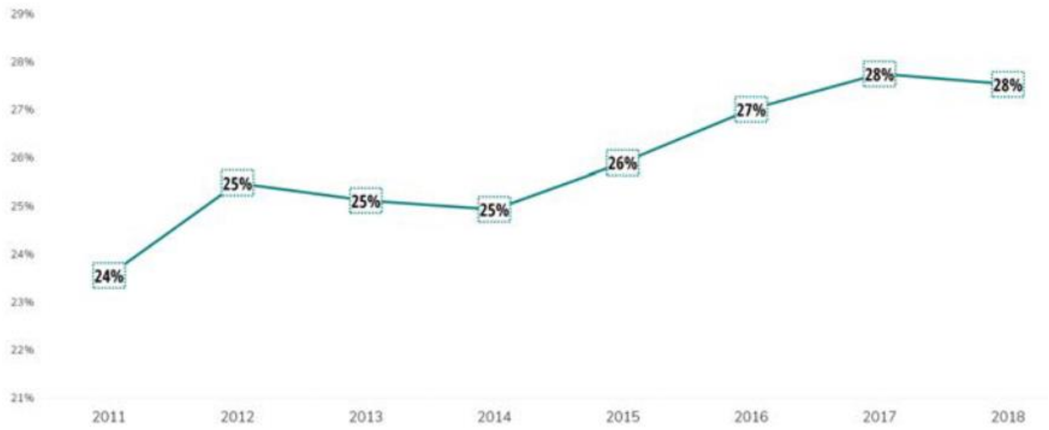


Fig. 3: *Share of technical textiles in total textile production, in the EU 27*

Source - ***https://euratex.eu/wp-content/uploads/EURATEX-Facts-Key-Figures-2020-LQ.pdf***

The technical textiles industry continues to grow in the EU27, where Germany is the European market leader. In 2018, the European countries with the highest volumes of technical textiles production were Germany (32 000 tonnes), Italy (18 000 tonnes), and the UK (15 000 tonnes), with a

[41] https://wwfasia.awsassets.panda.org/downloads/high_res_technical_textile_report_interactive_.pdf
[42] https://euratex.eu/wp-content/uploads/EURATEX-Facts-Key-Figures-2020-LQ.pdf

total production share of 47%, followed by the Netherlands, Spain, Belgium, France, the Czech Republic, Sweden, Poland, Hungary, and Romania, which together accounted for 43%.[43]

The production of technical textiles in the European Union has varied around 140K tons in the last 10 years. The Covid-19 pandemic also affected this industry, so 2020 have been resulting in a significant decrease in production. In 2021, as can be seen in figure no.4, was recovered a large part of the decrease from the previous year.

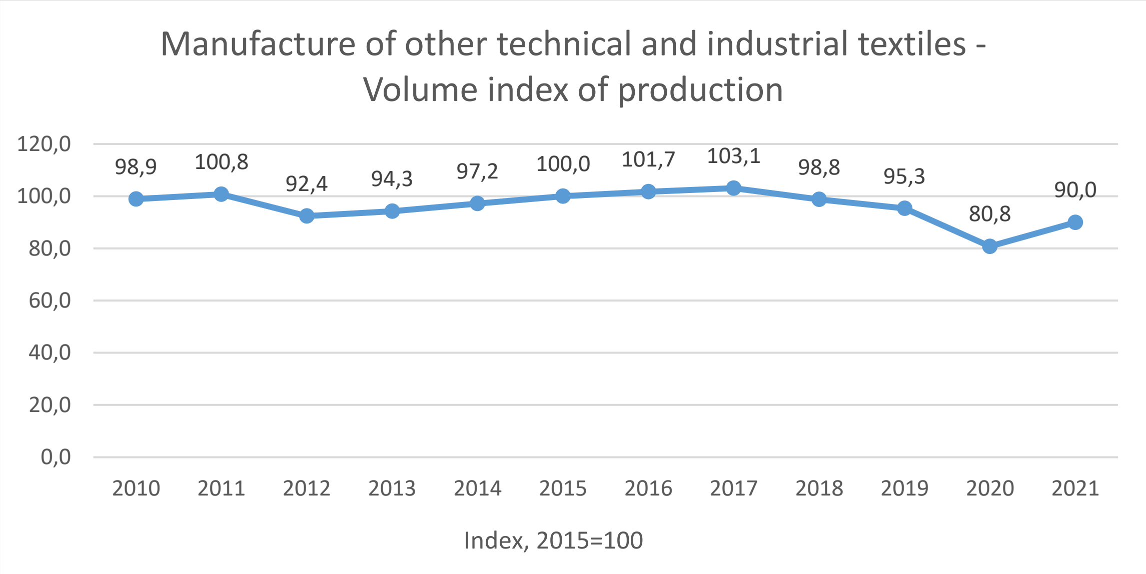
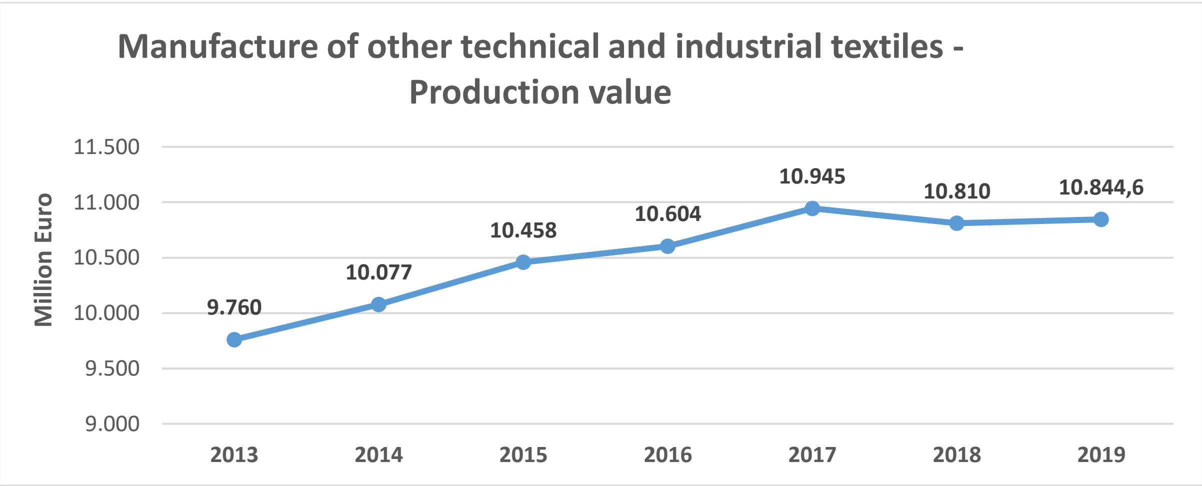


Fig. 2: *Evolution of the production of the technical and industrial textiles, in the EU27*

Source – Eurostat database

Statistical data show that the value of technical textiles production, at the EU level, reached EUR 10,844.6 million in 2019.



43 https://ati.ec.europa.eu/sites/default/files/2021-01/Technological%20trends%20in%20the%20textiles%20industry.pdf

Fig. 3: *Evolution of the production value of the technical and industrial textiles, in the EU27*

Source: Eurostat database

Technical textiles also play an important role in EU exports. Compared to 2009, they increased by 4,7% in 2019 and rank fourth in the top of EU exports of textile and clothing products.[44]

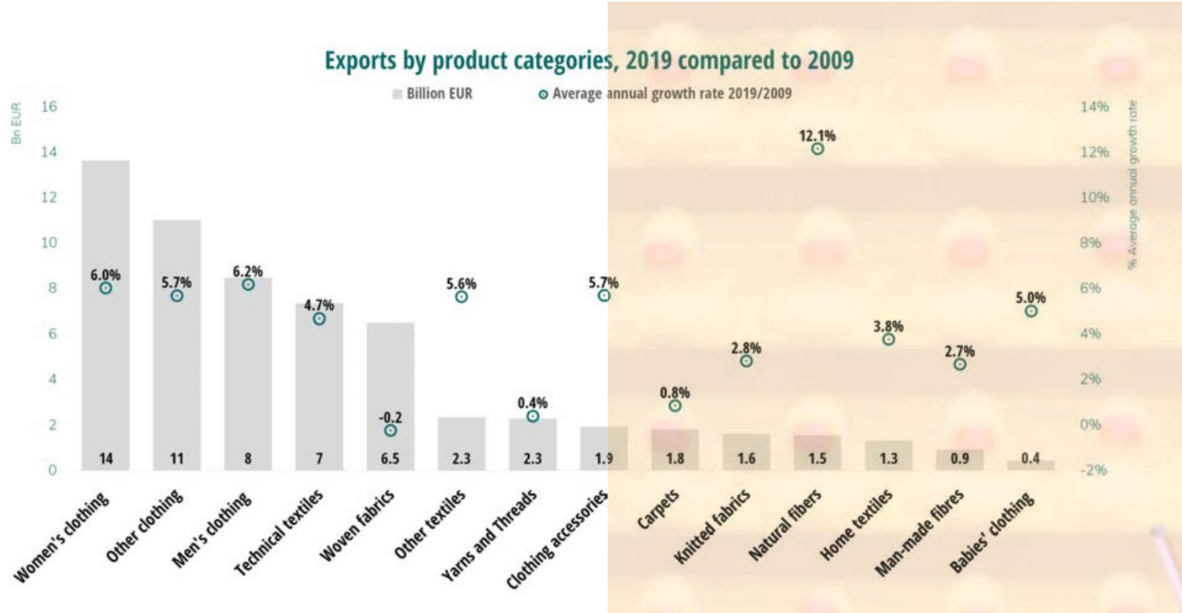


Fig. 4: *EU export by categories, 2019 compared to 2009*

Source: https://euratex.eu/wp-content/uploads/EURATEX-Facts-Key-Figures-2020-LQ.pdf

The figure below indicates an approximate breakdown of technical textile usage in different end markets in Europe.

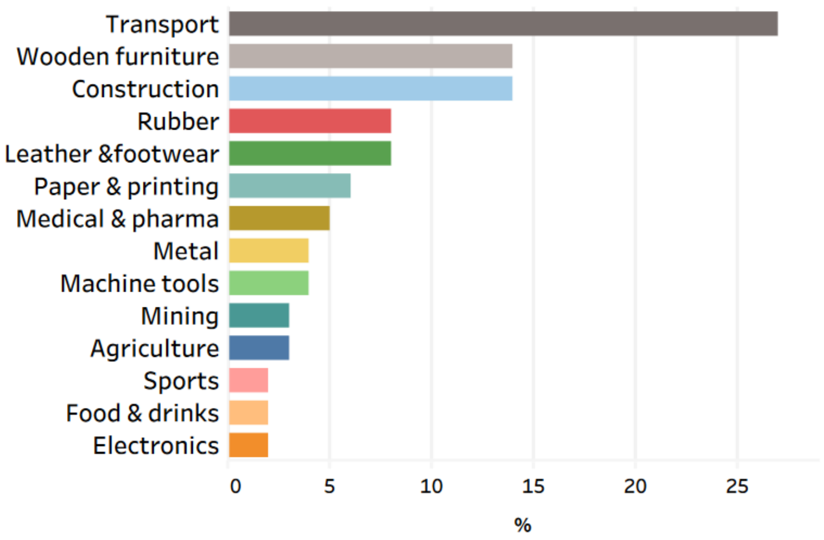


Fig. 5: *Technical textile usage in different end markets in Europe*

[44] https://euratex.eu/wp-content/uploads/EURATEX-Facts-Key-Figures-2020-LQ.pdf

Source:

https://ati.ec.europa.eu/sites/default/files/2021-01/Technological%20trends%20in%20the%20textiles%20industry.pdf

The global technical textiles market is predicted to increase further. The growth of automobile, construction, healthcare, packaging, and other sectors provides new opportunities for further development of the technical textiles sector. Technical textiles are used in crop protection, automotive applications, safety components, healthcare, protective clothing, and more (this market is expanding into packaging, sports, and protective wear). Textiles are widely used in the automotive sector for various applications such as airbags, seat belts, carpets, seat upholstery, and tyres. Non-woven textiles are utilized in the indoor lining, floor mats, headliners, belts, etc.18 Medical textiles are another dynamically expanding field in the technical textile market.[45]

[45] https://ati.ec.europa.eu/sites/default/files/2021-01/Technological%20trends%20in%20the%20textiles%20industry.pdf

2. THE CIRCULAR ECONOMY - A SUSTAINABLE SOLUTION FOR THE TEXTILE INDUSTRY

Textile production in Europe is regulated through a patchwork of EU and national legislation, including production methods and working conditions, fibre names, related labeling, and the marketing of the fibre composition of textile products (EC, 2019c). Legislation on chemicals, industrial emissions, product safety, etc. also regulates textiles. The production of textiles within the EU, for example, is covered by the EU Regulation on Evaluation and Authorisation of Chemicals (REACH) and the Industrial Emissions Directive (IED). Textiles produced outside the EU are also subject to product regulation, such as EU eco-label criteria and green public procurement criteria for textiles. Furthermore, the 2018 revision of the EU Waste Framework Directive (WFD) includes an obligation for the Member States to collect textiles separately by 1 January 2025 (EC, 2019b). [46]

As it is known, textiles are a necessity in people's lives, both for the realization of clothing products and due to the expansion of their fields of use - automotive industry, construction, computers, agriculture, etc. With the increase in textile consumption, the problems related to the scarcity of raw materials and environmental damage increase too. During the entire cycle of making textile products, they generate multiple sources of pollution in the air, water, and soil, noise, and visual pollution and contribute significantly to global warming.

Air pollution from textile industries influences humans, machinery systems, and final goods. There are growing health harms due to the textile industries, such as tuberculosis, byssinosis, and asthma. Air pollution may also occur upon using textiles after production and during the end-use by consumers. For home textile furnishings, various pollutants are due to construction substances, but furniture, rugs, clothing, and wood or fabric furnishes most likely give rise to further customer criticism. This can be attributed to the existence of formaldehyde or other volatile organic materials. Secondary emissions from floor covers include harmful materials such as formaldehyde released, for instance from back coatings.

Water pollution it manifests itself throughout the life cycle of textiles and is made in different forms. High-level pollution exerts the pesticides removed from cotton, flax, and hemp, but also other chemicals (lactic acid, alcohols, peptides, waxes) resulting during the melting process. Water use can be up to 29 m^3 per kg of cotton and the cultivation of cotton uses about 11% of the world's pesticides.[47]

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[46] Vercalsteren, A., Nicolau, M., & Lafond, E. (2019). Textiles and the environment in a circular economy, Eionet Report - ETC/WMGE 2019/6

[47] Palm D., (2011), Improved waste management of textiles, Project 9 Environmentally improved recycling, IVL Swedish Environmental Research Institute Ltd., Gothenburg, Sweden, On line at: https://www.ivl.se/download/18.34244ba71728fcb3f3f7b9/1591704633006/B1976.pdf

Cotton depends on pesticides more than any other crop, using 1/3 of a pound of pesticides per shirt.[48] In the processes of wool processing (degreasing, carbonizing, carding, washing, bleaching, dyeing, etc.) more than 800 chemicals are used, such as acid and alkaline substances, oils, detergents, dyes, SO_2, H_2O_2, etc., all negatively affecting water quality.[49] The negative effects on the water are manifested by the change of pH and color, by the presence of dissolved solids or in suspension, phenolites, chlorides, oils and fats, sodium sulphate, etc. In addition, the textile industry uses a variety of dyes, chemicals, and other materials for different forms of finishes applied to textile products in order to obtain different characteristics, properties or to provide the required qualities to the fabrics. This results in the production of wastewater. Its pollution load increases not only from the removal of impurities from the raw materials themselves but also from the residual chemical reagents used for processing.[50] If they are not properly treated before to discharging, the waste water from wet processing contains hazardous chemicals, including mutagens carcinogens, and teratogens, that cause serious environmental damage by contaminating exhaust gases, waste water. Loss of lubricants or spinning oil from machines can lead to an unintended discharge of harmful materials, and spillage of fuels from vehicles can also happen. Such pollutants have toxic effects on aquatic organisms or the improvement of species, such as algae which eliminate oxygen from water affecting aquatic organisms. Furthermore, aquatic organisms can sometimes survive when ingest such hazardous pollutants to be transmitted up the food chain to influence human beings.

Soil pollution is done through pesticides used, polluted water that seep into the soil and through the huge amount of textile waste that reaches the landfills. Fibers or chemicals can be harmful if their degradation under the effect of air, water or sunlight generates toxic agents. Examples demonstrating the problem involve a variety of toxic degradation products from nylon, polyester, or other polymeric materials which have been discarded in water streams and find their way to landfill locations.

Noise pollution arises in, for example, twist, spin, and weave processes. Unpleasantly, high noise may also occur from transportation systems or other equipment employed in loading, shipping, or handling in textile industries. Several effects may arise from noise pollution, the most apparent effect being hearing loss and deafness. Other effects of high noise levels are psychological problems such as frustration, carelessness, withdrawal, or sullenness.

The textile industry pumps between 1.22 and 2.93 billion tonnes of CO2 into the atmosphere every year. Estimates of the global warming potential of textile productions are 16.9 kg CO_2-equivalents per kg of 50% cotton and 50% polyester, 15 kg CO_2-equivalents per kg of 50% cotton and 50% polyester, and 25 kg CO_2-equivalents per kg of textiles. The result is that, by some estimates, the life-cycle of textiles (including laundering) accounts for 6.7% of all global greenhouse gas emissions.[51]

At the same time, considerable volumes of waste are created that can mainly be classified into three groups: production waste, preconsumer waste, and post-consumer waste. Production waste is composed of fiber, yarn, cloth scraps, flock, sweeping, fabric cut-offs, fabric roll ends, and selvage

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[48] Heuer M., Becker-Leifhold C., (2018), Eco-friendly and Fair: Fast Fashion and Consumer Behaviour, Routledge, 1st Edition, doi: 10.4324/9781351058353
[49] Kulkaria B.V., (2007), Sequential coagulation studies for primary treatment of textile process effluent instead of acid neutralization, Journal of the Industrial Pollution Control, 23, 123-130.
[50] Correia V.M., Stephenson T., Judd S.J., (1994), Characterisation of textile wastewaters ‐ a review, Environmental Technology, 15, 917-929
[51] Steve Trent, Clothes and climate: Is cotton best?, https://ejfoundation.org/news-media/clothes-and-climate-is-cotton-best

generated by fiber producers, weavers, knitting companies, and apparel manufacturers. Preconsumer waste consists of products that are manufactured with design mistakes, fabric faults, or the wrong colors being produced for sale and consumption and postconsumer waste consists of any types of household articles or garments made from fabricated textiles that the owner does not require anymore and has decided to discard. Consumers may discard these articles when they are worn out, damaged, outgrown, or out of fashion. At present, a part of the textile waste resulting from the production processes is used for the production of non-woven textiles, textile composite, the creation of collections of clothing products made entirely or partially out of different kinds of textile waste, etc.

Much of the literature that analyses the issue of waste generated by industry highlights the advantages of moving from the linear production model to the circular one. The linear production model consists of extracting materials from resource-rich countries and then manufacturing products using those virgin resources.[52] The four stages of a usual product life cycle are extraction and processing of raw materials, manufacture, use, and end of life. Stahel (2016) says that a linear economy flows like a river, turning natural resources into base materials and products for sale, through a series of value-adding steps. At the selling point, the customer is liable for risks and waste. They decide whether old things will be reused, recycled, or dumped.

Because of this linear production model, resources are lost unnecessarily in different ways: waste in the production chain, end-of-life waste, use of excessive energy, and erosion of ecosystems.[53] Materials that reach the end of their lives are considered waste and they are either sent to landfills or incinerated. This kind of economy has a major impact on the environment, namely – land-use change, climate change, resource scarcity, biodiversity loss, loss of biosphere integrity, an overload of nitrogen and phosphorus in biogeochemical cycles, and increasing levels of pollution.

Even the elimination of these materials results in hazardous waste. When compared to pre-industrial levels (1850 -1900), without modifying the usual business approach, it is predicted that the average temperature of the global surface will suffer an increase, from 3.7°C to 4.8°C in 2100.[54] The upper limit of temperature change is estimated to be roughly 2°C; exceeding this limit will most probably affect ecological systems, human health, and societies.[55] MacArthur (2013) shows that even at the microeconomic level it was found that the linear economic system increases its exposure to risks, most notably through volatility in resource prices and vulnerability to supply restrictions.[56]

In these conditions, the transition to a circular economy is considered a viable solution that will have the main effect of reducing our global sustainability pressures. Geissdoerfer et al (2017) define the Circular Economy as a "regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops". They also consider that this can be achieved through long-lasting design, maintenance, repair, reuse,

[52] Franco MA. 2017. Circular economy at the micro level: A dynamic view of incumbents' struggles and challenges in the textile industry. *Journal of Cleaner Production*, 168, 833-845
[53] Michelini G, Moraes RN, Cunha RN, Costa JM, Ometto AR. 2017. From linear to circular economy: PSS conducting the transition. *Procedia CIRP*, 2017, 64, 2-6
[54] The Core Writing Team, Pachauri RK, Meyer L. 2014. Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change, On line at: https://www.ipcc.ch/site/assets/uploads/2018/05/SYR_AR5_FINAL_full_wcover.pdf
[55] Field CB. 2014. *Climate change 2014–Impacts, adaptation and vulnerability: Regional aspects*, Cambridge University Press
[56] MacArthur E. 2013. Towards the circular economy. *Journal of Industrial Ecology*, 2, 23-44

remanufacturing, refurbishing, and recycling".[57] Jawahir and Bradley highlight the great potential for financial cohesiveness and environmental stability in the preservation of human life biodiversity and economic progression. All this led to resulted in CE being thrust at the forefront of sustainable development implementation.[58]

The concept of circular economy has gained popularity among manufacturing industries due to its untapped environmental and economic benefits and has particularly been identified with endeavors to accomplish a more sustainable society.[59] The circular economy is a cyclic framework that aims to dispose of waste by turning products that are toward the end of their life cycle into resources for new ones.[60]

The circular economy emerges as a potential strategy for the development of business practices based on environmental concerns. A study of seven European nations shows that a shift to a circular economy would reduce each nation's greenhouse-gas emissions by up to 70% and grow its workforce by about 4% — the ultimate low-carbon economy.[61]

Today, most authors agree that the circular economy refers to an industrial economy that is restorative and regenerative by intention and design.[62] Stahel (2016) compares a circular economy with a lake and highlights that the reprocessing of goods and materials generates jobs and saves energy while reducing resource consumption and waste.[63] In Sariatli's (2017) opinion, the strong points of the circular economy are considered to be: efficiency in the material flow cycle given by eliminating waste from the value chain, development of higher quality and more durable products through incorporating the attributes of CE in the R&D phase, growth of the less exposed economy to price fluctuations of the materials, and better use of resources.[64] Circular economy looks at the entire life cycle of a process, starting from the design stage, before considering the stage of the product and the actors participating in the cycle, with the ultimate goal of implementing a 'closed-loop 'cycle. The circular economy has been designed to achieve and understand new patterns and to help stabilize society with little, or zero, material, energy, and environmental costs in a sustainable manner.[65]

In textile and clothing manufacturing, the Circular Economy may be represented as shown in the following figure:

[57] Geissdoerfer M, Savaget P, Bocken N, Hultink E. 2017. The Circular Economy –a new sustainability paradigm?. *Journal of Cleaner Production*, 143, 757–768
[58] Jawahir, I. S., & Bradley, R. (2016). Technological elements of circular economy and the principles of 6R-based closed-loop material flow in sustainable manufacturing. Procedia Cirp, 40, 103-108.
[59] Alhawari, O.; Awan, U.; Bhutta, M.K.S.; Ülkü, M.A. Insights from Circular Economy Literature: A Review of Extant Defini-tions and Unravelling Paths to Future Research. Sustainability **2021**, 13, 859.
[60] Ferasso, M.; Beliaeva, T.; Kraus, S.; Clauss, T.; Ribeiro-Soriano, D. Circular economy business models: The state of research and avenues ahead. Bus. Strategy Environ. 2020, 29, 3006–3024.
[61] Stahel WR. 2016. The circular economy. Nature, 531, 435–438
[62] MacArthur E. 2013. Towards the circular economy. *Journal of Industrial Ecology*, 2, 23-44.
[63] Stahel WR. 2016. The circular economy. Nature, 531, 435–438
[64] Sariatli F. 2017. Linear economy versus circular economy: a comparative and analyzer study for optimization of economy for sustainability. *Visegrad Journal on Bioeconomy and Sustainable Development*, 6, 31-34
[65] Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner production*, *114*, 11-32.

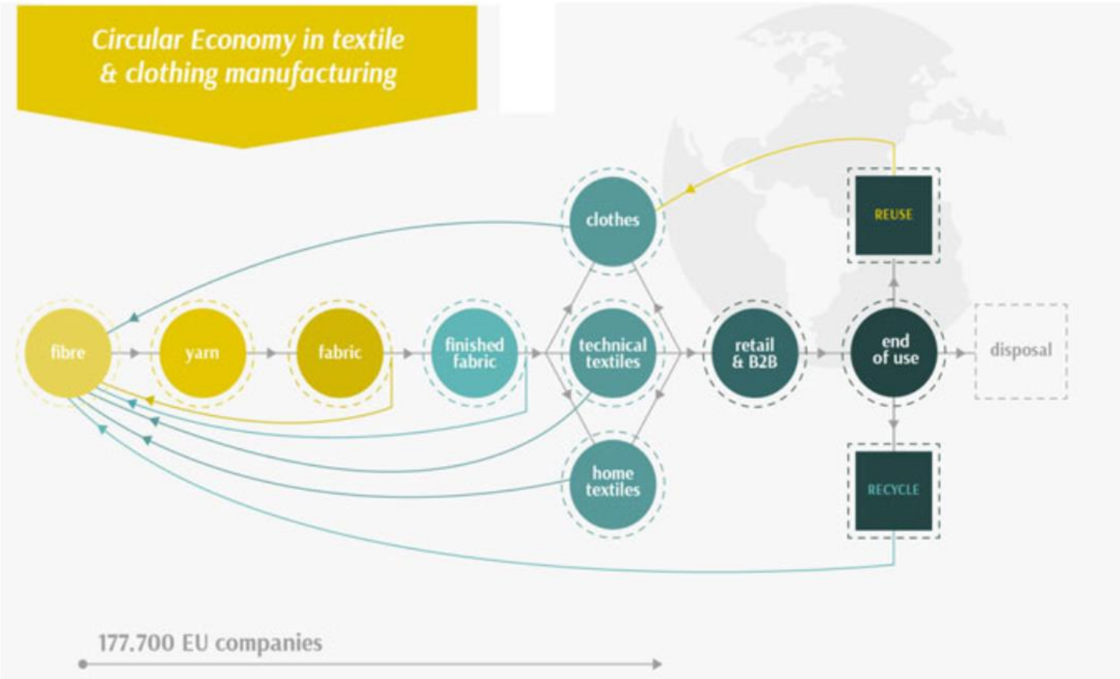

Fig. 6: *Circular Economy in textile & clothing manufacturing*

Source: https://library.oapen.org/bitstream/handle/20.500.12657/23059/1007099.pdf?sequence=1#page=262

In a circular economy, not only the aspects of sustainability are essential for shaping the performance of companies, but also the relationships among these and other social and economic agents. An important aspect of a circular economy is that it emphasizes the consumer's responsibility as well as the producers' responsibility (Zhijun & Nailing, 2007).[66]

According to the European Commission (EC), the EU's competitiveness could be stimulated by the circular economy. This type of economy promotes businesses' protection against deficiency of resources and volatile prices, contributing to the creation of new business opportunities and innovative, more efficient ways of producing and consuming. Also, it will save energy, create local jobs for all skill levels and opportunities for cohesion and social integration and help avoid the irreversible damage caused by using up resources at a rate that exceeds the Earth's capacity to renew them (EC Communication, 2015).[67]

2.1. CIRCULAR BUSINESS MODELS AND GOOD PRACTICES FOR TEXTILES

A business model with attributes of the circular economy implies "creating value by exploiting value retained in used products to generate new offerings".[68] Allen et al. (2021) consider that the

[66] Zhijun, F., & Nailing, Y. (2007). Putting a circular economy into practice in China. *Sustainability Science*, *2*(1), 95-101.
[67] EC Communication, COM/2015/0614 final, Closing the loop - An EU action plan for the Circular Economy, 2.12.2015, Brussels, On line at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015DC0614
[68] Linder, M., & Williander, M. (2017). Circular business model innovation: inherent uncertainties. Business strategy and the environment, 26(2), 182-196.

implementation of circularity solutions is an inter-organizational effort focused on innovation, collaborations with stakeholders, and consumer education.[69]

2.1.1. Choice of materials

The first choice to be made when developing textile products concerns the materials that are used in yarns and fabrics. Different fibres are produced from different resources and thus have different environmental and climate impacts. The chemicals used to dye them also have a significant environmental impact. In the case of technical textiles, the environmental impact is also manifested by the finishes to which they are subjected. These involve the application of chemicals to the yarn or the fabric to introduce a variety of functions, such as water-repellent, flame-retardant properties, antistatic or antimicrobial, and antifungal properties.

Strategies for moving towards more circularity and sustainability will vary between different fibre types.

In the case of natural fibres, such as cotton, the most pressure is on the land and water resources. Given that cotton farming is a major user of fertilizers and pesticides, potentially polluting the surface and groundwater through runoff. Sustainable cotton production would imply a more efficient use of water and agrochemicals, a shift to the use of less toxic chemicals, and the implementation of farming techniques that conserve soils, such as composting, crop rotation, and reduced tillage. A downside of organic cultivation is that it may reduce yields, leading to more land being used.

In the case of synthetic fibres, such as polyester, the environmental impact is manifested by the high consumption of energy and the use of fossil resources as feedstock for production. Other synthetic fibers high-energy-consuming are Acrylic and nylon fibres.[70] The proposed solution to reduce energy and resource consumption is the use of recycled fibers. The disadvantage of this solution is that the recycling processes cause fibers to deteriorate over time, limiting their potential for reuse.

At present a significant quantity of yarn is made of a mixture of fibers which makes it difficult to recycle them. The solution proposed in this case is the production of yarns only from those fiber combinations that can be recycled.

Chemicals used during textile production pose risks to the environment as they tend to leach out during use and washing. The proposed solutions refer to the reduction of chemicals used in the textile industry and substituting hazardous ones with environmentally less hazardous options. There is growing talk of the use of natural dyes, and the use of pigments, and enzymes to reduce the use of chemicals, water, and energy consumption. Another solution is the reuse of the products because as the reused clothes have been washed many times, fewer chemicals will be present in the fabric,

[69] Allen, S. D., Zhu, Q., & Sarkis, J. (2021). Expanding conceptual boundaries of the sustainable supply chain management and circular economy nexus. *Cleaner Logistics and Supply Chain*, *2*, 100011.
[70] Turley, D. B., Horne, M., Blackburn, R. S., Stott, E., Laybourn, S. R., Copeland, J. E. and Harwood, J., 2009, The role and business case for existing and emerging fibres in sustainable clothing: final report to the Department for Environment, Food and Rural Affairs (Defra), London, UK

making their use not only better for the environment, and a consumer's wallet, but also better for people's health.[71]

2.1.2. Examples of good practices

- *Developments of antistatic treatments*. One of the most remarkable developments in antistatic treatments has been the production of the durable antistatic finishing processes, such as the commercial Permalose antistatic agent, which is a series of treatments using block copolymer consisting of ethylene oxide and a polyester.[72]

- *Sustainable chemistry method to improve the wash-off process of reactive dyes on cotton.* Reactive dyes are extensively used for the coloration of cellulosic fibres because of their excellent wash fastness (stability to washing with aqueous detergent solutions), which arises from covalent bond formation between dye and fibre. Existing and developmental Dye Transfer Inhibiting (DTI) polymers were employed to remove unfixed (hydrolyzed) dyes. It was found that the use of DTI in the wash-off of reactive dyes enables a much more efficient, economical, and sustainable process to be developed, which significantly reduces operation time, water consumption, and energy consumption.[73]

- *Detox: from threat for brands to opportunity for labs and manufacturers.* Several chemical substances have always been used to make clothes, which through water discharges and household care can be harmful to the environment and toxic to human health. To protect fresh and seawater resources, in 2011 Greenpeace launched the Detox campaign, aimed at having cleaner and toxic-substances-free fashion. The list of substances to be eliminated has grown to around 430 compounds now.[74]

- *Medical antibacterial textiles were obtained on a pilot line based on the sonochemical process.* The good practice addressed to production of medical antibacterial textiles, to prevent, control, and reduce the nosocomial infections of patients and personnel in the hospital. Is known as hospital-acquired infections are a major financial issue in the European healthcare system. The good practice directly addresses the above problems by developing a pilot line for the production of medical antibacterial textiles based on the scale-up of a sonochemical process developed and patented by Bar Ilan University (Israel) laboratories.[75]

- *Sustainable textile finishing using ozone and nanobubble technologies.* The main problem addressed is the massive consumption of chemicals and water in textile finishing processes applied on fabrics or garments. Processes like desizing, bleaching, washing (roll-to-roll systems on fabrics), and dip-coating functionalization or dyeing (batch systems on garments) are currently developed by wet application systems and chemicals that require huge amounts of water and treatment of the wastewater released. This good practice (use of alternative chemistry like ozone for fabric treatment

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[71] Manshoven, S., Christis, M., Vercalsteren, A., Arnold, M., Nicolau, M., Lafond, E., ... & Coscieme, L. (2019). Textiles and the environment in a circular economy. *Eur Top Cent Waste Mater a Green Econ*, 1-60.
[72] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7794755/
[73] https://eprints.whiterose.ac.uk/84731/3/Nabeel%20-%20SCE%20Paper%202015%20-%20revised2.pdf
[74] https://projects2014-2020.interregeurope.eu/fileadmin/user_upload/tx_tevprojects/library/5.RESET%20GP%20Detox_01.pdf
[75] https://projects2014-2020.interregeurope.eu/fileadmin/user_upload/tx_tevprojects/library/RESET_GP_Sustaibable_chemistry_DAVO_SONO.pdf

in a continuous way, and use of nanobubble technology for garment finishing) can reduce the chemical consumption -also water consumption- in comparison with traditional systems. [76]

2.2. Design stage

The design stage is very important in the development of a circular value chain for textiles. It is at this stage that the choices are made that significantly determine the environmental and climate impact of textile products, as well as the potential for circularity in later stages of the product's lifecycle.

In literature, this stage is known under many terms, such as ecodesign, design for the environment, or sustainable product design.

Ecodesign is a design process that considers the environmental impact associated with a product throughout its entire life from raw materials through production and uses to the end of its life. Ecodesign aims to reduce environmental impact and seeks, at the same time, to improve the aesthetic and functional aspects of the product. It also includes the consideration of social and ethical needs.

Design for the environment is the analysis of the environmental, health, and safety issues relevant to the entire life of the product. The idea is to reduce resource depletion and waste during the manufacture, use, and disposal or reuse of the product.

Sustainable product design is a design philosophy and practice in which products contribute to social and economic well-being, have negligible impacts on the environment, and can be produced from a sustainable resource base.

Design choices have an impact on various stages of the material and product lifecycle. They are key drivers in enabling more circular products because they facilitate the introduction of novel business models, enable re-use and recycling and provide opportunities for integrating re-used parts or recycled material into new products.[77] *At the design stage, careful selection of materials increases the longevity, durability, and repairability of textiles. The materials used determine the potential to keep the product in use for longer and the ease of repair. Several underlying design principles increase the durability and quality of garments, including technical requirements for colorfastness and fabric resistance, and practical requirements that clothes are multifunctional and fit for purpose and that repair kits and/or spare parts are available.*[78]

A wide variety of ecodesign tools exists. These tools help designers to integrate environmental aspects into product development processes. They offer information about potential environmental problems and facilitate a choice between different aspects.[79] The most usable tools with quantitative

[76] https://www.interregeurope.eu/good-practices/sustainable-textile-finishing-using-ozone-and-nanobubble-technologies

[77] Le Blevennec, K., Jepsen, D., Rödig, L., Vanderreydt, I., & Wirth, O. (2018). For Better No t Worse: Applying Ecodesign Principles to Plastics in the Circular Economy. ECOS, VITO and ÖKOPOL. Belgium, Brussels.

[78] https://www.eea.europa.eu/publications/textiles-and-the-environment-the

[79] https://onlinelibrary.wiley.com/doi/full/10.1002/bse.2527

measures are life cycle assessment (LCA), streamlined LCA, ecolabels, matrices, and footprints. There are other types of environmental improvement tools, including mostly qualitative guidelines and manuals. These can be easier to apply and offer simpler information to be used early in the product development process with less product-specific data.[80]

In addition to introducing durable and eco-friendly materials, it is important to bring about behavioral changes in consumers. Ecodesign requires interdisciplinarity between designers, chemists, material developers, etc., and education, both during professional education and in life-long-learning programs for industry professionals.[81]

2.2.1. Examples of good practices

Swedish men's clothing company Nudie Jeans paid part of the living wages for their products to selected Indian suppliers. They started this initiative in support of the idea that anyone producing a Nudie Jeans product should have a salary that they can live on. Action plans were also established in 2020 for the conversion to fully renewable electricity subscriptions in their repair shops and sales offices before the end of 2023. Another decision was related to reducing the use of harmful chemicals and increasing the use of better chemicals.[82]

MUD Jeans

Design is how you control how the product is made, how it lives but also how it dies. To be a circular brand, you need to think of all of these stages. After all, you want a high-quality pair of jeans, that lives a long time, but that can also be easily recycled and reincorporated into production. At MUD Jeans we do this by keeping it simple. We work with 10 different fabrics, one button, and one rivet. We have substituted the leather patch with a non-toxic printed-on version. There are two fabric compositions available, the rigid which is made with 40% post-consumer recycled cotton and 60% GOTS certified cotton, and our stretch which is made from 23% post-consumer recycled cotton, 2% elastane, and 75% GOTS certified cotton.[83]

Finisterre

British swimsuits producing company Finisteree especial attention pays to the ecofriendly and recycled fibres, circular economy. Central to this mission is circular sourcing, which includes renewable and recyclable textiles and biodegradable natural fibres and finishes. Company Finisterre gos beyond designing for durability, creating circular low-impact products without waste, that can be fully recycled or returned to the land at the end of their useful life. Recycled materials from ocean plastics are used for innovative waterproof materials. The oceans of the world are polluted by around 640 000 tons of discarded nylon fishing nets. Nylon Is not only non-biodegradable, but the process of manufacturing it is also highly polluting. This is one of the reasons why Finisteree has invented a way of converting discarded fishing nets and other waste material into a high-performance fabric. It helps to close the loop and turn a plastic problem into fabric solutions. Also, the company has developed a technology

[80] Bovea, M. D., & Pérez-Belis, V. (2012). A taxonomy of ecodesign tools for integrating environmental requirements into the product design process. *Journal of Cleaner Production*, *20*(1), 61-71

[81] https://www.eionet.europa.eu/etcs/etc-wmge/products/etc-wmge-reports/textiles-and-the-environment-in-a-circular-economy/@@download/file/ETC-WMGE_report_final%20for%20website_updated%202020.pdf

[82] https://www.nudiejeans.com/sustainability/sustainable-production/

[83] https://cdn.shopify.com/s/files/1/0432/6427/8679/files/MUD_Jeans_Sustainability_Report_2020_Online.pdf?v=1626790590

which mechanically recycles post-consumer polyester back into clean, compact PET pellets. For example, dirty old jackets become a clean raw product – a resource that can be used again and again, made into new jackets or any other polyester item.[84]

Ioniqa

A clean-tech spinoff from the Eindhoven University of Technology (NL), The Netherlands, specializes in creating value out of PET waste by using its proprietary circular technology. With a cost-effective process, Ioniqa is able to close the loop for plastics, starting with PET plastics. This award winning innovation transforms all types and colors of PET waste into valuable resources for 'virgin-quality' new PET. The current scaling up of Ioniqa's novel technology is focussed on PET plastics only but could be applied in the future to other plastics and organic materials as well.[85]

2.3. Sustainable production

One of the important pathways is optimizing resource use to reduce pressures. Companies in the textiles sector are focusing on reducing and optimizing water and energy use, air emissions, and water pollution by using safe chemicals and diversified biodegradable materials.[86]

Modernization and automation of the industry are needed to develop cleaner production processes, which are less labor and resource-intensive. Resource-efficient production is a key element in a sustainable textiles system. Reducing production waste and the energy, material, and needs water of the sector, while switching to healthy and renewable materials and energy at the same time, would reduce the environmental impact of the textile industry. Additionally, to tackle the negative social impacts of the textiles industry, the wages and working conditions of the workers need to be improved.[87]

At the production stage, eco-design principles have been identified to optimize resource use. These include reducing emissions, waste, and inputs such as water, chemicals, and energy, and producing fibers from renewable sources and/or recycled content. Design requirements certifying a minimum content of recycled material could also optimize resource use. Design requirements could also indirectly increase the collection of materials for reuse and recycling and potentially bring new sorting and waste recovery streams. [88]

One of the most significant problems facing the fashion industry is over-production. In general, the industry states that a third of products are sold at full price, a third are sold in sales and the remaining third generates almost no revenue, takes up space as deadstock, and is eventually incinerated or landfilled.[89]

One of the solutions to this problem could be to move from push to pull sales models and support companies to deploy demand-driven production models. In this sense, the development of

[84] https://finisterre.com/
[85] https://ioniqa.com/
[86] https://www.eea.europa.eu/publications/textiles-and-the-environment-the
[87] https://www.eionet.europa.eu/etcs/etc-wmge/products/etc-wmge-reports/textiles-and-the-environment-in-a-circular-economy/@@download/file/ETC-WMGE_report_final%20for%20website_updated%202020.pdf
[88] https://www.eea.europa.eu/publications/textiles-and-the-environment-the
[89] https://www.eionet.europa.eu/etcs/etc-wmge/products/etc-wmge-reports/textiles-and-the-environment-in-a-circular-economy/@@download/file/ETC-WMGE_report_final%20for%20website_updated%202020.pdf

online commerce will have an essential role because online platforms not only enable the large retailers to reach their customers but also offer small manufacturers and even amateur artisans direct access to potential customers.[90]

The achievement of customized clothing is another way by which it is expected to reduce the number of clothes that reach waste because they are made in perfect accordance with the consumer's preferences and according to the size and conformity of the body.[91]

The revaluing of manual craftmanship can also play a role here, for example, in the creation of personalized items, enabling customer-led design and upcycling.[92]

2.3.1. Examples of good practices

- *Biological exhaust air purification in textile finishing – pilot plant for biological elimination of cyanide*. Saxon Textile Research Institute and its partners have gradually developed a market-ready technical solution for exhaust air purification for textile finishing processes using flame lamination. The work aimed to increase the environmental compatibility of the

flame lamination by further developing a novel biological exhaust air purification process, in particular by stabilizing the biological conversion processes.[93]

- *Integrated fashion project for eco-sustainable products.* PIMECO project aims to realize products with high technological content and low level of environmental impact thanks to the combination of experiences and technology gained in different areas of fashion: textiles, tanning, footwear, and furniture. The final goal of the project is to break down the manufacturing systems barriers to share the know-how and the various skills of the different sectors that compose the fashion industry. Through the combination of the data from the different sectors, it will be possible to get products that fully meet the market needs in terms of eco-sustainability.[94]

2.3.2. Sustainable textiles consumption

One measure, that is available to all consumers, is to reduce the volume of textiles purchased. This can lead to lowering the environmental and climate impacts of the textile system.

[90] Buchel, S., Roorda, C., Schipper, K., Loorbach, D., & Janssen, R. (2018). The transition to good fashion, https://drift.eur.nl/wp-content/uploads/2018/11/FINAL_report.pdf

[91] Indrie, L., Bellemare, J., Zlatev, Z., Tripa, S., Diaz-Garcia, P., Montava, I., & Ilieva, J. (2021). Contemporary customized clothes using folk moti. Industria Textila, 72(6), 632-638

[92] https://www.eionet.europa.eu/etcs/etc-wmge/products/etc-wmge-reports/textiles-and-the-environment-in-a-circular-economy/@@download/file/ETC-WMGE_report_final%20for%20website_updated%202020.pdf

[93] https://www.interregeurope.eu/good-practices/biological-exhaust-air-purification-in-textile-finishing-processes

[94] https://projects2014-2020.interregeurope.eu/fileadmin/user_upload/tx_tevprojects/library/INTEGRATED%20FASHION%20PROJECT%20FOR%20ECO-SUSTAINABILITY%20PRODUCTS.pdf

Production and distribution will decrease as well if the number of the products purchased will decrease, avoiding the associated environmental and climate impacts and the generation of waste.

This can be done through shared use, longer use, and reuse of textiles.

Shared use refers to renting or leasing. Through these services, the same product is shared among multiple users, either for a short period (renting) or for longer ones (leasing), and can significantly lengthen the active lifetime of textiles and in that way improve sustainability during the use phase. Shared use can be applied to both clothing and technical textiles.

Longer use or increasing garment lifetimes is one of the most effective means of reducing their environmental footprint. A study performed by the Ellen MacArthur Foundation pointed out that if the number of times a garment is worn were doubled, and garment purchases and production were reduced by half as a consequence, the greenhouse gas emissions of the textiles industry would be reduced by 44 % (Ellen MacArthur Foundation, 2017).

Another study shows extending the active life of 50% of clothing by 9 months would save: 8% carbon, 10% water, and 4% waste per tonne of clothing.[95]

Textiles are meant to be used for a longer period, so they must be repairable. This entails the need for repair centers. The repairs can come at a high cost, the consumer has to go to a repair shop, so as consequence he will prefer replacing defective products (in many cases) - these are some of the barriers to the widespread implementation of this way of reducing clothing consumption.

Strong awareness campaigns promoting longer use, and campaigns for slow fashion which try to convince consumers to buy fewer clothes and to keep them for longer can determine what people choose to repair.

The reuse of textiles has considerable environmental benefits. A study in Flanders illustrated that reuse of clothing and footwear can reduce primary raw material consumption by 24% and the greenhouse gas emissions of the textile value chain by 16%, compared to 8 % for fibre recycling.[96]

Textiles can be re-used as a product through, for example, second-hand stores and informal giving, or as material for up-cycling and recycling. These transactions take place among friends and relatives, in second-hand stores, or over online platforms. Most common, for clothing, are reuse stores and platforms that often link to the trend for vintage fashion. The terms swishing and swapping both refer to a peer-to-peer exchange of clothing, facilitated by online platforms or events.

Moving to consumption patterns based on shared use, longer use and reuse will require substantial behavioral change. Educating consumers on the environmental and social impacts of textiles can effectively reduce environmental and climate impacts, as consumers are unlikely to be aware of the full environmental and social impacts of the textiles they buy.[97]\

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95 https://wrap.org.uk/sites/default/files/2020-10/WRAP-valuing-our-clothes-the-cost-of-uk-fashion_WRAP.pdf

96 https://www.eionet.europa.eu/etcs/etc-wmge/products/etc-wmge-reports/textiles-and-the-environment-in-a-circular-economy/@@download/file/ETC-WMGE_report_final%20for%20website_updated%202020.pdf

97 https://www.eionet.europa.eu/etcs/etc-wmge/products/etc-wmge-reports/textiles-and-the-environment-in-a-circular-economy/@@download/file/ETC-WMGE_report_final%20for%20website_updated%202020.pdf

There are some reasons for which the technical textiles are not feasible for re-use[98]:

Technical textiles usually reach their end-of-life status because they got damaged and not because they are old-fashioned;

·Protective clothing (e.g. uniform) is inadequate for re-use as it serves as distinguishing features (e.g. military) and has to be destroyed. In EU, every year 70,000 tones of uniforms are landfilled or incinerated [9].

- Technical textiles /nonwovens are frequently integrated into complex products such as automobiles. Disassembly of end-of-life products is not justifiable for financial reasons. Frequently, vehicles end up in a shredder, after which any recycling of the fibrous components is impossible.

- Medical textiles, often contaminated, have to undergo an incineration process.

- In case of technical textiles used in composite materials, due to good adhesion between fiber and matrix the separation is difficult and it is not justifiable for financial reasons. Only for expensive fiber materials (e.g.carbon fibers) the separation would be economically viable.

2.3.3. Examples of good practices

- Swedish men's wear company Nudie Jeans operates in the maintenance, reuse, refurbishment, and recycling loops. Nudie Jeans has established a return system, where customers receive a 20% discount off a new pair of jeans on the return of an old pair. The returned jeans are washed, mended, and subsequently put up for sale in the stores as second-hand jeans. If the jeans are worn out, and thus not possible to reuse, they are recycled instead. To prolong the life of the jeans every pair of Nudie Jeans comes with a promise of free repairs. If there is no Repair Shop or Repair Partner near the customer he can order a free of charge DIY repair kit.[99]

-Mud Jeans is another company that operates in this business model category, although in a slightly different manner. The Dutch fashion company offers a range of apparel such as jeans, t-shirts, shirts, hoodies, and bags. What sets Mud Jeans apart from most other fashion companies is the fact that customers can lease jeans and hoodies. In the case of jeans, the customer pays a €25 member fee, in addition to a 12-month rent of €7,50. At the end of the 12-month lease, the customer has three choices: Keep the jeans, get a new pair of jeans in exchange for the old ones, or send the jeans back. When returning a pair of jeans, whether leased or purchased, the customer receives a €10 voucher for later purchase at Mud Jeans. The system of lease and deposit ensures that the least part of the jeans is returned to Mud Jeans at the end of their useful life with the customers. Through this, the company can minimize the consumption of virgin organic cotton for new jeans, and reduce material costs correspondingly [100]

98 https://www.textiletechnology.net/technical-textiles/trendreports/TRENDBOOK-Technical-Textiles-20182019-The-importance-of-recycling-for-the-areas-of-application-of-technical-textiles-TU-Wien-12387
99 https://www.nudiejeans.com/sustainability/sustainable-products/
100 https://cdn.shopify.com/s/files/1/0432/6427/8679/files/MUD_Jeans_Sustainability_Report_2020_Online.pdf?v=1626790590

-TrendSales, Depop, and Thrift + are some examples of companies that have developed online platforms, which connect private users that want to sell, buy or swap clothes. Users post items and negotiate prices or "swap-items" together with shipment terms.

2.3.4. TEXTILE WASTE MANAGEMENT

Better collection, sorting, and management of textile waste is fundamental to ensuring more reuse and recycling and preventing waste from being incinerated or landfilled.

Textile waste treatment strategies include reducing, reusing, and recycling.

Waste prevention means measures taken before a (textile) product has become waste. A distinction has to be made between quantitative and qualitative prevention. Quantitative prevention comprises the extension of the lifespan of textile products. However, in the field of apparel and home textiles, this measure is only a pious wish. On the one hand, these products are subject to quickly changing fashion trends. On the other hand, more and more cheap and low-quality textiles, in particular from Asia, are dominating the market. Both trends have caused a tremendous decrease in the useful life of apparel.

Once these wastes are produced, they must be collected. The variety of textile and technical textiles types makes it very difficult to collect them separately. Statistics and data on the volumes of technical textiles that are covered by a separate collection are hardly available. This is aggravated by the fact that the area of application for technical textiles is extremely broad which demands different collection systems and, later, distinct recycling schemes. In contrast to apparel, technical textiles (e.g. geotextiles) are in use for a quite long period and are not instantly available for recycling.

Recycling means any recovery operation by which waste materials are reprocessed into products, materials, or substances whether for the original or other purposes. It does not include energy recovery or backfilling operations.

Numerous studies show that recycling has more environmental benefits than landfills and incineration. For example, according to Dutch aWEARness's calculations, textiles recycling can offer energy, water, and carbon dioxide savings of 64%, 95%, and 73% respectively, in comparison to standard non-recycled textiles. This also reduces the consumption of raw materials by 61% because waste is eliminated. [101] Another study, comparing them, shows that textile recycling has a much higher potential for GHG emissions and energy savings than their incineration.[102]

[101] EC Eco-innovation, (2014), Clothing project to explore the circular economy for textiles, On line at: https://ec.europa.eu/environment/ecoap/about-eco-innovation/good-practices/eu/20140318-clothing-project-to-explore-the-circular-economy-for-textiles_en

[102] Zamani B., Svanström M., Peters G., Rydberg T., (2015), A carbon footprint of textile recycling: A case study in Sweden, *Journal of Industrial Ecology*, **19**, 676-687

Recycled textiles can be used in many industries/fields like:

1.Building industry and construction sector

E.g : use of woven fabric waste and a waste of this residue for as a thermal and acoustic insulation (Ahmad et al., 2016) [103] , ventilation purposes, conductivity, making lightweight materials (concrete and bricks) [104], (Briga-Sá et al., 2013) [105];

2. Environmental applications

E.g: Use of cotton waste as a sustainable and inexpensive catalyst for water treatment, pollution remediation and removal of Bisphenol A (BPA) in wastewater (Shirvanimoghaddam et al., 2019a; Shirvanimoghaddam et al.,2019b).

3. Paper industry

E.g: Use of textile waste for wearing felts for paper production (Bhatia et al., 2014)

Use of recycled denim for making paper (Travers, 2017);

4. Textile and fashion industry

E.g: Use of textile waste for production of new textile products.

5. Carpet industry

E.g: use of textile waste as a noise insulation and carpet underlay.

6. Automobile industry

E.g: Use of recycled textile waste as a sound and heat insulation web, making hard-pressed parts for seat linings, floors and bottom felts for carpeting (Bhatia et al., 2014)

7. Agriculture industry

E.g: use of textile waste as a layer for covering the surface for cultivation which can collect more water from air humidity to promote microbial life (Eriksson, 2017).

Use of recycled textiles as a covering and seed carrier web (Bhatia et al., 2014).

8. Furniture industry

E.g: use of recycled textile waste for making mattress cover and web for seating in furniture, upholstery material, wadding material and needled webs

103 https://reader.elsevier.com/reader/sd/pii/S1877042816315257?token=013207FD2794C145A0F409D0F1BE4B779BCA9DD099B7886096F306340A4EB889FE8D66765294CE7A8DE205F700FC91E9&originRegion=eu-west-1&originCreation=20220323114451

104

105 Ahmad, S.S., et al., 2016. The application of recycled textile and innovative spatial design strategies for a recycling centre exhibition space. Procedia - Social and Behavioral Sciences 234, 525–535

9. Toys manufacturing E.g: use of recycled textile waste for making stuffed toys manufactured from plain clothes and pile textile[106].

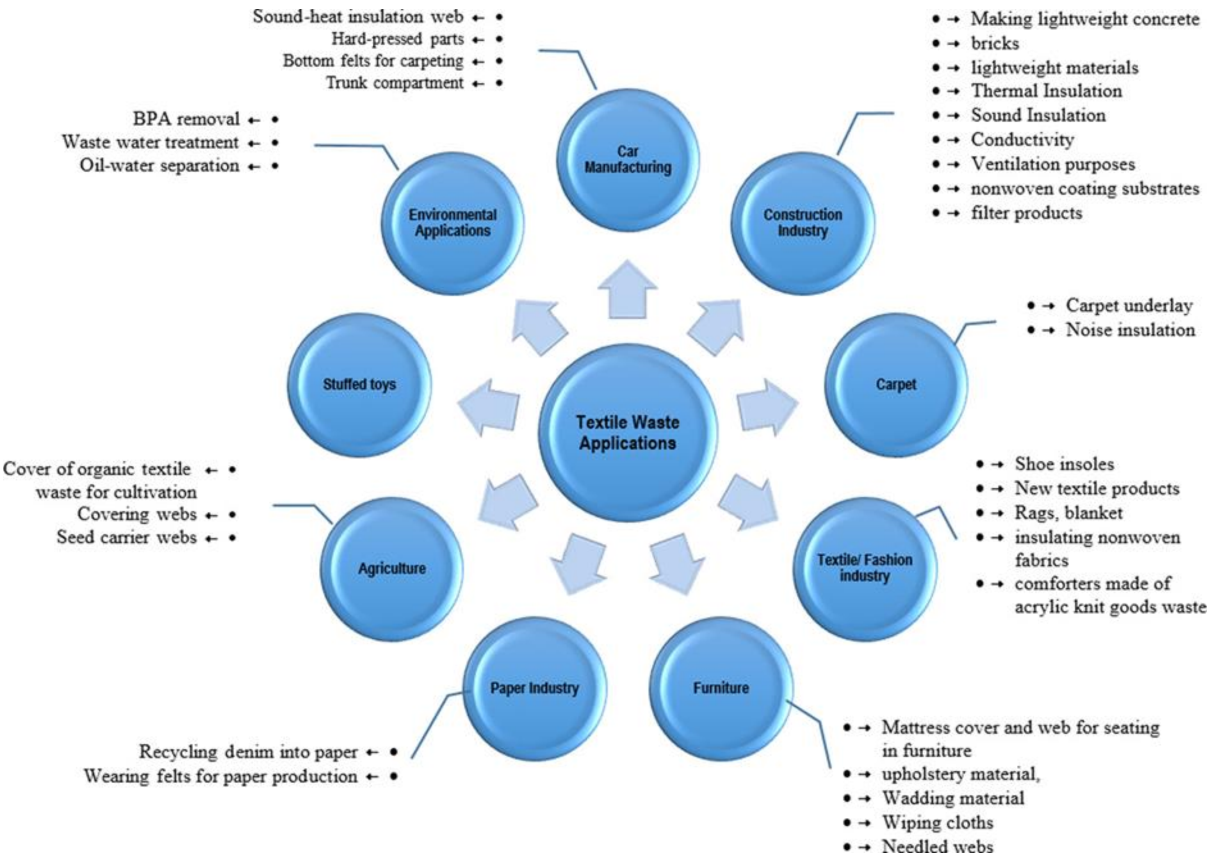

Fig. 7: *Industrial applications of recycled textile*

Source: Shirvanimoghaddam, K., Motamed, B., Ramakrishna, S., & Naebe, M. (2020). Death by waste: Fashion and textile circular economy case. *Science of the Total Environment*, *718*, 137317.

https://www.sciencedirect.com/science/article/abs/pii/S0048969720308275

2.3.5. EXAMPLES OF GOOD PRACTICES:

So that the textile waste does not reach the landfills a particularly important role is played by the collection of textile waste. Examples from many countries where there is a separate textile waste collection system is a practice that must be extended and put into practice in all countries.

Textile collection bins at supermarkets, recycling points, and recycling centers make it easy and more favorable to collect textile waste. Various private companies have introduced textile collection programs. For example, the company I: CO, collaborates with several companies internationally, such as Walmart, Esprit, American Eagle Outfitters, H&M, Jack & Jones, and NameIt.

[106] Shirvanimoghaddam, K., Motamed, B., Ramakrishna, S., & Naebe, M. (2020). Death by waste: Fashion and textile circular economy case. *Science of the Total Environment*, *718*, 137317, https://www.sciencedirect.com/science/article/pii/S0048969720308275

H&M collects the used clothes and gives vouchers to consumers. Their business partners are Adidas, Adler Alles Passit, Bingo, Blackout, Carharit, C&A and Foot Locker. In terms of commercial resellers, they both generate income by selling second-hand clothes at affordable prices. They also export to overseas clients.

Recycling technical textiles is more complicated, but much research in recent years led to the finding of solutions for recycling.

Some examples of good practice in this regard are:

– *The European patent EP3260595* describes the possibility to recycle flame-retardant protective clothes. Technical textiles go through an enzymatic hydrolysis process and the remaining fibers, commonly aromatic polyamides (aramids) or polyimides, undergo a fiber tearing process to obtain individual fibers ready for another yarn formation.[107]

– *The TEX2MAT project.* The TEX2MAT project aims to develop an idea, SME-compatible process for quality-assured, material recycling for specifically selected areas (workwear, towels, technical nonwovens) of the "multi-materials textile waste". The material cycle should be closed from the raw material to the raw material. Key elements of the new process are, for the first time, new technologies and methods introduced by the scientific project partners for the separation and processing of these wastes of polyester, polyamides, and blended fabrics. Thereby it is possible to obtain a pure polyester fraction feasible for re-granulation and re-spinning. The scheme is suitable for apparel, home textiles, and certain technical textiles. The separation of the materials will be enzymatic with a new methodical approach of IFA / TU. The resulting materials are characterized and sorted into quality classes.[108]

– The Dutch carpet manufacturer Desso was one of first companies to re-use closed-loop products in the carpet indusustry. Non-harmful, raw materials are re-used for the production of carpet tiles, Desso being a pioneer for the development of a remanufacturing process for the tiles. The modular carpet tiles permit a smart maintenance, since it is possible to change only the tiles which are visibly worn or torn. In this way, Desso prolongs the life span of tiles placed in “low-traffic” areas, before ultimately taking them in for remanufacturing[109]

– In the sector of bags and accessories, there are few companies manufacturing new products based on used materials.

– E.g.: FeuerWear manufactures bags, belts, and wallets out of discarded fire hoses and old life vests

– Bag to life produces bags out of old parachutes

– Freitag makes bags out of old tarps[110].

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107 https://www.textiletechnology.net/technical-textiles/trendreports/TRENDBOOK-Technical-Textiles-20182019-The-importance-of-recycling-for-the-areas-of-application-of-technical-textiles-TU-Wien-12387

108 https://www.vt.tuwien.ac.at/mechanical_process_engineering_and_clean_air_technology/projects/projects/tex2mat_new_treatment_methods_and_processes_for_the_recycling_of_textile_waste/EN/

109 Guldmann, E. (2016). Best practice examples of circular business models, https://www.researchgate.net/profile/Eva-Guldmann/publication/321760260_Best_Practice_Examples_of_Circular_Business_Models/links/5ae1935c458515c60f662aec/Best-Practice-Examples-of-Circular-Business-Models.pdf?origin=publication_detail

110 Guldmann, E. (2016). Best practice examples of circular business models, https://www.researchgate.net/profile/Eva-Guldmann/publication/321760260_Best_Practice_Examples_of_Circular_Business_Models/links/5ae1935c458515c60f662aec/Best-Practice-Examples-of-Circular-Business-Models.pdf?origin=publication_detail

Co-funded by the European Union

– Ioniqa. Ioniqa is a clean-tech spinoff from the Eindhoven University of Technology (NL), The Netherlands, specialized in creating value out of PET waste by using its proprietary circular technology. Following on its proven technology to upcycle PET Packaging, Ioniqa presented it developments to upcycle Polyester Textiles to virgin like monomers which can be used for foodsafe materials.[111]

2.3.6. COMPOSITES WASTE MANAGEMENT

There are several environmental concerns about the disposal of composites and these led to the introduction of legislations such as the Landfill Directive (1999/31/EC), the Framework Directive on Waste (2008/0241 (COD)), and Environmental Permitting Regulations 2007 (SI 3538). The success of the circular economy depends on effective end-of-life waste management, so it became very important to examine the duties and responsibilities of key players. The task of managing end-of-life waste is imperative, and the need for a genuine and fair delegation in accountability is even more necessary. An integral element in the circular economy is represented by the exigency towards identifying the responsible stakeholders in managing the collection and treatment of composite waste.

The availability of waste processing centres is very limited in case of composites, and this makes the situation even more difficult. Recycling technology is still new and the recyclated products hardly find application in the market. There are very few individual businesses that take responsibility for their waste because they are often confronted with many profound difficulities such as economics of scale and transportation costs.

There is also a limited available scale of composite recycling applications because of technological and economic constraints. However, the demand is incresing and the recent environmental legislation encourages the development of recycling technologies.

The main composite recycling methods are (1) re-melting and re-moulding, (2) chemical recycling, (3) thermal recycling, (4) mechanical recycling, and (5) re-melting-casting (Yang et al., 2012). Re-melting and re-moulding are usually applied in thermoplastic matrix composite recycling where mechanical breakdown into granules for use in the original processing stream takes place. Their fundamental ability to be re-shaped upon heating ensures the thermoplastic matrix composites could be recycled directly by re-melting and remoulding high value materials. In the case of thermoplastic matrix, the difficulty is represented by the high viscosity of their melts which requires high pressure for the impregnation of reinforcement fibres. By consequences, the product tooling and significant energy input in heating and cooling the tooling are highly expensive. Commercial application and market development are yet to be enhanced [112].

Leveraging on a cross-sectorial approach can open new potentials for the composite made parts recycling, remanufacturing, and re-use under a systemic circular economy perspective.

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[111] https://ioniqa.com/polyester-textiles-ready-for-recycling/

[112] AL AMIN, B. M. S. (2018). *Decision Tools for Recycling with A Focus on Fibre Reinforced Composites* (Doctoral dissertation, University of Manchester). https://www.research.manchester.ac.uk/portal/files/178946027/FULL_TEXT.PDF

2.3.7. Examples of good practices

– Design and manufacturing SME Cecence (Salisbury, U.K.), in collaboration with the National Composites Centre (NCC, Bristol, U.K.) and Gen 2 Carbon (Coseley, U.K.), have developed a composite airplane seatback that could reduce CO_2 emissions by more than 320 tonnes during the aircraft's service life, paving the way for more environmentally friendly air travel.[113]

– C. Alves et al. have proposed the replacement of glass fibers with jute fibers as reinforcement of composite materials to produce automotive structural components. In regards to the composite materials, the buggy case study demonstrated that jute composite presents the best solution for enhancing the environmental performance of the buggy's enclosures, hence improving the environmental performance of the whole vehicle.[114]

– The ZEBRA (Zero wastE Blade ReseArch) project, driven by French research center IRT Jules Verne (Bouguenais), brought together industrial companies and technical centers to demonstrate on a full scale the technical, economic, and environmental relevance of thermoplastic wind turbine blades, with an eco-design approach to facilitate recycling. To accelerate the wind power industry's transition to a circular economy for wind turbine blades, the ZEBRA project reportedly establishes a strategic, cross-sector consortium that represents the full value chain: from the development of materials, to blade manufacturing, to wind turbine operation and decommissioning, and finally recycling of the decommissioned blade material. Within the ZEBRA project, LM Wind Power will design the product, process, and manufacture two prototype blades using Arkema's Elium resin, to test and validate the behavior of the composite material and its feasibility for industrial production. In parallel, the ZEBRA project partners will focus on developing and optimizing the manufacturing process by using automation, to reduce energy consumption and waste from production. Project partners will then explore methods to recycle the materials used in the prototype blades into new products. Finally, a life cycle analysis (LCA) will assess the environmental and economic viability of further using the thermoplastic material in future wind turbine blades.[115]

Ana Paula et al.[116]propose and alternative to mitigate negative environmental impacts that is consistent with a circular economic system is to encourage interdisciplinarity between sectors, that is, one production sector can provide a function for waste from another. The article gathers scientific information on two sectors relevant to the global economy (textiles and food), with the aim of reusing waste from the food industry to manufacture a new textile product with added value. Specifically, the focus is on the use of bacterial cellulose from the probiotic drinks from kombucha, for the manufacture of biotextiles for fashion industry. This develop is strongly linked to the SDGs 12 - Responsible Consumption and Production.

[113] https://www.compositesworld.com/news/cecence-ncc-and-gen-2-carbon-develop-sustainable-airplane-seatback-

[114] Alves, C., Silva, A. J., Reis, L. G., Freitas, M., Rodrigues, L. B., & Alves, D. E. (2010). Ecodesign of automotive components making use of natural jute fiber composites. *Journal of cleaner production*, *18*(4), 313-327.

[115] https://www.compositesworld.com/news/zebra-project-launched-to-develop-first-100-recyclable-wind-turbine-blades

[116] https://www.sciencedirect.com/science/article/abs/pii/S0040162521002900

Another example of the union between the textile and food sector is Piñatex® [117], It was developed over many years of R&D by Dr. Carmen Hijosa. Piñatex® is made of fibre from the waste leaves of the pineapple plant. After pineapple harvest, the suitable plant leaves which are left behind are collected in bundles and the long fibres are extracted using semi-automatic machines. The fibres are washed then dried naturally by the sun, or during the rainy season in drying ovens. The dry fibres go through a purification process to remove any impurities which results in a fluff-like material. This fluff-like pineapple leaf fibre (PALF) gets mixed with a corn based polylactic acid (PLA) and undergoes a mechanical process to create Piñafelt, a non-woven mesh which forms the base of all Piñatex collections. The rolls of Piñafelt are then shipped by boat from the Philippines to Spain or Italy for specialised finishing. To make the Original, Pluma and Mineral collections, the Piñafelt is coloured using GOTS certified pigments and a resin top coating is applied to give additional strength, durability and water resistance. A foil is heat pressed on to create the Metallic collection and a high solid PU transfer coating is used to create Piñatex Performance. Piñatex is fit for use across fashion, accessories & upholstery and has been used by over 1000 brands worldwide including Hugo Boss, H&M and the Hilton Hotel Bankside.

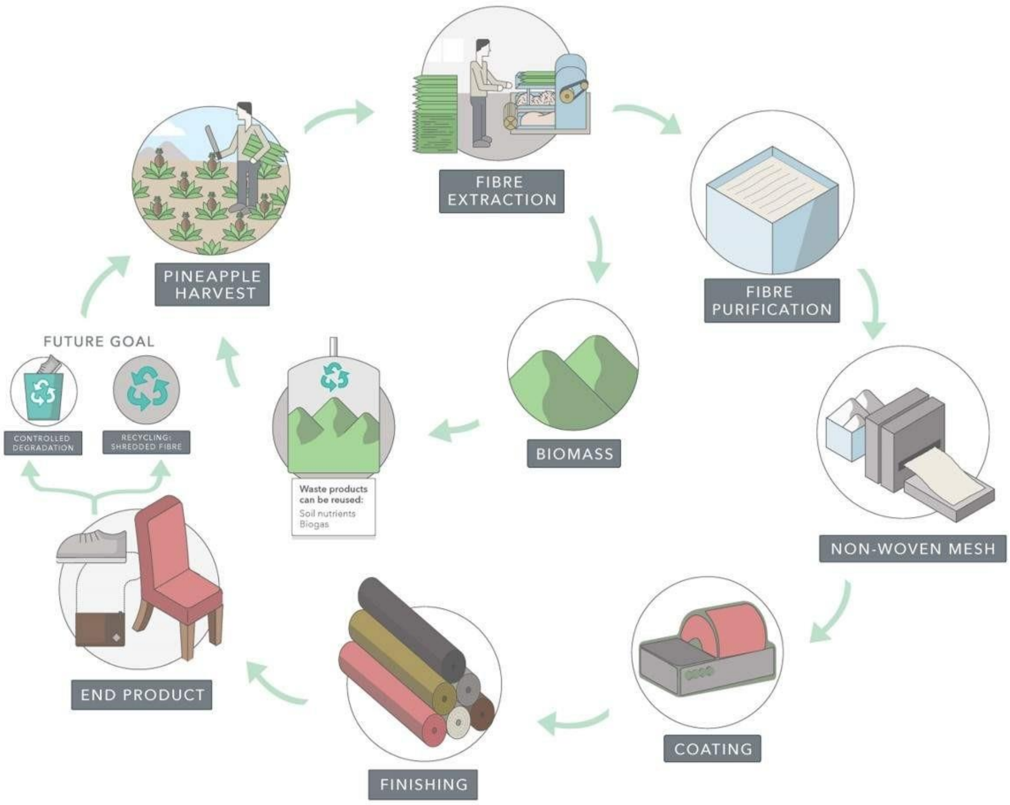

Fig. 8: *The life cycle of Piñatex®*

Source: https://www.ananas-anam.com/about-us/

[117] https://www.ananas-anam.com/about-us/

Siti Hajar Mohamed et al. [118], propose in their research theoretical the utilization of waste cotton cloths as promising raw materials for the isolation of cellulose nanocrystals CNCs and utilization in the production of value-added products. Waste cotton cloths generated are disposed of in a landfill, which causes environmental pollution and leads to the waste of useful resources. The waste cotton cloths collected from the landfill were sterilized and cleaned using supercritical CO_2 ($scCO_2$) technology. The cellulose was extracted from $scCO_2$-treated waste cotton cloths using alkaline pulping and bleaching processes. Subsequently, the CNCs were isolated using the H_2SO_4 hydrolysis of cellulose. The isolated CNCs were analyzed to determine the morphological, chemical, thermal, and physical properties with various analytical methods (ATR-FTIR, FE-SEM, DSC, TGA).

The Valencian company Laserfood launches the first vegan textile substitute for animal leather from persimmon in Spain. The new product PersiSKIN proposes a solution for the surplus of persimmon from the Valencian fields through the manufacture of a vegan textile substitute for animal and synthetic leather made of 100% natural products. [119]

The main objective of this vegan textile substitute for animal leather that we have created is the establishment of a new industrial sector that allows the full use of the waste and surplus generated in the production of persimmon to give an outlet and a new life to this raw material.

Xing Zhong Rong et al. [120] propose Eco-fabrication of antibacterial nanofibrous membrane with high moisture permeability from wasted wool fabrics. Wasted wool fabrics are a kind of textile waste source and the upcycle of them can not only benefit the environmental protection, but also turn waste into treasure by developing other potential applications. In the research is used a green solvent to upcycle wasted wool fabrics into a wool keratin (WK)/IL/polyacrylonitrile (PAN) composite nanofibrous membrane with good antibacterial and high moisture permeability through electrospinning.

Jeanologia[121] is a Spanish denim finishing machinery manufacturer that offering sustainable textiles soluctions and creating new operating models. Today the company leads the transformation of the textile industry with disruptive technologies: laser, ozone, e-Flow, SmartBoxes and H2 Zero technologies capable of enhancing productivity, reducing water and energy consumption and eliminating damaging emissions and discharge, guaranteeing ZERO pollution.

From fabric to finish, Jeanologia acknowledges responsibility for the social and environmental footprint of this technologies and operations.

[118] https://www.proquest.com/docview/2492518214/fulltextPDF/B5CCFC08AF0C409CPQ/1?accountid=28445

[119] https://agroinformacion.com/laserfood-lanza-el-primer-textil-vegano-sustitutivo-del-cuero-animal-procedente-del-caqui/

[120] https://reader.elsevier.com/reader/sd/pii/S0956053X19307019?token=DD40DC6A04B1379138D271FE1FD2BEC3A938EFBC811EAE276F5EBAAAD25940FC95A03A61F0D7633A3C76B15AE27F718E&originRegion=eu-west-1&originCreation=20220522121112

[121] https://www.jeanologia.com/about-us/

Fig. 9: *Jeanologia*

Source: https://www.jeanologia.com/about-us/