SUSTAINABLE FIBRE TOOLKIT 3

SST
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SUSTAINABLE FIBRE TOOLKIT 3

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The original edition of the Sustainable Fibre Toolkit was written by ANNIE GULLINGSRUD (Former McCourt) on behalf of “The foundation for Swedish textile research”, with support from their reference group. Parts of the original has been revised and new texts and pictures have been incorporated. A new chapter about recycling, reuse, redesign and how to think in different about the whole textile supply chain has been added. The updated version also contains information about the environmental impacts of textiles in a life cycle perspective – this thanks to several researchers co-writing and contributing with valuable knowledge from their experiences and projects.

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Part 1: Introduction

Definitions circular economy and sustainability

Transitioning to a circular economy is crucial for addressing the challenges of resource depletion, environmental degradation, and waste reduction, needs our current economic model do not sufficiently fulfil. The European Parliament defines circular economy:

*The **circular** economy is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended.*

In practice, it implies reducing waste to a minimum. When a product reaches the end of its life, its materials are kept within the economy wherever possible thanks to recycling. These can be productively used again and again, thereby creating further value.

This is a departure from the traditional, linear economic model, which is based on a take-make-consume-throw away pattern. This model relies on large quantities of cheap, easily accessible materials and energy.

Furthermore, part of this model is planned obsolescence, when a product has been designed to have a limited lifespan to encourage consumers to buy it again.[1]

The concept of **sustainability** is extensive and has taken place in many contexts in recent years. It can mean, among other things, environmental sustainability, social sustainability and that something lasts a long time. There is no precise definition of what sustainability actually means. One way to explain sustainability is that it means meeting our needs without compromising the ability of future generations to meet their needs.

Sustainability is an umbrella term that includes environmental, social and economic dimensions and that these are closely interconnected.

These are usually called the three pillars of sustainability:

Environmental sustainability – all ecological systems are balanced, and natural resources are used in a way that they have time to restore and renew themselves.

Economic sustainability – society has access to the resources required to meet its needs. Economic systems are intact and accessible, for example through means of earning a living.

Social sustainability – human rights and basic necessities are available to all. Society is governed by leaders who ensure safety on both personal, work and cultural levels and protect all people from discrimination.[2]

Making physical products always involves the use of resources and materials. Therefore, it is important to keep track and use sustainable fibre, material and energy sources that contributes to circular cycles, technical as well as biological. Another important aspect is longevity, quality that enables reuse, remanufacturing, remake and service-based business models.[3]

To step into sustainable circular economy, based on a system perspective, business model, design and material use must be tightly intertwined. The following basic points can give you some food for thoughts and guide your company's transformation to be part of the circular economy.

Road map to more sustainable and circular fibres and materials in your company[4]

Strategy

Define and include what sustainable circularity means to your company in the general company strategy. Connected to the general strategy formulate a fibre and material strategy based on circular fibres and materials, longevity and reuse and recycling of materials and fibres.[5]

Factors to consider are upcoming regulatory and policy changes, profitability, possibilities to scale business models and most value according to the waste hierarchy. Set up Key Performance Indicators for circularity and frequently evaluate them. Reserve money in the budget to prioritised research and development focusing on sustainability and circularity.

Sustainable resource use – Create a overview of preferred fibres/materials and combinations relevant to the company's context

Map material flows and rank fibres and materials based on your own business and the product's goals for purpose. Evaluate and document the environmental impact of

1 https://www.europarl.europa.eu
2 Hållbarhetsguide, TEKO Sveriges Textil & Modeföretag
3 Circular Business Toolkit, Science Park Borås, ISBN 978-91-89833-07-4(print)
4 Based on Circularity Checklist in Mind the gap(s), Kairos Future and Science Park Borås, June 2023
5 Circular Business Toolkit, Science Park Borås, ISBN 978-91-89833-07-4(print)

all materials. Remember that sustainability and ability for a specific fibre to be circulated is dependent of how it is treated in the whole supply chain.

Transparency and Traceability

When mapping material flows; map your supply chains down to raw materials. Set targets for social conditions, climate impact, water consumption, chemical use and wastewater treatment. It could be reduction targets (%) for climate impact, water consumption, chemical use and/or reuse and wastewater treatment and/or reuse of wastewater. Monitor continuously social conditions, climate impact, water consumption, chemical use, wastewater treatment and the impact of your circular solutions and perform corrective actions together with your partners in the supply chain/supplier network.

Transparency and traceability are crucial for circulation of fibres, materials and products. Simply to make it possible to find the right streams for reuse, remanufacture and recycle to highest value.

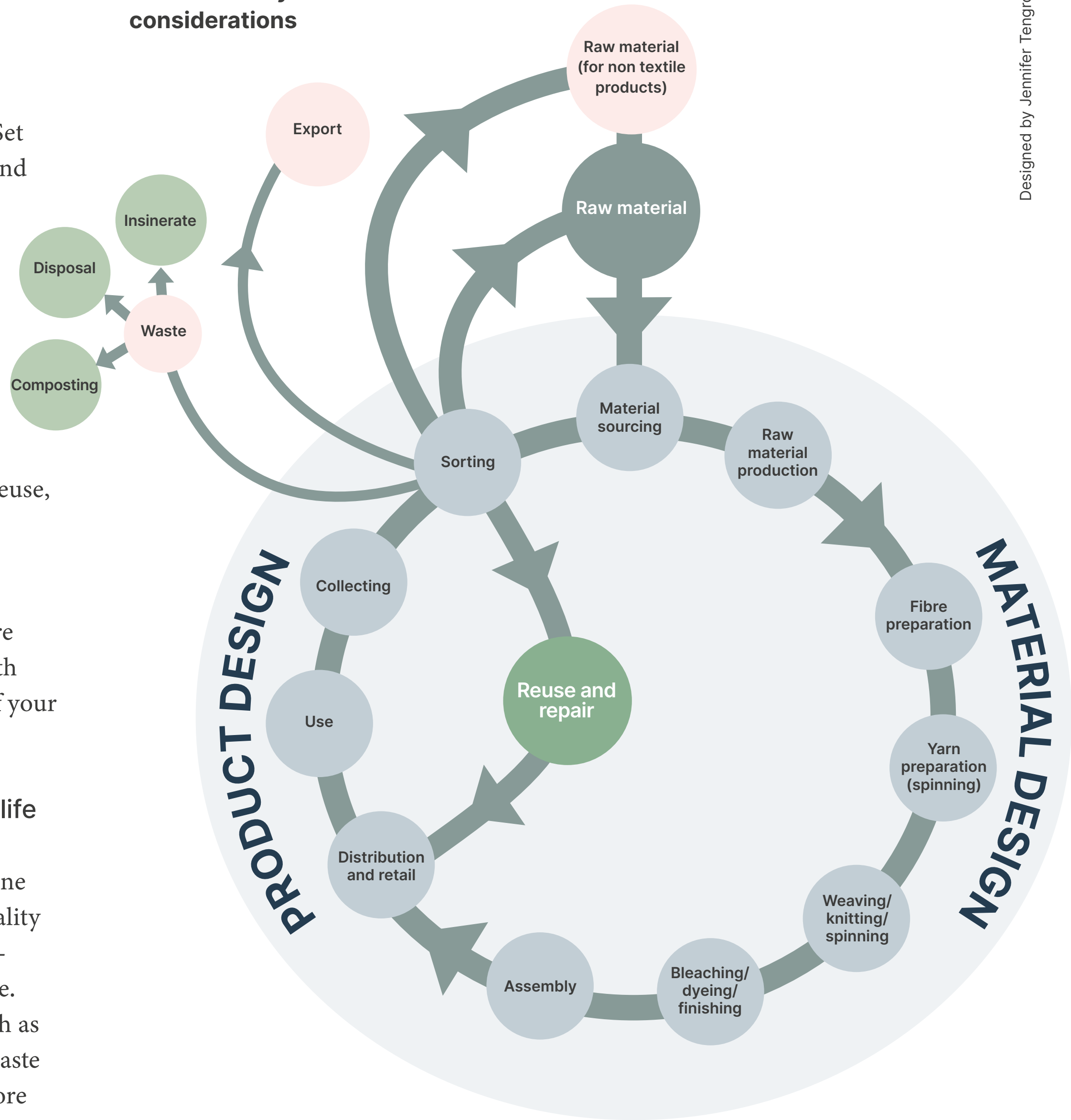
Resource efficiency

Optimize the need of materials and resources. Create conditions for efficient fibre and material use regarding raw materials, energy, water and chemicals. Work with continues monitoring of planning and sales to avoid overproduction. Examine if your waste could be someone else's valuable resource.

Material and Product design – Take a comprehensive approach to the life span of the fibres, the materials and the product.

Select fibres and material construction from durability and function aspects in line with the purpose of the product. Use materials that last over time in terms of quality and aesthetical aspects. Plan for a second, third etc life cycle of the product, materials and fibres. Avoid mixing fibres which do not have the same recycling cycle. Balance through wise and knowledge-based decisions conflicting objectives, such as minimal use of fibres contra long life span of the product. Eliminate or reduce waste and pollution by design. Identify unintended consequences. Remember that before recycling comes reuse and remanufacture.

Product life cycle and considerations



Designed by Jennifer Tengroth.

Services related to fibres and materials

Provide services to extend lifetime of the product like providing replacement parts or ability to disassemble products. Take back worn-out products and see to that they will be recycled in a proper decent way.

Collaborate

We are only in the beginning of the transformation to a circular economy. Many new business models, techniques, regulations and new ways of approaching circularity is on its way. To be tomorrow's winners it is essential to actively participate in partnerships for sustainable circular development, setting common goals and plan and conduct actions together with suppliers, customers, researchers and other sectors. For example, a push for greater use of natural or biobased feedstock fibres will require strong collaboration with the agricultural, forestry or livestock producers to ensure scalable win-win solutions.[6]

Our ambition for the Swedish textile industry is to have the highest possible sustainability profile in its operations. We believe that cooperation on a broad front creates sustainable textile production, sustainable fashion and a sustainable society. Through our foundation, ”Stiftelsen Svensk Textilforskning”, we support both education and research for a sustainable circular textile industry. Our vision is an innovative textile industry, where sustainable solutions and economic incentives together create a dynamic and competitive industry for the future.[7]

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6 Research Gaps and Needs for the Green Transition of the European Textile Ecosystem, HORIZON EUROPE Input paper by the ECOSYSTEX Community, July 2023

7 Hållbarhetsguide, TEKO Sveriges Textil & Modeföretag

Part 2: Natural fibres


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Cotton

Natural fibre

The high global demand for cheap cotton fibre encourages large-scale intensive production with significant ecological and social impacts.

Finding alternatives that mitigate the ecological impacts of cotton will not only reduce the company's environmental impacts, but may also influence the textile industry as a whole.

Cotton

Cotton represents 22 % of the world's textiles and is the second largest fibre category worldwide. India, China, the United States, and Brazil account for more than 73 % of global cotton production.[1]

The cotton value chain

The general cotton value chain includes the following processes:
Farming – growing and harvesting raw cotton.
Ginning – Separation of cotton fibres from seeds and other contamination and pressing the fibres to bales.
Spinning – Cotton fibres is blended, spun and twisted into yarn.
Weaving/ Knitting the – Production of raw fabric.
Fabric finishing – The fabric is washed, dyed, printer or in other way treated to achieve final appearance and characteristics.
Product production – includes cutting and assembling into garments and other products.
Retail – The product is shipped and sold to customers.
Consumers – Buy and use, reuse the cotton products.
Recycling – As the valuable resource cotton is, it must be reused, repurposed and in the end recycled.[2]

Benefits

Cotton is a renewable natural resource and is readily available and inexpensive. Cotton fibre is almost pure cellulose, and is soft, breathable, and absorbs moisture readily, making cotton clothes particularly comfortable in hot weather. The fibre's high tensile strength in soap solutions renders cotton garments easy to wash, and no dry-cleaning is required.

In 100 % pure form, cotton fabric is biodegradable after its useful life, though absolute biodegradability depend on the dyes and trims used, and route of disposal.

By-products from cotton include cottonseed oil, cottonseed meal, and cottonseed hulls, which are mainly used to feed livestock, and can also be used for petroleum refining and plastics manufacturing.

Potential impacts

Cultivation: Chemical

Conventional cotton cultivation uses some of the most toxic chemicals (pesticides, defoliants, and fertilizers) available for use in agriculture. A little bit more than 10 % of the global sales of insecticides and almost 5 % of pesticides are used for cotton plantations[3], and it counts only for about 2,5 % of the worlds crop land.[4] Many of these chemicals are used by farmers in developing countries where education, access to information and understanding of the dangers posed by hazardous chemicals are lacking. Consequently, cotton farmers may experience acute pesticide poisoning, which can result in illness and death. The use of toxic chemicals can diminish soil fertility over time, and irrigation run-off can pollute regional water bodies.

Cultivation: Water

Unlike flax, which is rainfed, cotton generally requires irrigated water during its cultivation. Water management practices vary from growing region to growing region and are influenced by several factors including the farming system used, water costs, local climate, etc. Water footprint information for cotton products is available in the public domain, but because different organizations use different parameters for their calculations, water footprint estimates for a particular product vary widely and can be somewhat unreliable. According to The Swedish Consumer Agency it takes, on average, 9,000 litres of water to produce one kilogram of cotton.[5]

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1 Preferred Fibre & Materials Market report oct 2022, Textile Exchange
2 Solidaridad, Pesticide Action Network UK (June 2023) 'Cotton and Corporate Responsibility'
3 'Silenced Data' Means We Don't Know Global Impacts Of Cotton Pesticides, Brooke Roberts-Islam, Senior Contributor, Published Dec 6, 2021 in Forbes website
4 COOL COTTON Organic cotton and climate change, The Soil Association, September 2015 https://www.hallakonsument.se/miljo-och-hallbarhet/material-i-klader-och-textiler
5 https://www.hallakonsument.se/miljo-och-hallbarhet/material-i-klader-och-textiler

AS BRANDS IN THE INDUSTRY COLLABORATE ON INFORMATION AND STRATEGIES FOR SUSTAINABILITY, FOOTPRINT TOOLS WILL BECOME MORE NORMALIZED, CONSISTENT AND RELIABLE.

Cotton is mainly grown in Mediterranean desert or near-desert climates, where fresh water is in short supply. Consequently, much of the global cotton crop is irrigated and this can have extensive impacts on regional freshwater resources.

Cultivation: Labor

In countries where cotton is handpicked, fair treatment of the farm workers may be of concern. For example, Uzbekistan, one of the largest exporters of cotton in the world, was in the mid-2010s recognized by Human Rights Watch and other organizations for their activities in bringing forced labour to the cotton fields.[6] In 2022, the Cotton Campaign, an alliance of human rights nongovernmental (NGO) groups, trade unions, and business associations, confirmed that during the most recent cotton harvest in autumn 2021, for the first time local authorities did not systematically force people to go to the fields to pick cotton.[7] Lately the Xinjiang-region in China is in focus for labour conditions.

Potential impacts

Dyeing

The dyeing process for cotton involves the use of standard industry chemicals and water. Certain types of dyes are suspected carcinogens and mutagens, and dye water can negatively impact receiving water bodies and harm aquatic ecosystems if left untreated before it is release.

MORE INFO: DYEING & PRINTING

Consumer care/washing

Textiles made from cotton is often washed and tumble-dried at high temperatures and can require pressing (ironing).

MORE INFO – APPENDIX: CONSUMER CARE/WASHING

End of use

Cotton can be mechanically recycled or be used as raw material for chemical recycling to MMCF such as lyocell and viscose.

Pure cotton fibre is biodegradable. The amount of time it could take for a cotton product to decompose naturally is dependent upon several conditions such as how much oxygen, temperature and sunlight the fibre is exposed to. If cotton waste is buried in a landfill, it can take significantly longer for it to break down.[8]

MORE INFO – APPENDIX: BIOGRADABILITY

Alternatives

Alternatives to conventional cotton include genetically modified (GM), certified organic, transitional organic/organic in-conversion and Integrated Pest Management (IPM).

Genetically modified (gm) cotton

Due to its high susceptibility to pests and pathogens, and high pesticide consumption, cotton has been a major focus for genetic modification. In the United States and India in 2022, sources state that more than 90% of cotton crops are genetically modified.[9],[10] GM is a relatively new technology, and its long-term effects are not yet fully understood. So, the positive and negative impact of GM technology are still debated lively. For example, in humid growing regions, such as the U.S. state of Georgia, where boll weevil is rampant, the introduction of GM (Bt) cotton has significantly reduced the need of pesticides.

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6 https://www.hrw.org/news/2017/06/27/uzbekistan-forced-labor-linked-world-bank

7 Uzbekistan Ends Systemic Forced Labor, Civil Society Says – 330 Companies Lift Boycott of Using Uzbek Cotton, Article on HRW homepage March 11, 2022 by Hugh Williamson, Director, Europe and Central Asia Division https://www.hrw.org/news/2022/03/11/uzbekistan-ends-systemic-forced-labor-civil-society-says

8 ec.europa.eu/environment/waste/compost

9 www.ers.usda.gov/data-products/adoption-of-genetically-engineered-crops-in-the-us.aspx

10 https://www.fibre2fashion.com/news/textile-news/india-s-non-bt-cotton-area-below-10-lakh-ha-for-4th-consecutive-year-282842-newsdetails.htm

On the other hand, herbicide tolerant (Ht) GM cotton, otherwise known as "Round-up Ready," has led to a sharp increase in herbicide use, which has in turn caused genetic resistance in weeds. Farmers report having to use more toxic herbicides to suppress "super weeds."

To add to this complex picture, proponents of GM cotton note that herbicide tolerant (Ht) varieties have also led to reduced soil tillage, which results in less topsoil erosion.

Certified organic cotton

Certified organic cotton don't allow the use of GM seeds and restricts or disallows the use of many synthetic agricultural chemicals. Organic farming aims to self-stabilize agro-ecosystems and uses crop rotation and biological means to control pests and pathogens.

Studies show that organic farming:

> Accumulate organic matter in the soil
> Reduces soil, air and water contamination
> Increases soil fertility and biodiversity
> Reduces human and wildlife health hazards
> Reduces greenhouse gas emissions resulting from the production of synthetic fertilizers and pesticides.

In some regions, organic cotton farmers may gain more income than conventional farmers do, though this is by no means universal. Potentially lower yields, higher labour costs and a market price determined by the commodity price index, means that organic cotton cultivation is a tenuous financial risk for the farmer, which is often captured in a higher market price.

Organic cotton represents approx. 1,4 % (2022) of all cotton grown worldwide[11] and is therefore in short supply. The price of organic cotton tends to be higher than conventional due to the increased labour costs necessary for its cultivation. Organic fibres also require special processing since it falls outside the usual scope of the commodity cotton supply chain. For example, track and trace mechanisms must be implemented in developing countries where bar code and bale identification systems


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11 Preferred fibre & Materials Market report October 2022, Textile Exchange

are not in place. This requires additional labour and monitoring. Certified organic cotton must also remain segregated through processing into yarn and fabric, and this special handling adds additional costs.

Certification by a third party ensures that all the proper documentation is in place, and that the organic claims are valid.[12] Exact cultivation requirements vary from region to region, since each bioregion has different pest pressures and resources, but there is international reciprocity between most certification agencies accredited by International Federation of Agriculture Movements (IFOAM).

Organic certification does not necessarily guarantee low water use, fair labour practices or a fair price to the farmer.

Global Organic Cotton Production Top 5 countries 2021/2022[13]

Country	Metric tonnes	Fibre production % of total
India	130 849	38 %
Turkey	80 830	24 %
China	33 687	10 %
Kyrgyzstan	30 945	9 %
Tanzania	20 932	6 %

Total global organic cotton production 2021/2022: 342 265 tonnes.

Transitional organic cotton/Organic in-conversion

In order to be certified as organic, cotton fields must go through a 2-year transition period (3 years in the United States) where disallowed chemicals are not used. Transitional organic cotton uses non-GM seed and is grown in the same manner as organic but still need to go through the 2-year transitioning phase for certification. Once the land intended for transition to organic cultivation has been approved according to the 2-year requirement, the cotton.

Transitional cotton creates a bridge for farmers to switch from conventional to organic cultivation and it may be cheaper than organic; since it isn't yet certified it doesn't command the same ”added value” in the market. However, transitional organic cotton is not as readily available as conventional and reciprocity in labelling from nation to nation has yet to be established. Currently, labelling for transitional cotton is only allowed in Europe, where it is called “organic in-conversion” and must be certified under the European organic standard. The U.S. does not allow labelling of transitional. The Organic Exchange in Europe has a transitional cotton task force lobbying to allow labelling of transitional cotton in the United States.

Integrated pest management (ipm) cotton

Integrated Pest Management (IPM) is an approach to farming that focuses on long-term prevention of pests by integrating biological controls, habitat manipulations and modification of cultural practices. Pesticides are used only after monitoring and established guidelines indicate that pests exceed acceptable levels.

There are many different IPM cotton initiatives globally, and IPM can be interpreted and implemented in many different ways. However, there are two notable IPM programs emerging that are based on clear and accessible data, interpretations, and strategies.

Better Cotton Initiative (BCI)[14]

The Better Cotton Initiative (BCI) was established in 2005 and is active globally, addressing environmental, social and economic issues in an integrated program that reduces water and chemical use. BCI does not allow child or bonded/forced labour; incorporates better treatment of female workers, proper handling and training for the use of pesticides and fertilizers; and encourages a number of techniques that will reduce water use. BCI engages and supports all cotton supply participants, from producers to retailers, and provides a central digital repository of BCI bales with unique bale identification codes.

In the 2019/20 cotton season 6.2 million metric tonnes of Better Cotton lint was produced by 2.4 million licensed farmers from 23 countries.

BCI members are found along the whole cotton supply chain, retailers and brands, suppliers and manufacturers, producer organisations, civil society members, and associate members.

12 https://www.ifoam.bio
13 Organic Cotton Market report oct 2022, Textile Exchange
14 https://bettercotton.org/

Shutterstock

Some other cotton programs are more or less in line with BCI like Cotton grown/produced in Africa, described below. Another example of BCI partner is the Israel Cotton Production and Marketing Board (ICB), a farmer-owned producer organisation representing all cotton farmers in the country. All Israeli cotton producers take part in the program and since 2020, the Israel Cotton Production Standard System (ICPSS) is recognized as equivalent to the Better Cotton Standard System (BCSS).[15]

Also, the Australian program myBMP[16] and Responsible Brazilian Cotton (ABRAPA) are considered as BCI equivalent.

Cotton made in Africa (CmiA)[17]

Cotton made in Africa cotton (CmiA) is an initiative of the Aid by Trade Foundation (AbTF) started in 2005 and is leaning on the principle of helping people to help themselves through trade. The cotton is grown in the region of Sub-Saharan Africa and through training programs cotton farmers are trained about modern, efficient, and environmentally friendly cultivation methods. By this the yields and the quality of the cotton will increase, and the cotton farmers will earn a better income and at the same time, preserve their and their families' health. CmiA has established a network of partners with retailers and fashion brands together with cotton companies and traders, and supporters like Textile Exchange, WWF Better Cotton Initiative (BCI) and others. In July 2012 CmiA andBCI extended their earlier cooperation with a partnership agreement on a permanent basis. Both initiatives remain independent organizations working with their partners respectively, but the agreement allows for CmiA cotton to be sold as BCI cotton but not vice versa until end of 2022.

Sustainable Cotton Projects

Other cotton categories

Organic content standard (ocs)[18]

In 2020 a new version of OCS was launched, OCS 3.0. This is a voluntary standard for tracking and documenting the purchase, handling and use of certified organically farmed cotton fibre in yarns, fabrics and finished goods and is verified by third party. The standard applies to all goods containing a minimum of 5% to 100% organic cotton and help consumers and companies to confirm the correct percentage of organic cotton in their product. The standard is not certifying the raw material itself, which has to be certified by an organic standard approved in the IFOAM Family of Standards.

Other cotton categories

Adjacent to the OCS 100 logo shall "Made with/contains 100% Organically Grown Cotton" or "Made with/contains Organically Grown Cotton" appear. For OCS blended logo the following text shall be find "Made with/contains X% Organically Grown Cotton" or "Made with/contains a minimum of X% Organically Grown Cotton".

15 https://bettercotton.org/where-is-better-cotton-grown
16 https://www.mybmp.com.au/home.aspx
17 https://cottonmadeinafrica.org/en/
18 https://textileexchange.org/organic-content-standard/


Unsplash/Karl Wiggers

Global organic textile standard (gots)[19]

Global Organic Textile Standard was introduced in 2006 and only textile products that contain a minimum of 70% certified organic fibres can become certified. The criteria also set requirements on the entire textile chain such as processing, manufacturing, packaging, labelling, trading and distribution of the textiles. 9414 facilities were GOTS certified in July 2023. GOTS is also an affiliate member of the International Federation of Organic Agriculture Movements (IFOAM).

Fairtrade cotton[20]

The Fairtrade program is active globally, primarily in developing nations, and secures a minimum fibre price for the farmer aiming to cover the average costs of sustainable production. In addition to this baseline price for their fibre, farmers also receive a Fairtrade premium, which allow them to invest in community projects, such as schools, roads, or health care facilities. Most Fairtrade cotton is neither organic nor IPM. However, Fairtrade standards encourage sustainable farming practices by restricting the use of certain agrochemicals.

International Sustainability and Carbon Certification (ISCC)

ISCC certification system is built on 6 principles for Agricultural Production of Biomass and covering renewable energy, prevent contamination, degradation and depletion of the environment due to agriculture and forestry production, safe working conditions at farm level, rural and social development based on labour standards, all biomass production is in compliance with regional and national laws, and finally, ensure good management practices of farms and to facilitate the continuous improvement process.[21] An example from the EU is the Greece cotton production where almost half of the production is in some way certified by ISCC.

REEL

REEL Cotton Code is a training program for farmers focusing on sustainable cotton farming practices. It is driven by Cotton Connect and operates in India, Pakistan, China, Bangladesh, Egypt and Peru. The program aims to reduce the use of water, chemical pesticides and fertilisers, thereby reducing environmental impact. The

19 https://global-standard.org/
20 https://www.fairtrade.net/
21 https://www.iscc-system.org/

Optimize sustainability benefits

Design Opportunity	Production Opportunity	Marketing Opportunity	Considerations
Promote the use of organic cotton.	Work with design and marketing to forecast styles and volumes and contract organic fibre in advance to ensure supply.	• Consumers are familiar with the term "organic."	• Higher price. Less availability. • Design high value items in organic, which can absorb higher fibre costs. • Design organic into items that are highly processed, so the fibre cost is a smaller percentage of the total garment cost.
Promote the use of biological IPM cotton.	Work with design and marketing to forecast styles and volumes and contract IPM fibre in advance to ensure supply.	• More limited marketing opportunity than organic, but this is shifting with the expansion of Better Cotton Initiative. • Better Cotton Initative is not generally noted in POS materials, but on company CSR websites.	• Lower price than organic; only slightly more expensive than conventional. • Readily available fibre; limited spinners and supply chain participants.
Promote the use of Fairtrade cotton.	Work with design and marketing to forecast styles and volumes and contract Fairtrade cotton fibre in advance to ensure supply.	• Strong marketing opportunity since there is wide consumer awareness of "Fairtrade."	• Higher price, less availability. • Forecasting/planning may be required.
Promote the use of natural coloured cotton.	Work with design and marketing to forecast styles and volumes and contract natural coloured cotton fibre in advance to ensure supply.	• Limited marketing opportunity due to low consumer awareness and limited colours.	• Higher price, less availability. • Delicate fibre. • Limited supply chain participants (growers, ginners, spinners. • Forecasting required to ensure supply.
Promote the use of GOTS certified cotton products.		• The GOTS standard is recognized world-wide and the number of licensees are steadily growing.	

farmers are introduced to composting and crop rotation methods which reduce the need for chemical fertilisers and are also taught to use non-chemical methods of pest control, identify friendly and enemy insects, and apply pesticides accordingly.[22]

Regenerative Organic Certified (ROC)

Regenerative Organic Certified (ROC) is a global farm-based certification for food, textiles, and personal care ingredients. Built on regenerative organic agriculture, ROC covers soil health, land management, animal welfare and equity for farm workers and farmers.

ROC was established in 2017 by a group of farmers, business leaders, and experts in soil health, animal welfare, and social equity collectively called the Regenerative

22 https://www.cottonconnect.org/resources-hub/the-reel-cotton-programme

Organic Alliance, or ROA. Examples of non-profit partners “1% for the planet” and Textile Exchange.[23]

U.S. Cotton Trust Protocol

The U.S. Cotton Trust Protocol launched in 2020, is a U.S. transparency program for data capture, aggregation and reporting water use, energy efficiency, greenhouse gas emissions, soil conservation, soil carbon and land use that drives continuous improvement in cotton production.[24]

Availability

All the above-mentioned alternatives to conventional cotton are now available in yarns and knitted and woven fabrics.

Organic cotton is available in a variety of fabrics from 100% organic cotton to numerous blends with other fibres.

Due to high demand, the availability of organic cotton products is restricted. Forward projections and contracting are essential to secure supply for future seasons.

Applications

Approximately 60% of cotton fibre is used in clothing, most notably in shirts, T-shirts, jeans, coats, jackets, underwear and foundation garments.

Organic and transitional cotton is the same quality as conventional cotton and appropriate for any fabric.

Practical & feasible advice

1. Set up system for traceability through the whole value chain
2. Experiment with blends of different types of cottons to balance cost and aesthetics: primary cotton and recycled, organic cotton and other types of certified cotton
3. Explore innovative fabrications that use blends with cotton (Tencel/organic cotton, for example).
4. Design the cotton product for long life, considering aspects of function, aesthetics and durability.
5. Decide already in design phase how the cotton product should be recycled.
6. Due to higher price of organic fibre, consider designing fashion products that command a higher retail price, rather than designing organic into basic commodities.
7. Consider knitting or weaving coloured cotton yarns with dyed yarns to create more varied products, whilst reducing overall volume of dyes (and associated pollution) for green and brown shades.
8. Blend coloured cotton with white organic cotton to create mélange effects and strengthen the yarn.
9. Partner with Cotton Connect to help your company implement Better Cotton, or another sustainable cotton initiative.
10. Use tags and hangtags to encourage consumers to wash cotton garments in low temperature and tumble dry and iron only when necessary.
11. Develop a concept featuring wrinkled cotton to influence the customer to reduce ironing of the final product and the energy it uses.
12. Create a cotton product that is both 100 % biodegradable and 100% compostable: the product can degrade in a reasonable amount of time and is equipped with an ingredient that provides valuable nutrients to the soil after disposal.
13. Take a multi-layered approach: combine several of the above opportunities together for a full lifecycle approach.

23 https://regenorganic.org/
24 https://trustuscotton.org/

Flax

Natural fibre

Flax is a bast fibre and a fast and easy growing annual, which requires a cool and relatively humid climate.[1]

In its growing and processing, flax has minimal impacts on the environment in comparison to other fibres.

Linen, the fabric derived from the flax plant, may offer a more sustainable alternative to cotton and polyester.


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Flax

Benefits

Flax is a good rotation crop, grows quickly and requires low use of chemicals in its cultivation.[1] Some sources state that flax production requires half the amount of pesticides per acre compared to that of conventional cotton.[2] Fertilizers such as nitrogen, phosphorous, potassium and calcium are however required to obtain good quality crop yields and fibre properties.[3] In addition, flax is a rain fed crop and generally doesn't require irrigation.

It is found that the optimal time to harvest plants for fibre extraction is during the flowering stage before seed maturity to prevent stem lignification.

Fast-growing renewable fibres

Fibre	Length	Timing
Bamboo	24 meters	40 days
Hemp	4 meters	3 months
Jute	1-4 meters	3-4 months
Flax	1 meter	3-4 months

Flax may be grown organically, and when claimed "organic" must meet the standard certification requirements by an internationally recognized certification agency accredited by International Federation of Agriculture Movements (IFOAM).

Flax fibre has a high natural lustre and its natural colour ranges from beige to light tan to grey.[1]

Once the fibre is extracted from the stem, processing flax into yarn is largely mechanical, with minimal environmental impact. However, to obtain a high-quality fibre, retting process is required to degum the fibres and separate them from the bark of the stem, this may result in impacts on environment depending on the retting method chosen for each case.[4]

Flax fibre and the resulting linen fabric have unique thermo-regulating properties, providing insulation in the winter and good breathability and a cool feeling in the summer.[1]

In 100 % form, linen from flax fabric is biodegradable after its useful life, though absolute biodegradability depends on the dyes and trims used, and route of disposal.

MORE INFO – APPENDIX: BIODEGRADABILITY

Potential impacts

Cultivation

Flax does require herbicides to control weeds and, as a cellulosic fibre, it also requires some fertilizers. Synthetic fertilizers contain nitrogen salts which salinate the soil and over the long term decrease the productivity of the soil and pollute aquatic ecosystems.

1 "Beginner's Guide to Sustainable Fibres," Textile Exchange, 2011.
2 "The Linen Shirt Eco Profile," Bio Intelligence Service, February 2008. http://www.saneco.com/IMG/pdf/linen_shirt_eco-profile.pdf http://www.thehindubusinessline.com/industry-and-economy/agri-biz/govt-may-use-wastelands-for-tasar-silk-cultivation/article4479274.ece.
3 A.P. Manian, M. Cordin, T. Pham, Extraction of cellulose fibres from flax and hemp: a review, Cellulose. 28 (2021) 8275–8294. https://doi.org/10.1007/s10570-021-04051-x.
4 Q.Y. Zhang, Z. Di Liu, Y. Zhang, L.B. Xu, The difficulties of dyeing of flax fibre and the improving method, in: Adv Mat Res, Trans Tech Publications Ltd, 2014: pp. 450–453. https://doi.org/10.4028/www.scientific.net/AMR.989-994.450.

Retting process comparision chart

Type	Description	Advantage	Impacts	Duration
Dew Retting	Plant stems are cut or pulled out and left in the field to rot.	Returns nutrients back into the soil.	Reduced fibre strength; low and inconsistent quality; influenced by weather; product is contaminated with soil.	2–3 weeks
Water Retting	Plant stems are immersed in water (rivers, ponds or tanks) and monitored frequently.	Produces fibre of greater uniformity and higher quality.	Extensive stench and pollution arising from anaerobic bacterial fermentation of the plant; high cost; low-grade fibre. Requires water treatment maintenance.	7–14 days
Chemical Retting	Boiling and applying chemicals, normally sodium hydroxide, sodium benzoate, hydrogen peroxide.	More efficient and can produce clean and consistent long and smooth surface bast fibre within a short period of time	Unfavourable colour; high processing cost. The wastewater is concentrated and rich in chemicals and biological matter, which negatively impacts receiving water bodies, harming aquatic ecosystems, if left untreated before its release.	60 – 75 minutes
Enzymatic retting	The use of enzymes such as pectinase, hemicellulases and cellulases in the form of enzymatic cocktail is established. Pectinase was shown to be the most important enzyme.	The use of moderate pH levels is usually sufficient to conduct the retting with mild temperatures.	Might affect the fibre strength. Additional agents to facilitate the reaction are required such as chelator agents. Some difficulties in separation of enzymes after treatment.	12- 24 hours

Processing

Flax is a bast fibre and is extracted directly from the stalk of the plant in a process similar to that used for jute, hemp and other bast fibres. The fibre is extracted through a process called retting (see table), which separates the fibre from the stems by removing the gum layer that holds the fibre bundles together in the stem, therefore separating them.[4] The traditional ways of retting depend on the effect of using microorganisms and moisture. This is carried out in the field (as with dew retting) or in tanks (water or chemical retting). Dew retting is preferred as it utilizes the natural moisture of dew, but is the longest process, taking over 2–3 weeks to break down the stems slowly. Although chemical retting is the fastest process, the wastewater is concentrated and rich in chemicals and biological matter, which negatively impacts receiving water bodies, harming aquatic ecosystems, if left untreated before its release. It is worth mentioning that it is possible to extract flax and other bast fibres without retting using a sequence of mechanical, chemical and biological treatments. However, these processes are still not optimized, and the mechanical extraction alone may lead to more moisture absorption in the fibres, and thus fungal attacks.[3]

The obtained fibres possess many desirable properties with diameter range of 15-30 µm, tensile modulus of 58 GPa, tensile strength of 500-1500 MPa and elongation at break of around 3,27%.[4] These numbers may vary according to source, maturity of the fibres and other factors.

Dyeing

The natural colour of flax fibre is beige and can be in the shades of tan and gray. If a white product is required flax yarn or fabric must be bleached with chlorine or other substances to render it light enough to receive dyes for light or clear shades. Chlorine bleach can form halogenated organic compounds in the wastewater. These compounds bioaccumulate in the food chain, are known teratogens and mutagens, are suspected human carcinogens and cause reproductive harm. Alternative and more sustainable methods can be used to bleach and dye flax fibres.

Overall, flax fibres can be dyed after different pretreatments to improve the dye affinity.[5] These treatments may add to the negative environmental impacts of flax pro-

5 Y. Ma, H. Zheng, X. Xiong, T. Cai, F. Zheng, L. Zheng, Dyeing of Linen Fabrics in Supercritical CO 2 Using a Reverse Micellar System with Ionic Liquid Domains, Journal of Natural Fibres. 20 (2023). https://doi.org/10.1080/15440478.2023.2222555.

Retting process comparision chart

Opportunity	Benefits	Considerations
Promote suppliers using organic flax.	Ensures that no disallowed fertilizers or pesticides are used.	• Organic certification must be in place by a recognized international certification agency accredited by IFOAM. • Organic linen from flax is not as readily available as conventional linen from flax and commands a premium.
Promote the use of natural colour.	No bleaches or dyes are used in this case, and associated pollution impacts are avoided.	• Produces fibre of greater uniformity and higher quality.
Promote the use of non-chlorine bleaches, such as hydrogen peroxide, to lighten the natural beige colour for dyeing dark shades and bright/light shades.	Hydrogen peroxide harmlessly decomposes into water and oxygen gas.	• Non-chlorine bleaches do not strip out the original colour of the fibre. Consequently, lighter and brighter colours will be duller due to the over-dyed effect. Non-chlorine bleaching is adequate for dark colours, which mask the original beige tone. • Hydrogen peroxide maybe dangerous to transport and store.
Promote the use of ozone bleaching processes to strip out the natural beige colour of flax linen. Promote the particular aesthetic of ozone bleach effects.	Ozone can be used with no water at all.	• Ozone has maybe relatively expensive since it requires investment in ozone generating equipment. • Ozone processes produce a different aesthetic than chlorine derivative or permanganate bleaching.

duction. Nowadays, efforts are made introducing alternative natural dyes and super critical carbon dioxide $ScCO_2$ as dyeing medium instead of water.[6]

MORE INFO: WET PROCESSING

Consumer care/ washing

Linen (from flax) may be washed. Electricity and water use in the care of the garment can cause significant environmental impacts. Moreover, linen from flax wrinkles easily and require heavy pressing to render it smooth after wash. This builds up to significant amounts of electrical energy throughout the life of the garment.

MORE INFO – APPENDIX: CONSUMER CARE & WASHING

End of use

Although 100% flax fibre is claimed to be biodegradable, the amount of time it could take for a flax product to decompose naturally is dependent upon several conditions—for example how much air/oxygen, temperature and sunlight the fibre is exposed to. If the waste is buried in a landfill, it will take even longer for it to decompose.[7] It is worth mentioning that some treatments of the fabric during processing slow down the biodegradation of flax, these treatments include coatings or antimicrobial finishes that will hinder the microorganisms from degrading the fabric at the end of its life. Additionally, when flax fibres are included in composite materials, their biodegradability depends heavily on the matrix used for the composite material.

MORE INFO – APPENDIX: BIODEGRADABILITY

Availability

The highest quality flax fibres are produced in Europe, in an area that reaching from Normandy region in France to Amsterdam in the Netherlands, because of the good climate conditions for fibre flax varieties. That is presence of a temperate climate and drained land.

6 Q.Y. Zhang, Z. Di Liu, Y. Zhang, L.B. Xu, The difficulties of dyeing of flax fibre and the improving method, in: Adv Mat Res, Trans Tech Publications Ltd, 2014: pp. 450–453. https://doi.org/10.4028/www.scientific.net/AMR.989-994.450.

7 www.greenlivingtips.com/articles/waste-decomposition-rates.html

Optimize sustainability benefits

Opportunity	Benefits	Considerations
Promote the use of enzymes to strip out the natural beige colour of linen from flax.	Can be good alternative to harsh chemical processes	• Enzymes used may not be allowed in GOTS standards. • Enzymes produce a different aesthetic than chlorine derivative or permanganate bleaching.
Promote suppliers who use sustainable retting methods or no retting methods	Dew retting reduces the biological load in the receiving water bodies and adds nutrients to the soil.	• The natural colour may vary slightly from lot to lot, since the process is influenced by weather.
Promote suppliers who use enzymatic retting over water or chemical retting.	Process is faster and leaves the water less contaminated. Can be commercially reproduced.	• Low fibre strength. • Process is less common compared to other retting processes. • Additional costs.
Promote the use of European Flax®.	Ensures that crop is rain fed, disallows use of GMO seed and ensures retting process does not pollute water.[13]	• Does not consider environmental impacts from dyeing, transportation, consumer care and disposal/end of use. • Not necessarily organic.
Actively seek out stain-resistant finishes for flax linen.	Will reduce washing, ironing and dry-cleaning by the consumer, and the water and pollution associated with consumer care.	
Promote the use of flax fibres as a natural alternative for composite reinforcement	Flax is a strong, biodegradable and durable fibre that has the potential to replace oil-based fibres in composites	• The properties must be optimized to fit the application such as pretreatments of the fibres to improve affinity with matrix

Cultivated surfaces of fibre flax are increasing every year in Europe (from 70,000 ha to 162,580 ha in) the last decade.[8] Other countries such as China, Russia and Argentina produce big amounts of fibre flax as well. One hectare of cultivated fibre flax allows one to produce between 1200 to 1700 kg of long fibres that can be sold for 3-5 EUR / kg in the case of high-quality fibres, which is 10 to 20 times higher than wheat or corn according to the year 2022 statistics.[9]

Organic linen from flax is less available and more expensive than conventional linen from flax. Organic certification by an internationally recognized certification agency accredited by IFOAM must be in place.

Photo by Bea Marciniak, Unsplash.

Applications

Textiles made from 100% linen from flax is durable and available in a variety of yarn counts and fabric types. Suitable product applications (made from 100% linen) in-

8 J. Moyse, S. Lecomte, S. Marcou, G. Mongelard, L. Gutierrez, M. Höfte, Overview and Management of the Most Common Eukaryotic Diseases of Flax (Linum usitatissimum), Plants. 12 (2023). https://doi.org/10.3390/plants12152811.

9 www.knittingindustry.com/uploads/2048/BE_LINEN_MAP_10-1.pdf

clude jeans, dress pants, jackets, dress shirts, handkerchief-weight blouses, knits, bed linens and outdoor fabrics. Blends of cotton/linen from flax are machine washable and suitable for sportswear, wovens and knits. Linen fabrics are getting more attention due to their organic feel and comfort for apparel and home furniture. However, nowadays flax fibres are used as reinforcement fibres in composite structures to replace synthetic fibres such as glass or carbon, especially for the green or biocomposite materials such as the PLA-based PLA-based biodegradable or all-cellulose based composites.

Advantages

Fast-growing natural resource
Low water footprint in cultivation
Natural colour If not bleached or dyed.
Organic If organic flax fibre is used. All fibres, yarn, trims and dyes used to manufacture the garment must comply with the GOTS organic garment standard.
Biodegradable All fibres, yarns, trims and dyes used to manufacture the product or garment must also be biodegradable, or disassembled before disposal where non degradable materials are removed.

Non-chlorine bleached If alternative bleach is used.
Dew retted If dew retted processed, or No retting used when mechanically extracted without retting.
European Flax™ If European Flax is used.

Innovation opportunities

1. Use linen from flax fibre in blends with cotton or other fibres to achieve grey/beige heather effects, then over-dye the cotton side to achieve heathered colours without using chlorine bleach.
2. Use 100 % flax linen in stripes with cotton, then over-dye to achieve tonal colours without using chlorine bleach.
3. When used in 100 % form, design “culturally durable” (i.e., styling that doesn’t date with passing trends) products in linen from flax to optimize the fibre’s physical durability.
4. Since linen from flax wrinkles easily and washing and caring for the garment can cause significant environmental impacts, design garments that utilize the natural wrinkling of the fabric as a design feature to influence the customer to reduce ironing of the final product and the energy it uses.
5. Create a flax product that is 100 % biodegradable and compostable: the product can break down in a reasonable amount of time and is equipped with an ingredient that provides valuable nutrients to the soil after disposal.
6. Encourage handwashing or spot cleaning on the hangtag and labelling/Point of Sales (POS) to influence the consumer to take an active role in reducing environmental impacts of linen from flax garment/product care.
7. Use flax in green composite materials for furniture, interior design, and technical applications.

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Hemp

Natural fibre

Hemp is known as Cannabis sativa L., is used for industrial applications, including fibre production. Hemp fibres are found in the outer stem tissue. It is a bast fibre with high cellulose content that is regaining attention in Europe and worldwide. With its ability to grow without irrigation or fertilization and minimum waste production, this crop is a strong competitor among natural fibres due to its sustainability.

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Benefits

Hemp "Cannabis sativa L." is authorized under the EU's Common Catalogue of Varieties of Agricultural Plant species (Reg. 1308/2013) and contains less than 0,3% of THC, which means it is not psychoactive.[1] It is one of the faster growing plants with growth rate of 15 cm per day and can reach up to 5 m in height. This crop can grow in different type of environmental conditions and soils, makes it possible to grow in many parts of the world. A crop like cotton requires three times more water to produce 1 kg of final fibre compared to hemp fibre. Additionally, hemp fibre has low ecological footprint, with potential reduction of agricultural activities cost of 77.63% when compared to cotton for medium yield estimate.[2] All parts of the plant can be harvested and processed, making it versatile for use in many applications. Hemp offers other environmental benefits including soil regeneration, absorbing heavy metals, and can absorb up to 1.6 tonnes of CO_2 per tonne of hemp. Hemp is a low input crop, it doesn't need care in between sowing and harvesting, and it rarely need irrigation due to long roots up to 140 cm deep into the soil. Due to its growth rates, it suppresses the growth of weeds, thus it needs a minimum of herbicides to thrive. After extraction from the stem, hemp fibre may be found in different colours including yellow, beige, tan and brown. Additionally, it can be bleached in the chemical cottonized form to give off-white colour. Hemp showed to be beneficial when included in crop rotation hemp cultivation leads to a 10 % to 20 % increase in wheat yields. In 100 %, hemp fibre is fully biodegradable, depending on the disposal route.

Photo by May Kahoush

Potential impacts

Cultivation

The plant stem has primary and secondary fibres. The primary fibres are used for textile production since they possess better quality than the secondary fibres. The percentage and quality of the primary and secondary fibres are affected by the time of the year it is harvested and thereby the maturity of the plant. Therefore, for better fibre production, crops are preferably harvested after the end of flowering. Scientists are working on developing better hemp cultivars for the purpose of fibre production. Cultivars with late flowering and high bast content are preferred to obtain long hemp fibres with low lignin content and high cellulose content. Maintaining the land for good quality fibres requires N-fertilization (nitrogen fertilizer, refers to fertilizers that contain nitrogen as the primary nutrient) which can add to the costs and environmental impact on long term.

Processing

Regardless of the great benefits and sustainability of hemp fibres, it is similar to other bast fibres in regard to high costs related to processing until this date. Various stages must be conducted for extraction of the fibres from the stems after harvest. The first step is usually retting, including traditional methods such as field retting, dew, and water retting. The retting process in the traditional methods takes a long time and causes pollution of the surrounding waters. Thus, current research focuses on

1 G. Gedik, O. Avinc, Hemp Fibre as a Sustainable Raw Material Source for Textile Industry: Can We Use Its Potential for More Eco-Friendly Production?, in: 2020: pp. 87–109. https://doi.org/10.1007/978-3-030-38541-5_4.
2 EIHA – The Voice of the European Hemp Industry, (2023).

optimizing the retting process or degumming of the hemp fibres using mechanical, chemical, and enzymatic methods, to reduce time, costs and improve the quality of the obtained fibres.

After the retting/degumming process, a sequence of steps such as breaking, scutching and hackling are performed to release the fibres from the shives and separate and comb them before further processing. The obtained hemp then can be used as loose fibres for insulation, reinforcement in composites or made into textile structures including nonwovens for technical use, and long-fibre spinning. To obtain higher quality fibres in terms of comfort, a cottonization process need to be performed to shorten and smoothen the fibres using heavy chemicals and steam. This process has a big environmental impact, and it adds to the costs of hemp production. However, the obtained cottonized hemp fibres are often blended in small percentage with other fibres such as cotton, viscose or wool, to be further spun into yarns prior to weaving or knitting.

The obtained fibres have a diameter ranging from 10 to 40 μm with length ranging from 20 to 200 mm and possess many desirable properties; tensile modulus of 70 GPa, tensile strength around 900 MPa and elongation at break of around 1,5%. These numbers may vary according to source, maturity of the fibres and other factors (cottonization and other processes).

Dyeing

The natural colour of the hemp fibres differs depending on the time of harvest, retting level, storage conditions and extraction methods. It can be different shades of yellow, beige or even brown. These natural colours are preferred for most of the applications. For other colours, it is preferable to bleach the hemp fibres in order to obtain the bright colours when required. However, the bleaching process add to the costs and environmental footprint of the process and may cause damage to the fibres resulting in lower mechanical and physical properties if not optimized. Additionally, and similar to other natural bast fibres, when chlorine-based bleach is used, this can have direct impact on human health and affect the surroundings. Enzyme washing as finishing method for hemp textiles has been shown to be beneficial in improving the dyeing process and colour uptake.[3]

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Consumer care / washing

Hemp textiles that are used for apparel can be washed but the result depends on a number of factors including the yarn composition (100% hemp or blended with other fibres) and how it has been processed. However, these textiles have the tendency to wrinkle, which results in higher electricity consumption while ironing or steaming. To improve the wrinkle resistance of hemp textiles, enzyme washing finishing is advisable.[4]

End of use

Hemp fibres are biodegradable and decompose naturally in the environment. However, this process depends on many conditions including disposal manner, humidity, temperature, UV exposure and presence of microorganisms. Textiles treated with antimicrobial materials require longer periods to degrade.

3 A.G. Duque Schumacher, S. Pequito, J. Pazour, Industrial hemp fibre: A sustainable and economical alternative to cotton, J Clean Prod. 268 (2020). https://doi.org/10.1016/j.jclepro.2020.122180.

4 H.Y. Bao, Y. Hong, T. Yan, X. Xie, X. Zeng, A systematic review of biodegradable materials in the textile and apparel industry, Journal of the Textile Institute. (2023). https://doi.org/10.1080/00405000.2023.2212848.

Retting process comparision chart

Opportunity	Benefits	Considerations
Promote suppliers using organic hemp	Organic process ensures lower emissions due to prohibition of synthetic fertilizers and pesticides	Organic certification must be carried out by an authorized certification agency accredited by IFOAM
Promote of natural colour hemp	Hemp can be obtained in many different natural colours. Thus, the impacts associated with dyeing and bleaching can be limited	
Promote developed retting processes such as enzymatic and combined approaches	Reduction of the time needed for the retting, with controlled water consumption and pollution	These processes might add to the cost of the process
Promote the use of hemp-blended fabrics	This helps in combining benefits from different fibres	Hemp better be cottonized to adapt to processes with other fibres
Promote the use of hemp in technical textiles	Hemp possesses great properties for technical use such as geo-textiles and construction applications	Flammability of hemp should be reduced with eco-friendly agents to prevent accidents

Availability

As awareness rises based on the benefits of hemp, the global market could hit $18.6 billion by 2027 – almost four times the amount in 2020, a new UNCTAD (United Nations Conference on Trade and Development) report says.[5]

According to European Commission statistics, recently the area dedicated to hemp cultivation has increased significantly in the EU from 20,540 hectares (ha) in 2015 to 33,020 ha in 2022 (a 60% increase). In the same period, the production of hemp increased from 97,130 tonnes to 179,020 tonnes (84.3% increase). France is the largest producer, accounting for more than 60% of EU production, followed by Germany (17%) and The Netherlands (5%).[6]

Worldwide, about 40 countries produced some 275,000 tonnes of raw or semi-processed industrial hemp in 2019, according to the latest available statistics according to United Nations Conference on Trade and Development (UNCTAD), 2022. Four countries account for more than half of global output. China leads the growth, followed by France, Canada and the United States.

In Sweden, a total of 220 hectares were cultivated in 2021/2022, according to Axfoundation, it is estimated that there are about 150 hemp operators in Sweden, most of which are small family businesses.

5 UNCTAD, Hemp's versatility and sustainability offer huge opportunities for developing countries, (2022).

6 European Commision, Hemp, 2023.

Applications

Hemp fibre and textiles have a wide range of applications due to their unique properties and environmental benefits. Some of the main applications include clothing, specially made from blended yarns of hemp with cotton or viscose. Additionally, accessories such as bags, hats, belts, and shoes are being made of hemp and its blends. These products are valued for their natural appearance and strength. Other applications include home textiles, heavy-duty industrial textiles including canvas, ropes, twines, and nets. Hemp fibres can also be used in making paper and packaging instead of traditional wood-based paper. The potential of hemp is being explored in automotive industry as nonwovens for interior to replace oil-based materials, or in composites as reinforcement fibres as well as in agricultural as biodegradable alternatives to prevent soil erosion and retain moisture in the soil.

Advantages

Fast growing sustainable crop

Carbon-neutral When processing is optimized.

Reduced costs Related to agriculture activities compared to cotton.

Biodegradable when in natural state (this depends on other treatments while processing, the dyes used and disposal conditions). Thus, instructions should be provided for consumer care and disposal while conducting tests to verify that the residuals are nontoxic.

Organic If certified according to standards.

Local Swedish product If grown and processed in Sweden.

Innovation opportunities

1. Innovative hemp-based blends for sustainable textiles and fashion products: hemp fibres are strong, durable, and biodegradable. To improve their spinnability and softness, innovations in textile processing, dyeing techniques, and blending hemp fibres with other fibres/materials could lead to the creation of eco-friendly and stylish clothing lines.
2. Construction materials: hemp fibres can be used as reinforcement in concrete, creating a composite that is both lightweight and strong. Researchers and engineers can explore the development of more advanced hemp-based construction materials, such as hempcrete, which could lead to eco-friendly and energy-efficient building material.
3. Biodegradable plastics: hemp fibres can be used as a reinforcement in bioplastics to enhance key properties as well as reducing their environmental impact. Innovations in hemp-based biodegradable plastics can help to address the growing plastic pollution problem and reduce reliance on oil-based plastics.
4. Automotive industry: hemp fibres can be utilized to manufacture interior components and panels in automobiles. Their low weight and robust properties can help improve fuel efficiency and reduce the overall weight of vehicles. The main goal is to improve their flammability resistance to compile with safety standards.
5. Paper and packaging: Hemp fibres have historically been used as fibre source in paper production. Innovations in processing and refining hemp fibres could lead to more sustainable and eco-friendly paper products, reducing the need for traditional tree-based packaging.
6. Medical and healthcare products: hemp fibres can be used in the development of bandages, wound dressings, and other medical products. Their antimicrobial properties and biocompatibility make them potentially valuable in the medical field.
7. Marine applications: hemp fibres' strength and their resistance to water and humidity make them suitable for marine applications, such as ropes, nets, as a biodegradable alternative to synthetic materials.
8. Composites: hemp fibres can be used as or be combined with other natural fibres as reinforcement to create strong lightweight composites. These composites can be used in various industries, including aerospace and sports equipment.

Jute

Natural fibre

Jute has a good reputation as a strong sustainable fibre. In 100 % form, it is biodegradable, with relatively harmless processing. Although jute is generally used for sacks and bags, it represents an opportunity in other applications to feature its sustainable qualities.

Jute

Benefits

Jute is a natural bast fibre along with kenaf, hemp, ramie, bamboo and flax.

Jute fibre and fabric are often called Hessian. Jute sacks are called Gunny Bags in some European countries. In North America, the fabric made from jute is known as Burlap. In Spanish, jute is called Yute and jute fabrics are called Arpillera.

Jute is a long, soft, shiny plant fibre that can be spun into coarse, strong threads.

JUTE IS ONE OF THE MOST INEXPENSIVE NATURAL FIBRES AND IS SECOND TO COTTON IN THE AMOUNT PRODUCED AND VARIETY OF USES.

Jute is a fast-growing renewable fibre that is annually farmed. Jute will grow to a length of 1 to 4 meters in 3 to 4 months.[1] Jute is a biologically efficient, low maintenance crop that don't require use of chemicals during the growing season. It is mainly rain fed, traditionally farmed and grown similarly to organic produce.[2]

Jute has a natural lustre and is valued for its durability, fair abrasion resistance, and high tensile strength. Jute fibre has anti-static properties, heat insulation and low elongation, which helps to retain its shape.

Jute may be grown organically, but must meet the certification requirements of an internationally recognized certification agency accredited by International Federation of Agriculture Movements (IFOAM).

Studies show that the CO_2 assimilation rate of jute is several times higher than that of trees.[3] During the jute growing period, one hectare of jute plants can absorb about 15 metric tonnes of CO_2 from the atmosphere and release about 11 metric tonnes of oxygen.[4]

In 100% form, jute is biodegradable. Although collective data does not exist regarding how long it takes for jute to fully decompose, one source reports that jute will completely decompose in 2 to 3 years (as opposed to polyester which can take anywhere from 40 to 1000 years to break down).[5]

Due to its extensive root system, jute can help reduce soil loss and erosion and is particularly suitable for crop rotation. Since the leaves of the plant are left in the field after harvest. The nitrogen they contain absorbs into the soil and food crops can be grown immediately without having to leave the fields fallow.

Once the jute fibre is extracted from the stem, processing the fibre into yarn is largely mechanical with minimal environmental impact, if retted in an optimized manner.

Fast-growing renewable fibres

Fibre	Length	Timing
Bamboo	24 meters	40 days
Hemp	4 meters	3 months
Jute	1-4 meters	3-4 months
Flax	1 meter	3-4 months

Potential impacts

Processing

Jute is a bast fibre and is extracted directly from the stalk of the plant in a process similar to that used for flax, hemp and bamboo (for linen). The fibre is extracted through a process called retting, which separates the fibre from the stems using microorganisms and moisture. This is carried out in the field (with dew retting) or in tanks (water or chemical retting). Dew retting is preferred as it utilizes the natural moisture of dew, but is a more time-consuming process, taking 2 to 3 weeks to break down the stems slowly. Although chemical retting is a faster process, the wastewater is concentrated and rich in chemicals and biological matter, which negatively impacts receiving water bodies and aquatic ecosystems if left untreated before release.[5]

1 fao.org/economic/futurefibres/fibres/jute/en/
2 purejute.com/en/pure-jute/jute-environment.html
3 Inagaki, H (2000). Progress on Kenaf in Japan. Third Annual Conference, held at American Kenaf Society,Texas, USA, 2000Lam Thi Bach Tuyet, Hori Keko and Iiyama Kenzi (2003). Journal of Wood Science 49(3): 255-261.
4 freesetglobal.com/who-we-are/faq.html
5 "Beginner's Guide to Sustainable Fibres," Textile Exchange, 2011

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As of today there are No alternative retting options used on large scale to minimize the impacts of the retting process, through direct mechanical extraction of the fibre after harvest, although organic certification don't allow the use of chemicals in the growing of jute. However, certification does not necessarily guarantee low water use, fair labour practices or a fair price to the farmer.

The obtained fibres possess properties including tensile modulus of 60 gpa, tensile strength of 860 mpa, and elongation at break around 2%. These numbers may vary according to source, maturity of the fibres and other factors.

Dyeing, blending and treatments

The natural colour of jute fibre is beige, and jute yarn or fabric must be bleached with chlorine to render it enough to receive dyes for light or clear shades. Chlorine bleach can lead to halogenated organic compounds in the wastewater. These compounds may bioaccumulate in the food chain, and are known teratogens and mutagens, are suspected human carcinogens and cause reproductive harm.

Jute can also be blended with other fibres such as wool. By treating jute with caustic soda (also called "lye"), crimp, softness, pliability and appearance are improved, which make the fibre easier to be spun together with wool. However, this alkali treatment add to the environmental impacts and reduces the sustainability benefits for jute fibres.

MORE INFO – APPENDIX: BIODEGRADABILITY

Consumer care/washing

Jute may be washed or dry-cleaned. Electricity and water required in the care of the garment can cause significant environmental impacts. Moreover, jute wrinkles easily and requires heavy pressing to render it smooth after wash, which require significant amounts of electrical energy over the long term.

MORE INFO – APPENDIX: CONSUMER CARE & WASHING

End of use

Although pure jute when used as is biodegradable, the amount of time it could take for a jute product to decompose naturally in a short period of time is dependent upon a number of conditions such as how much air, temperature and sunlight the fibre is exposed to. The more air/oxygen, the higher the temperature and the more sun light (UV) the faster is the decomposition. If the waste is buried in a landfill, the time for it to decompose will be significantly longer. It should be mentioned that some textile finishing and treatments such as antimicrobial agents hinder the biodegradability of jute fibres.

Optimize sustainability benefits

Opportunity	Benefits	Considerations
Promote suppliers using organic jute.	In addition to the general ecological benefits of jute, organic processes ensure that no disallowed pesticide or fertilizers are used.	• Organic certification must be in place by a recognized international certification agency accredited by IFOAM • Organic jute is not as readily available as conventional jute and commands a premium.
Promote the use of natural colour jute.	No bleaches or dyes are used in this case, and associated pollution impacts are avoided.	
Promote suppliers who use dew adding or no retting over water or chemical setting.	Dew setting reduces the biological load In the receiving water bodies and add nutrients to the soil	• The natural colour may vary slightly from lot to lot, since the process is influenced by weather.
Promote suppliers who use enzymatic retting over water or chemical retting.	Process is faster and leaves the water unharmed. Can be commercially reproduced.	• Low fibre strength. Process is less common compared to other retting processes. • Enzymes add to the cost of the process
Use hydrogen peroxide to lighten the natural beige colour for dyeing dark shades and bright/light shades.	Hydrogen peroxide harmlessly decomposes into water and oxygen gas.	• Non-chlorine bleaches do not strip out the original colour of the fibre. Consequently, colours will be duller due to the over-dyed effect Non-chlorine bleaching is adequate for dark colours, which mask the original beige tone. • Hydrogen peroxide may cause danger while storing and transportation.
Use ozone bleaching processes to strip out the natural beige colour of jute. Promote the particular aesthetic of ozone bleach effects.	Ozone can used be with no water at all.	• Ozone has limited availability and is relatively expensive since it requires investment in ozone generating equipment. • Ozone processes produce a different aesthetic than chlorine derivative or permanganate bleaching.
Promote the use of enzymes to strip out the natural beige colour of jute. Promote the particular aesthetic of enzyme e bleaches.	More info: see Bleaching	• Some enzymes might not be allowed in GOTS standards • Enzymes produce a different aesthetic than chlorine derivative or permanganate bleaching.
Promote the use of jute-blended fabrics.	Can achieve the property benefits of both fibres.	• Sometimes requires further processing, which could include chemicals.
Promote the use of jute fibres in composite materials and technical textiles	Can achieve biodegradable composites	• Some additional treatments might be necessary to change surface properties to increase affinity with composite matrix

See retting process comparision chart, page 21.

Availability

Jute is readily available in pure form as well as blends with wool and silk.

About 95% of the world's jute is grown in India and Bangladesh. Nepal, Myanmar, China, Thailand, Vietnam and Brazil also produce jute. Pakistan imports a substantial amount of raw jute from Bangladesh for processing.

Several farmers in Bangladesh are currently growing organic jute. Organic certification by an internationally recognized certification agency accredited by IFOAM must be in place.

Applications

In pure form, jute is highly durable and suitable for many applications including twine and rope, sackings, carpets, wrapping fabrics (cotton bale), and the construction fabric manufacturing industry.

It can be used in curtains, chair coverings, carpets and carpet backing, rugs, and backing for linoleum.

Jute can be used in home textiles, either replacing cotton or wool or blending with it.

Finest jute threads can be separated out and made into imitation silk. In pure form, jute can be used as is and as well as in fabric blends, jute fibre is suitable for jackets and skirts.

Recently, jute fibres are increasingly being used together with other bast fibres, as reinforcement for green composite materials, to replace oil-based fibres, or to obtain all-cellulose composites.[6, 7]

Advantages

Fast-growing natural resource

low water footprint in growing stage

Biodegradable (depending on dyes and trims used) All fibres, yarns, trims and dyes **Used to manufacture** the product or garment must also be biodegradable or disassembled before disposal.

This should be substantiated with documentation that the product can completely be broken down into non-toxic material by being processed in a facility where compost is accepted.

Non-chlorine bleached If alternative bleach is used.

Organic If certified with GOTS, all fibres, yarn, trims and dyes used to manufacture the garment must comply with the GOTS organic garment standard.

Innovation opportunities

1. As an alternative to plastic bags, develop a 100 % biodegradable jute bag (undyed with biodegradable trims) with instructions to the customer on proper disposal.
2. Create a jute product that is 100 % biodegradable and compostable: the product can break down in a reasonable amount of time and can provide valuable nutrients to the soil.
3. Use jute fibre in blends with cotton to achieve grey/beige heather effects, then over-dye the cotton side to achieve heathered colours without using chlorine bleach.
4. Use jute in stripes side by side with cotton, then over-dye to achieve tonal colours without using chlorine bleach.
5. Strategically introduce/design with jute in products subjected to high stress, as inserts or full design such as the knees or elbows, to maximize its physically durable properties.
6. Reduce or minimize the negative environmental impact from growing and using cotton by replacing cotton for jute in denim.
7. Develop/design garments and products that are designed to facilitate or enable a take-back and easily fit into a recycling program. Experiment with seaming and a variety of disassembly mechanisms in different fabrics.
8. Use jute fibres as reinforcement for green biodegradable composites to replace oil-based fibres.
9. Use jute fibres in technical textiles for construction and insulation applications.

6 H. Chandekar, V. Chaudhari, S. Waigaonkar, A review of jute fibre reinforced polymer composites, in: Mater Today Proc, Elsevier Ltd, 2020: pp. 2079–2082. https://doi.org/10.1016/j.matpr.2020.02.449.

7 U.K. Sanivada, G. Mármol, F.P. Brito, R. Fangueiro, Pla composites reinforced with flax and jute fibres—a review of recent trends, processing parameters and mechanical properties, Polymers (Basel). 12 (2020) 1–29. https://doi.org/10.3390/polym12102373.

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Other Cellulosic natural fibres

Ramie fibres

Ramie (Boehmeria nivea L.), is a type of bast fibres similar to hemp and flax, used for a long time in many regions worldwide, mainly in Asia. It possesses a lustrous appearance and can withstand wetting.

Cultivation and availability

Ramie is harvested approximately every 60 days by cutting the mature shoots without destroying the roots; thus, the root system develops continuously in the soil. Ramie is cultivated in China with approximately 500,000 tons of fibre per year, which represents 96% of global production. Ramie farming and trade provide livelihood support to millions of people. The major export markets for ramie-based products are Japan and Europe.[1]

Properties

The extracted fibres possess good characteristics of lustre and silk-like appearance, high tenacity, strength, and good microbial resistivity. It demonstrates tensile strength of 400–1000 MPa with an average elongation at break of 2.5%. The strength of the fibre is increased in wet conditions, and it resists high temperatures in wet conditions as well. It is known for its ability to hold its shape. It is resistant to bacteria and insects. It can also be used in blends with other fibres such as cotton, wool and even silk to make different industrial products. Moreover, ramie fibres are known for their biodegradability, thermo-stability, and low cost.[2]

Ramie fibres are not easy to dye, and the ramie yarns usually are hairy due to lack of elasticity, The brittleness of the fibres therefore affects their ability to be easily woven.

Like other bast fibres, degumming or retting is needed to extract the ramie fibres from the plant. Low degumming efficiency and high environmental pollution due to water retting are the major problems hindering the utilization of ramie fibres on larger scales. If the fibres are treated with alkali and bleached to improve fibre colour and appearance, that can lead to big impact of the environment and reduces the benefits.

Benefits and applications

Ramie is environmentally friendly in many aspects; it can resist heavy metals in soil to grow and colonize diverse heavy metal mine sites. Another benefit is its positive influence on the soil organic matter pool. It is found that nitrogen and phosphorous significantly increase after 13 years of ramie cultivation.[3]

Ramie fibres can be used in a wide range of products such as apparel, furniture, hammock, belts, chords, fire hoses, fishing nets, car covers and other products.

Nowadays, the ramie fibre, among others, is a popular fibre to be included in biodegradable green composites for example as in PLA matrix.

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1 M. Rehman, D. Gang, Q. Liu, Y. Chen, B. Wang, D. Peng, L. Liu, Ramie, a multipurpose crop: potential applications, constraints and improvement strategies, Ind Crops Prod. 137 (2019) 300–307. https://doi.org/10.1016/j.indcrop.2019.05.029.

2 L. Cheng, S. Duan, X. Feng, K. Zheng, Q. Yang, H. Xu, W. Luo, Y. Peng, Ramie-degumming methodologies: A short review, J Eng Fibre Fabr. 15 (2020). https://doi.org/10.1177/1558925020940105.

3 F. Bogard, T. Bach, B. Abbes, C. Bliard, C. Maalouf, V. Bogard, F. Beaumont, G. Polidori, A comparative review of Nettle and Ramie fibre and their use in biocomposites, particularly with a PLA matrix, Journal of Natural Fibres. 19 (2022) 8205–8229. https://doi.org/10.1080/15440478.2021.1961341.

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Nettle Fibres

Nettle (Urtica dioica L.), or stinging nettle as it is called sometimes, grows in moderate and cold climatic regions like Europe. It is a strong and durable fibre extracted from the stem of the stinging nettle plant.

Cultivation and availability

Since the nettles can grow in cool and cold climates, it has been harvested in Canada, USA, and Europe successfully, especially in Germany, Austria, and Scandinavia. These fibres are used mainly on smaller scales for local products and crafts, and it is not yet harvested for industrial use. However, it is now studied for semi-industrial production. Nettles prefer loose soils that are rich in nitrogen for rapid growth.[4]

Properties

Nettle fibre is similar to ramie fibres in its appearance. The high-quality fibres have a silky feel with a dim shine. It is soft and flexible when processed, with high breaking tenacity. The length of the fibre (uncut) can reach up to 80 cm with diameters up to 50 μm. Some less processed coarse fibres can be separated out to be used in apparel or technical uses. It is a breathable fibre, with a good performance also under wet conditions and can be dyed easily. Its average stiffness is around 75 GPa and tensile strength around 1100 MPa.[4]

Nettles requires a retting process for degumming to extract and separate the fibre bundles.

However, water retting involves higher labour costs and disagreement such as fermentation odour and environmental problems due to effluent discharge, thus mechanical processing is preferred based on environmental considerations.

Benefits and applications

The nettle crop is considered to have low requirement for fertilizers and pesticides, additionally, irrigation is not needed in nettle fields. It may improve soils overloaded with nitrates and phosphates and it can grow on soils that are not good for food crops like contaminated soils. The fibres can be harvested once a year.

Nettle fibre can be used in wide range of applications such as clothes, furniture, green composites for automotive and construction. It can be used as a green alternative to glass fibres in technical textiles and composites as well.

4 C. Viotti, K. Albrecht, S. Amaducci, P. Bardos, C. Bertheau, D. Blaudez, L. Bothe, D. Cazaux, A. Ferrarini, J. Govilas, H.J. Gusovius, T. Jeannin, C. Lühr, J. Müssig, M. Pilla, V. Placet, M. Puschenreiter, A. Tognacchini, L. Yung, M. Chalot, Nettle, a Long-Known Fibre Plant with New Perspectives, Materials. 15 (2022). https://doi.org/10.3390/ma15124288

Wool

Natural fibre

Wool is the textile fibre obtained from sheep and certain other animals, including alpacas, goats, rabbits, sheep and camels. Wool fibres have inherent sustainability attributes. It is a renewable, natural fibre that can be used as a viable alternative to synthetic fabrics.


Unsplash/J. Schiemann

Wool

Benefits

Wool is a natural fibre and renewable. It is valued for its natural warmth and water repellence.

In 2016 the wool fibre counted for about 1 % of the total global fibre consumption.[1] Australia produce approx. 25 % wool of the total world wool market and is as such the largest wool producer and when it comes to the global production of fine Merino wool to the international trade, Australia dominates the market with over 90 %.[2,3]

Merino, cashmere, mohair, alpaca, camel, and angora wools are all valued for their softness, comfort, wrinkle resistance and lustre. Mohair and alpaca are even naturally non-pilling.

The surface of wool fibres are water- dirt- and stain-repellent, whilst the fibre interior is highly moisture absorbent, making it a comfortable fabric to wear.

wool burns slowly and is self-extinguishing per def. which often makes the need to use flame retardants unnecessary. Wool fabrics are often used for furniture as sofas etc. and for train and bus seats.

Wool absorbs odors and tends not to smell bad, even after long use. Wool is considered to be self-cleaning and does not need to be washed as often, but can be aired with advantage instead of refreshing the garment.

A 100 % wool fabric is biodegradable and can be discarded after use or throughout its lifetime, although absolute biodegradability depends on the dyes and other trims used.

Potential impacts

Cultivation/animal welfare

Wool from sheep

Merino sheep have been specially bred to produce more volume of higher quality wool than other sheep. This is enabled by their convoluted skin, which provides a greater surface area on which more fibre can be grown. But some reports indicate that the increased weight of wool can strain the sheep and lead to heat stroke, dehydration and even death. In addition, urine and moisture tend to build up in the wrinkles of the skin, attracting flies, particularly the blowfly, and maggots around the sheep's rump. A compensation procedure known as mulesing involves carving skin from the back legs of the sheep to make the area smoother and less prone to attract flies.

Mulesing has been a hotly debated subject amongst activist groups and the textile industry as a whole. Activist reports note significant cruelty to animals during this procedure, whereas farmers describe mulesing as cost-effective and simple way to protect against flystrike.

Spray-on chemicals are used as an alternative to mulesing to prevent flystrike. These chemicals can be harmful to humans and can contaminate watercourses if not used properly.[4,5]

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1 Preferred Fibre and materials Market Report| https://textileexchange.org/knowledge-center/reports/preferred-fibre-and-materials/
2 Wool.com| https://www.wool.com/market-intelligence/woolcheque/wool-characteristics/diameter/
3 World's largest wool producing countries|https://blog.bizvibe.com/blog/textiles-and-garments/top-10-largest-wool-producing-countries
4 International Wool Textile Organization| https://iwto.org/
5 Wool Facts| https://www.woolfacts.com/wool-and-animal-welfare/mulesing/

WOOL TYPES AND CHARACTERISTICS

	Merino	Cashmere	Mohair	Camel	Angora
Microns	10-24,5*, **	14-19	23-45	16-20	14-16
Source & exclusivity	Sheep; common	Cashmere goat; common	Angora goat; common	Two-humped Bactrian camel; rare	Angora rabbit; limited producers
Major producers	Australia, China, New Zealand, Iran, Argentina, UK	India, Mongolia, China	South Africa, United States	Mongolia, China	China, Europe, Chile, United States
Fibre collection	Shearing	Combing or Shearing	Shearing (twice annually)	Combed, shorn or collected during the 6-8 weeks moulting season	Hair removed every 3 months by shearing or gentle plucking
Cost	Low–moderate	High–luxury fibre	High	High–luxury fibre	High–luxury fibre
Blends well with	Natural and synthetic fibres	Wool and nylon (for knitwear)	Wool	Cashmere, wool, nylon (to make it more economical for manufacturer to produce)	Wool (to increase warmth and enhance softness)
End use	Outerwear, knitwear, active-wear, durable upholstery	Knitwear, babywear, blazers, coats, underwear, sleepwear, rugs, carpets	Clothing, rugs, carpets, blankets, durable upholstery	Knitwear garments, coats, suits, blazers, jackets, gloves, hats, scarves	Luxury undergarments, un-derwear, thermal base layers, scarves, sportswear, sweaters
Natural colours	White, brown, grey, charcoal, black	White, grey, brown, red, yellow, almond, apricot	Blacks, greys, silvers, reds, apri-cots, copper	Golden tan, red to light brown	Black, blue, chocolate, brown, greys, white, reds
Consumer care & washing	Hand-washable	Dry-clean	Dry-clean	Dry-clean	Hand-washable

Cultivation/animal welfare

Wool from Swedish Sheep

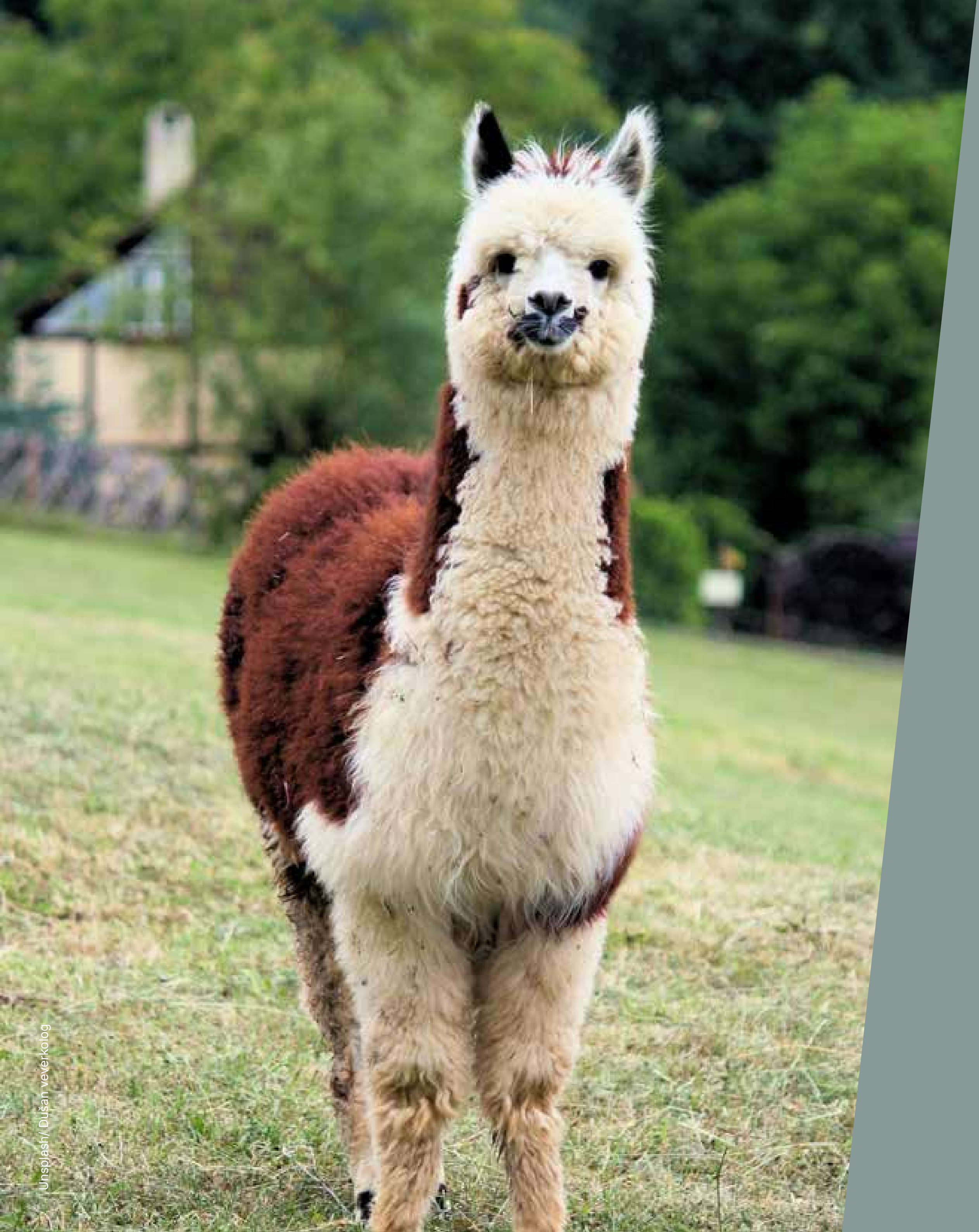
The Swedish Sheep Breeding Association makes annual overviews of Swedish sheep farming and estimates that approx. 1,000 ton of wool was produced in Sweden by almost 8,000 herds and companies (2020). This corresponds to a little over half a million sheep with about forty different sheep breeds spread all over Sweden, which makes the disposal and processing of wool complicated. The largest sheep breed is Gotland sheep, which accounts for roughly a quarter of the total/overall Swedish wool production, followed by two types of crossbreds, one consisting of at least 50% Texel, the other of at least 25% Gotland or Leicester sheep. Jämtland sheep, which has the finest wool, is right now a fairly small breed of sheep, 4.5 tons (2020). Almost as large as the share of wool from Gotland sheep is the group "Other crossbreds", where the wool is unspecified.

Particularly worth mentioning when it comes to Swedish sheep farming is animal husbandry. The World Animal Protection Index (API) ranks 50 countries around the world according to their animal welfare policies and animal husbandry legislation. A range of indicators are assessed in the areas of recognition of animal sentience and prohibition of animal suffering, presence of animal welfare legislation, existing government support bodies and support for international animal welfare standards. All indicators are assessed according to a scale A to G where A is the best, then the indicators are summed according to the same scale. No country achieves A. Sweden is at the top of level B together with Denmark, Great Britain, the Netherlands, Switzerland and Austria. The countries in the world that produce most wool are ranked as follows Australia D, China E, New Zealand C and Turkey D. Norway is not among the countries ranked.[6] What makes Sweden top ranked is our strict legislation and control of animal husbandry and animal welfare, which creates security for both animals and those who use the wool. During the summer months, Swedish sheep and lambs graze and during the winter they are kept freely in flocks in well-ventilated buildings. Swedish farmers are not allowed to use chemical insecticides, which is common throughout the world except in the Nordic countries. Castration without anaesthesia, mulesing and tail docking, which occur in some wool-producing countries, are prohibited in Sweden. The sheep must be sheared at least once a year. Animal protection also includes sheep transport, marking and health. In 2018, Sweden had the lowest antibiotic use for animals within the European Union.

The IVL report shows that Swedish wool production can offer lower climate impact and more positive effects compared to other countries' wool production.[7]

6 World Animal Protection | Animal Protection Index https://api.worldanimalprotection.org/

7 Sustainability Assessment of Swedish Wool |https://www.diva-portal.org/smash/get/diva2:1766792/FULLTEXT01.pdf



Unsplash/ Dušan veverkolog

Alpaca

Natural fibre

The textile fibre obtained from alpaca is simply called "alpaca fibre." Alpaca fibre has inherent sustainability attributes: It is a renewable, natural fibre that can be used as a viable alternative to cashmere, wool from sheep and even synthetic fabrics.

Alpaca

Potential impacts

Cultivation/animal welfare

Wool from Alpaca

There are two different breeds of alpacas: huacaya and suri. The main physical difference between these two alpaca breeds is the fleece. Like wool from sheep, fibres from huacaya have a natural crimp and when the fleece grows, they look fluffy. Suri fibre has no crimp in its fleece, and the fibre drapes down from its body. It is soft and silky and can be used as an alternative to silk.

Alpacas have padded feet rather than hooves. Because of this, they are very gentle on the pasture. Alpacas don't consume the root of grass like sheep and Kashmir goats, so the grass can continue to grow after been eaten it.

Alpaca fibre is a natural and renewable fibre. It is valued for its natural warmth and water repellence.

Alpaca fibre is highly valued for its softness, durability and silkiness. Due to the low count of the fibres (20-70 μm), it is very comfortable to wear and is also lightweight. It is naturally non-pilling.

Unsplash/Dušan veverkolog

Alpaca fibre comes in 22 natural colours, including white, browns, greys and black, potentially eliminating the need to use synthetic dyes.

Alpaca fibre does not contain lanolin or grease, so it can be easily cleaned in a rinse bath with natural products.[1, 2]

Regarding animal welfare The Responsible Alpaca Standard (RAS) is a voluntary standard that require all sites, from alpaca farms through to the seller in the final business-to-business transaction, to be certified. RAS farmers and ranchers must meet animal welfare, land management, and social requirements.

The purpose of the standards is to give the industry a tool to recognize farming best practices and ensure that alpaca wool comes from farms that take a progressive approach to land management and respect the Five Freedoms of animal welfare. It will also ensure strong chain of custody for certified materials as they move along the supply chain.[3]

Cultivation/animal welfare

Cashmere from goats

Although wool from animals is a profitable source of income for farmers, the impact of overgrazing of cashmere goats has been reported to contribute to land degradation and desertification, and as a result has led to loss of biodiversity in Mongolia and other countries. This is because goats are insatiable eaters compared to other livestock and consume the root of the grass as well, thereby stopping it from growing altogether. To accommodate the growing cashmere industry, and the resulting drop in cashmere wool prices, farmers increase the size of their herds to compensate for this, therefore increasing the impact on land as there will be more animals per unit area.[4]

There is little reliable information supporting animal cruelty to cashmere goats. However, due to increased consumer demand for cashmere wool, overall consumer demand for inexpensive products, increase in herd size, and lack of standards regulating proper treatment of animals in cashmere-producing countries, relationships with producers need to be closely monitored to ensure friendly practices are being implemented.

Angora wool from rabbits

Animal cruelty to Angora rabbits was published in 2013. Typically, the wool from angora rabbits is either shorn or gently plucked every 3 months. Undercover video footage has shown farmers vigorously ripping out fibre from the rabbit's body. The reason for this is that these farmers receive a higher price for the entire length of the

1 US Alpaca Company | http://www.usalpacacompany.com/Alpaca-Fibre.html
2 Wild hair Alpacas | www.wildhairalpacas.com/pages/1414/wild-hair-alpacas-llc-whats-so-special-about-alpaca-fibre
3 The Responsible Alpaca Standard | http://textileexchange.org/responsible-alpaca-standard/
4 High cost of cashmere on Mongolia plains | http://edition.cnn.com/2010/WORLD/asiapcf/09/12/mongolia.cashmere.herders/index.html

hair. Several companies have ceased production of angora products in response to the allegations. Relationships with producers need to be closely monitored to ensure friendly practices are being implemented.

Processing

Scouring

Around two-thirds of the total weight of the wool fibre by weight consists of grease, dried sweat salts, skin flakes, dirt and dried plant matter. To remove these substances from the wool fibre, a cleaning or scouring process is carried out at high temperatures (approx. 60-66°C) in an aqueous solution of sodium hydroxide and detergent.[5] Scouring consumes large amounts of water, and produces an effluent with high biological oxygen demand (BOD) and high-suspended solids content.[6] This reduces the dissolved oxygen (DO) levels meaning less oxygen is available to fish and other aquatic organisms. Trace elements of pesticides also remain in the wastewater. Some of these detergents used for scouring are banned in Europe, but not elsewhere.[7] Scouring Alpaca wool can be a slightly different process as it does not contain grease or lanolin.

Shrink proofing

Anti-shrinking treatments prevent wool from felting during the washing step/process and generally include chlorine in some form. Chlorine-Hercosset is a treatment used on wool fibre. Dry chlorination is a treatment carried out on wool fabric using chlorine gas. Repeated exposure to chlorine can affect the human respiratory system. In addition, depending on the amount used and how it is handled, chlorine may be released into the air and water and in certain conditions may form dioxins. The wastewater from the wool chlorination process contains chemicals of environmental concern. Due to these chemicals, this wastewater is not accepted by water treatment facilities in for ex the United States. Therefore, all chlorinated wool is processed in other countries, and then imported.

Wool garment can be chemically treated with enzymes to reduce hairiness of the wool fibre and in that way also contribute to anti felting properties.[8] It has also been shown that plasma treatment can improve both anti-felting and shrink resistance to wool fabrics.[9]

Dyeing

The dyeing processes for wool involves standard industry chemicals and water use. Some types of dyes are suspected carcinogens and mutagens, and untreated dye water can negatively impact receiving water bodies and harm aquatic ecosystems if left untreated before released.

MORE INFO: DYEING & PRINTING

Consumer care/washing

Wool fabrics may be washed by hand or with a special program in the washing machine, spot cleaned, or dry-cleaned, depending on the product. The recommendation is to wash less and vent more. Washing and caring for any product can have negative environmental impacts due to harmful chemicals used in cleaning products.

MORE INFO – APPENDIX: CONSUMER CARE & WASHING

End of use

Although pure wool fibres are biodegradable, the amount of time it could take for a wool product to decompose naturally is dependent upon a number of conditions – including how much air, temperature and sunlight the fibre is exposed to. If the waste is buried in a landfill, it will take even longer for it to decompose.[10]

MORE INFO – APPENDIX: BIODEGRADABILITY

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5 Russell I. M., Sustainable Wool Production and Processing, in Blackburn R.S. (Ed.) Sustainable Textiles Lifecycle and Environmental Impact, Woodhead Publishing, Cambridge, p63-87.
6 OECOTEXTILES | https://oecotextiles.blog/2009/08/11/what-does-organic-wool-mean/
7 Chemistry of the Textiles Industry, C. Carr
8 Textiles and Clothing Sustainability: Sustainable Textile Chemical Processes, edited by Subramanian Senthilkannan Muthu
9 Green Living tips | https://www.greenlivingtips.com/
10 OEKOTEX | https://www.oeko-tex.com/en/

Optimize sustainability benefits

Opportunity	Benefits	Considerations
Promote suppliers using certified organic Merino wool.	No disallowed chemicals used. Organic feed fed to animals. Carrying capacity of the grazing land is considered and the size of the flock is monitored to avoid land degradation. Animals are quarantined when sick, rather than continuously fed with antibiotics.	Organic wool is available, though not so readily as conventional. Organic wool is more expensive than conventional wool.
Promote suppliers who use natural substances to scour wool tops.	Provides "gentle" scour, which results in less biological load and fewer toxic chemicals in the wastewater	
Implement humane methods of flystrike control in Merino sheep.	Sheep are treated holistically as a first resort if flystrike occurs.	Methods of mulesing and chemical application are used only when absolutely necessary. Less available than conventional wool.
Promote the use of nonmulesed merino wool		
Promote the use of chlorine-free wool.	Chlorine is not used during the shrink proofing process.	Chemical treatment with enzymes could be used.
Promote suppliers who treat the effluent after the scouring process, and reclaim the lanolin.		
Promote suppliers who use recycled Merino wool.	Available in Northern England and Prato, Italy. Since wool is a renewable resource, the primary benefit of recycled wool is in reducing loads on landfill. However, using recycled wool may also ease the pressure that industrialized sheep ranching places on the land.	Recycling wool creates shorter fibres, which need to be blended with a percentage of virgin wool or synthetic fibre to maintain strength for finer-count yarns. The coarser the yarn count, the less virgin wool or synthetic fibre is required.
Promote suppliers using Cardato Regenerated CO_2 Neutral products.	The Cardato Regenerated CO_2 Neutral brand certifies both the carbon footprint of the textile production process and the use of regenerated raw materials. To carry the label, products must be produced in Prato; produced with at least 70 % of recycled material (recycled clothing or textile off-cuts); and be made by mills that have accounted for their CO_2 emissions and have purchased emission credits from the Prato Chamber of Commerce.	
Promote the use of natural colour wool.	No bleaches or dyes are used in this case, and associated pollution impacts are avoided.	
Promote wildlife-friendly grazing practices for Cashmere goats. Prioritize sites that have endangered wild species.	Decreases impacts of overgrazing and loss of biodiversity due to desertification.	
Develop relationships with producers and monitor farmers.	Ensures animal-friendly practices are being implemented.	
Promote OEKO-TEX certified wool.	Ensures that products pose no risk to health. These products do not contain allergenic dye-stuffs and dye-stuffs that form carcinogenic arylamines, and several other banned chemicals. The certification process includes thorough testing for a long list of chemicals.	

Availability

There are several companies supplying organic wool fabrics and yarns internationally. Recycled wools are readily available in West Yorkshire, UK, and Prato, Italy. Mulesing free wool is available in Patagonia, South America, and in certain areas of Australia, where the blowfly does not exist. Alpaca fibre is available from producers in Peru, North America and Australia.

Obtaining Swedish wool is currently limited, but availability will increase as methods and processes are implemented. In the autumn of 2023, the first Swedish classification system for wool will be introduced. The standard makes it easier to both sell and buy in Swedish wool raw material of high and uniform quality. The classification system for Swedish wool has been developed by The Swedish Wool Initiative, a broad collaboration between stakeholders across the entire value chain.

End use

The applications for wool vary according to the type of fibre/breed of sheep and animal. The wool fibre is useful both in clothing and home furnishings as well as sports and technical textiles.

Organic certification is now available for a variety of wool types and certified organic wool fabrics range from fine knit wool crepes to woven melton.

Recycled wool lends itself more to knitting, for example sweaters and coarser fabrics, though smaller percentages of recycled wool are found in high-end tweed fabrics made by Italian mills.

In Sweden, the interest for locally produced wool from Swedish sheep has been growing. Many projects and initiatives are underway to make use of the wool that is thrown away. Arena Svensk Ull is a national initiative where the purpose is to strengthen cooperation for Swedish wool and work for increased use of Swedish wool with a special focus on strengthening the large-scale handling of wool with the aim of developing the Swedish wool industry.[11]

Innovation opportunities

1. Use organic wool in blends to add character and texture to organic cotton.
2. Use naturally coloured wool (black/brown) to create heathers with white wool or cotton.
3. Implement an integrated strategy to prevent flystrike and work with ranchers to combat flystrike with animal-friendly methods.
4. Consider using a coloured wool wrap around a less expensive cotton core to create a marled yarn.
5. Combine stripes of organic wool with stripes of organic cotton and agitate in hot water to felt the wool and pucker the cotton.
6. Use wool in strategic areas of a garment to emphasize its self-cleaning and moisture absorbent attributes, such as under the arms.
7. Partner with a local cleaner to promote wet or steam cleaning to the customer instead of dry-cleaning.
8. Work with Australian Wool Innovation Limited (AWI) or e-wool to obtain a list of Australian Merino ranchers that have incorporated methods to replace mulesing: wool.com, e-wool.com.au
9. Work directly with producers of wool from cashmere goats to strategize wildlife-friendly grazing practices and to ensure animal friendly practices are being implemented.
10. Instead of boycotting, work directly with producers of Merino and angora wool to request the implementation of animal- friendly practices.
11. Know where your fibre or product is being sourced from. Be aware that when there is high demand for a fibre – a fibre that typically is produced in poor countries with little or unenforced regulations for workers and animals – the likelihood of animal cruelty and poor worker conditions increases.

11 Arena Svensk Ull | https://www.arenasvenskull.se/

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Silk

Natural fibre

Silk can play a strategic roll as sustainable textiles from a producer. At the high end of the market, silk products may offer greater price elasticity at retail with greater potential to absorb the typically higher costs of sustainable fibres.

Silk

Silk is a protein fibre produced by silkworms. As a silkworm develops into an adult it feeds on leaves and then spins a cocoon from one continuous silk strand or filament, 900–3,000 meters long. Inside the cocoon the worm changes into a chrysalis, then into a moth, which then seeks to leave the chrysalis.[1] The moth achieves an escape path by secreting a liquid, which dissolves a hole in the cocoon through which the moth can then escape.[2]

Heat is used to soften the hardened filaments so they can be unwound. Single filaments are then combined with a slight twist into one strand, a process known as filature or "silk reeling."

Benefits

Silk is a renewable natural resource and biodegradable in its pure form. Since the silk filament is a continuous thread, it has high tensile strength. In woven fabrics, silk's triangular structure acts as a prism that refracts light, giving silk cloth its highly prized "natural shimmer."[3]

Silk has good moisture absorbency, low conductivity and dyes easily.[4]

Being a natural fibre, silk is biodegradable after its useful life, though absolute biodegradability depends on chemical use, and route of disposal.

The silkworms used for wild or "tussah," or "tasar" feed on leaves, not necessarily mulberry, and does not harm the chrysalis. Tussah silk is derived from cocoons collected after the moth has emerged naturally in the field. Because the continuous silk fibre is broken into smaller pieces as the moth leaves the cocoon, wild silk has a rougher and slubbier surface than cultivated silk.[5]

Sericulture (silk farming) is labour-intensive. About 1 million workers are employed in the silk sector in China. Sericulture provides income for employment to 7.9 million people in India, and 20,000 weaving families in Thailand.[6] Wild silk can provide a year-round income for tribal people in India and some areas of China.[7]

Potential impacts

Animal welfare

On domesticated silk farms the chrysalis is killed to prevent the moth from making a hole in the cocoon. The reason for this is that the hole breaks the highly prized long silk filament into thousands of short lengths, which are useless for higher quality spinning.

Processing

Cocoons are soaked in sodium carbonate to soften in preparation for reeling (unwinding the filament from the cocoon). Silk fabric is then woven with the natural gum or sericin still on the yarn, acting as a natural sizing agent. After weaving, the gum is removed by boiling the fabric in alkali. This can result in a 20 % reduction of the harvested weight of the silk. Some of this lost weight is added back by saturating the silk fabric in a bath of tin-phosphate-silicate salts. This process can create a high biological risk on the water and consume available oxygen for aquatic species if left untreated. Exposure to tin through breathing and skin contact can have acute and long-term effects on worker health if proper equipment is not used.[8]

Lightweight silk fabrics (fine gauge silk) are easily worn and are degraded by exposure to sunlight and high temperatures. They can also be susceptible to abrasion and twisting in laundering.[9]

1 www.textileexchange.org/node/1096
2 www.naturalfibres2009.org/en/fibres/silk.html
3 www.naturalfibres2009.org/en/fibres/silk.html
4 www.naturalfibres2009.org/en/fibres/silk.html
5 Article in The hindu businessline March 5 2013 Govt may use wastelands for tasar silk cultivation www.thehindubusinessline.com/industry-and-economy/agri-biz/govt-may-use-wastelands-for-tasar-silk-cultivation/article4479274.ece
6 http://inserco.org/en/statistics "Silk Industry: Statistics." International Sericultural Commission, United Nations Regional Number 10418.
7 Article in The hindu businessline March 5 2013 Govt may use wastelands for tasar silk cultivation www.thehindubusinessline.com/industry-and-economy/agri-biz/govt-may-use-wastelands-for-tasar-silk-cultivation/article4479274.ece
8 Slater, K. (2003), Environmental impact of textiles: production, processes and protection. Cambridge: Woodhead Publishing, p27
9 www.lenntech.com/periodic/elements/sn.htm

Dyeing

The dyeing processes for silk involve standard industry chemicals and water use. Certain types of dyes are suspected carcinogens and mutagens, and untreated dye water can negatively impact receiving water bodies and harm aquatic ecosystems if left untreated before its release.

MORE INFO: DYEING & PRINTING

Consumer care/ washing

Due to the delicacy of the fabric, silk products are typically handwashed or dry-cleaned. Washing and caring for any product can cause significant environmental impacts due to chemicals used in detergents. Certain chemicals used in dry-cleaning and at-home products have been reported to have detrimental effects or on humans and the environment, contribute to ozone depletion and can pollute wastewater.

Silk tends to crush and wrinkle easily. This wrinkling creates a need to more intense ironing. This can consume significant amounts of electrical energy over the long term.

MORE INFO – APPENDIX: CONSUMER CARE & WASHING

End of use

Although pure silk fibre is biodegradable, the amount of time it could take for a silk product to decompose naturally and in a short period of time is dependent upon a number of conditions—including how much air, temperature and sunlight the fibre is exposed to. If the waste is buried in a landfill, it can take even longer for it to break down.[10]

MORE INFO – APPENDIX: BIODEGRADABILITY

Availability

Silk represents less than 0,2% of the global textile market. 90% of the producers of mulberry silk and almost 100% of non-mulberry silk are in Asia. In 2021 China produced about 54% of the world's silk, followed by India with 40%. Others are Uzbekistan, Vietnam, Thailand, Brazil, North Korea, Iran. USA, Italy, Japan, India, France and China are main consumers of silk.[11]

Organic silk is available in small quantities at premium prices. Certification of organic silk must be in place by an internationally recognized certification agency accredited by IFOAM.

Most wild silk is cultivated in China, India and Japan.[12] Verification of the source of the wild silk must be provided. Ahimsa silk is cultivated in India.

End use

Silk's natural beauty and properties—such as comfort in warm weather and warmth during colder months— have made it sought after for use in high-fashion clothes, lingerie and underwear.[13]

Due to its coarseness, wild silk is largely used in furnishings and interiors.[14]

Unsplash/Susan Wilkinson

10 www.treehugge6r.com/culture/qa-is-silk-green.html

11 http://inserco.org/en/statistics "Silk Industry: Statistics." International Sericultural Commission, United Nations Regional Number 10418.

12 Article in The hindu businessline March 5 2013 Govt may use wastelands for tasar silk cultivation www.thehindubusinessline.com/industry-and-economy/agri-biz/govt-may-use-wastelands-for-tasar-silk-cultivation/article4479274.ece

13 www.naturalfibres2009.org/en/fibres/silk.html

14 http://inserco.org/en/statistics "Silk Industry: Statistics." International Sericultural Commission, United Nations Regional Number 10418.

Innovation opportunities

1. Encourage handwashing or spot cleaning on the hangtag and labelling/Point of Sales to convince the consumer to take an active role in reducing environmental impacts of silk garment care.
2. Wild silk is an important income source for farmers in India, and areas of China. An artisan project would bring an additional social/fairtrade element to a sustainable fabric program.
3. Blending with another fibre that is washable, such as cotton, reduces the impact of consumer care/dry-cleaning.
4. Design garments that utilize the natural wrinkling of silk as a design feature to influence the customer to reduce ironing of the final product and the energy it uses.
5. Create a silk garment that is 100% biodegradable: the product is either undyed or natural-dyed, with biodegradable trims and thread material, and is equipped with secondary label or marketing material that instructs the customer on how to dispose.

Optimize sustainability benefits

Opportunity	Benefits	Considerations
Promote the use of wild or "Tussah" silk.	• Wild silk doesn't require the chrysalis to be killed. • Wild silk provides a year round income for tribal people in India and some areas of China.[15]	• Due to the shorter (less prized) fibre length, wild/Tussah silk is less expensive than domesticated silk. Tussah silk fabrics have a coarser texture and are typically stiffer and heavier than domesticated silk. • Wild/Tussah silk is available in small quantities.
Promote the use of Ahimsa silk.	• Cultivated in India and doesn't require the chrysalis to be killed. • The fibres are spun into "slubby threads" instead of reeled. • The quality of Ahimsa silk is softer and finer in comparison to regular silk and has a pearl matte natural finish.	• More costly than regular silk due to its laborious process of spinning the many pieces of yarn into one continuous thread. • Not all slubby silks are Ahimsa silk. • Manufacturers often label these slubby silks as Dupioni or shantung, and claim they are Ahimsa silk. This should be substantiated with documentation.
Promote the use of **Organic** silk.	• Since pesticides are rarely used on silk fibre production (this would kill the silk worm), the main benefit of organic certification is using organically cultivated mulberry bushes. • Organic cultivation has wide ranging benefits for the surrounding ecosystem.	• Organic silk is available in small quantities and carries a price premium. • Certification of organic silk must be in place by an internationally recognized certification agency accredited by International Federation of Agriculture Movements (IFOAM).
Promote the use of **Fairtrade** silk.	• Ensures the proper treatment of workers.	• Fairtrade silk products are less available then conventional silk. Does not necessarily mean "organic."
Blend silk with organic cotton, organic wool, organic linen, etc.	• Brings a "luxury" element to the product and commands a higher retail price. • Blending with a washable fibre reduces the impact of consumer care/dry-cleaning	

15 Slater, K. (2003), Environmental impact of textiles: production, processes and protection. Cambridge: Woodhead Publishing, p27

Part 3: Man-made fibres

Man-made fibres

Man-made fibres are divided into three main classifications: cellulosic, protein and synthetic fibres.

Man-made cellulosic fibres, so called regenerated cellulose accounted for approximately 6 % of global man-made fibres in 2021.[1] These fibres are derived from a range of plant-based and woody materials, which require intensive chemical manufacturing processes to be transformed first into pulp and then into "regenerated" cellulosic filaments. These fibres include modal, lyocell, viscose made from wood and viscose made from bamboo.

Man-made protein fibres, such as PLA and Azlon, are fibres which are composed of regenerated, naturally occurring protein derived from a number of sources, including: soybean, peanut, casein (from milk), zein (from maize), and collagen/gelatine (from animal protein) to name a few.

These fibres are considered as biobased synthetic fibres.

Man-made synthetic fibres with origin from petrochemicals, accounted in 2021 for 64 % of the global fibre market.[2] They are produced/synthesized using a polymerization process combining many small molecules (monomers) into a large molecule (a polymer). Many of the polymers that constitute man-made fibres are similar to compounds that make up plastics, rubbers, adhesives and surface coatings. Examples of man-made synthetic fibres include polyester, polyamide (nylon), acrylic and elastane. Polyester is the largest of the major fibres of the global consumption share in 2021 with 54 % (vs cotton with 24 %) and polyamide has 5 %.[3] Over 300 million tons of plastics are produced yearly for different products where synthetic fibres and synthetic rubber are not included. The figure for synthetic fibres produced is 72 million tons according to Textile Exchange (2021).

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Today microplastics in the oceans is a growing environmental problem and where textiles contribute mainly when fibres are discharged from households washing machines and industrial laundries because of abrasion and shedding of fibres during the processes. Typical fibres (fibres or/and microplastics?) to be found in samples from open water and marine sediments are polyester, polyethylene, acrylic or elastane[4].

1 https://textileexchange.org/app/uploads/2022/10/Textile-Exchange_PFMR_2022.pdf
2 https://textileexchange.org/app/uploads/2022/10/Textile-Exchange_PFMR_2022.pdf
3 http://textileexchange.org/wp-content/uploads/2017/02/TE-Preferred-Fibre-Market-Report-Oct2016-1.pdf
4 IUNC, Primary Microplastics in the Oceans. http://storyofstuff.org/wp-content/uploads/2017/02/IUCN-report-Primary-microplastics-in-the-oceans.pdf

Acrylic

Man-made fibre

The environmental impacts of acrylic greatly outweigh its benefits.

This lack of balance indicates the necessity of exploring more sustainable options – from using other fibres entirely, to working with partners to develop recycling capabilities for acrylic.

Acrylic

Acrylic fibres, produced from polyacrylonitrile, have established themselves as a significant component of the modern textile landscape, offering a blend of affordability, comfort, and diverse applications. However, the use of acrylic fibres is gradually decreasing and over the past five years, there has been a decline of approximately 14% in the worldwide manufacturing of acrylic fibres. As of 2021, the production of acrylic fibre reached 1.7 million metric tons which is approximately 1.5% of the global fibre market share. Globally about 60 % of the acrylics are produced in Asia, with 35 % in China alone.[1, 2, 3]

Benefits

Acrylic, a synthetic man-made fibre, is characterized by its chemical structure that facilitate fibre formation. The production of acrylic fibres entails a multi-step chemical process, utilizing a predominant 85% content of acrylonitrile. These acrylonitrile monomers are derived through a chemical conversion of polypropylene gas, a by-product generated from refinery operations, and ammonia. The acrylonitrile monomers are then combined or polymerized to form long chains of polymers, with high molecular weight with the help of catalysts and initiators facilitating this process. The acrylonitrile polymer can then be extruded/spun to form acrylic fibres.[4, 5]

The tactile attributes of acrylic position it as a viable alternative to natural fibres like wool, offering a comparable level of comfort. What makes acrylic interesting is its cost-effectiveness, rendering it an economical choice for various textile applications. Moreover, acrylic fibres are resilient and have exceptional resistance to sunlight and general wear, ensuring extended garment longevity and is instrumental in optimizing the life cycle energy and resources withing the fabric.[6]

Acrylic fabric is easy to take care of. Its machine-washable with cold water, additionally the practice of air-drying aligns with sustainability objectives by minimizing water consumption and reducing the energy footprint associated with laundering processes. These qualities make acrylic a smart choice for today's modern textiles.

Potential impacts

Processing

Acrylic fibres consist of a minimum of 85% acrylonitrile. Studies conducted by the United States Environmental Protection Agency (EPA) have indicated that workers who are repeatedly exposed to small quantities of acrylonitrile monomer over long periods of time may be at risk of developing cancer. Acrylonitrile monomer can enter the body through inhalation or absorption through skin contact.[7] To minimize the potential risks, the Centers for Disease Control and Prevention (CDC) recommend minimizing skin contact.[8]

Moreover, the processing emits substantial amounts of Volatile Organic Compounds (VOCs) into the environment. These air emissions during the acrylic production process encompass volatile residues of monomers, organic solvents, additives, and other organic compound utilized in fibre processing. This underscores the need for careful consideration of the environmental impact associated with acrylic processing.

Dyeing and finishing

Acrylic fibres are easy to dye, and they have ability to retain vibrant colours through dying processes. However, certain types of dyes are suspected carcinogens and mutagens, while other dyes are known to have a sensitizing effect and should be avoided. If dye water is not treated properly, there is a significant risk for pollution of water that could harm aquatic ecosystem severely. So, it is important to treat dye water before releasing it into the wastewater treatment system.

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2 http://textileexchange.org/wp-content/uploads/2017/02/TE-Preferred-Fibre-Market-Report-Oct2016-1.pdf
3 http://www.cirfs.org/KeyStatistics/AcrylicinEurope.aspx
4 Cohen, Allen and Ingrid Johnson. Fabric Science. New York: Fairchild Books, 2010.
5 http://www.acs.org/content/acs/en/education/whatischemistry/landmarks/acrylonitrile.html
6 http://www.dow.com/productsafety/finder/pro.htm
7 http://www.epa.gov/chemfact/acry-fs.txt
8 http://www.cdc.gov/niosh/npg/npgd0014.html

Anti-pilling treatments

Acrylic fibres tend to form pills quite easily. In order to minimize this, some extra steps are added in the manufacturing process such as, chemical treatment of the fibres. The chemically treated fibres show much improved resistance to pilling, but the overall cost of the fibre is then increased significantly.

MORE INFO: DYEING & PRINTING

Consumer care/washing

Acrylic garments are usually suitable for machine washing. However, it is important to stress that certain household products have been identified as having harmful effects on both human health and the environment.

MORE INFO – APPENDIX: CONSUMER CARE & WASHING

End of use

Acrylic textiles are known for their durability, capable of lasting several years when worn. However, it is commonly utilized in inexpensive, fast-fashion garments that are often- worn briefly and then discarded. Most Synthetic fibres, including acrylic, are made from a carbon-based chemical feedstock, and are recognized as non-biodegradable materials.[9]

Currently, there is no sufficient data supporting how long it takes for an acrylic fabric to decompose in landfills, where the conditions for degradation are not optimal. Estimates suggest that complete decomposition of acrylic fibres may take hundreds of years or even longer in a landfill. The rate of degradation relates to multiple factors, including the presence of air, actual temperature, and sunlight.

MORE INFO – APPENDIX: WASTE TO ENERGY

Availability

Acrylic fibres are produced worldwide, with a significant concentration to Asia, particularly China, which stands for approximately 35% of the global acrylic fibre production. Overall, Asia accounts for about 60% of global production, together with other Asian countries like India, Taiwan, and South Korea also playing significant roles.

Acrylic fibre production also occurs in other regions like Europe and the Americas, but their profitability it is suffering from factors such as technology, raw materials, labour costs, and market demand.[10,11]

OEKO-TEX certified acrylic is available in China.

Applications

The versatility of acrylic fibres extends across numerous domains such as, sweaters, women's and children's apparel, sportswear, socks, knitted underwear, pyjamas, gloves, carpets, rugs, upholstery, cushions, blankets, outdoor umbrellas, tents.

Innovation opportunities

1. Shift to existing more environmentally friendly materials whenever possible. These fabrics include materials derived from organic wool, recycled fabrics, and lyocell.
2. Recycled fibres, including cotton, wool, and polyester, experience a loss of strength during shredding. To enhance yarn strength and promote durability, consider using acrylic fibres blended in with various combinations of recycled fibres, but overall recyclability of product will be reduced.
3. Investigate alternative technologies for colouring acrylic fabrics, such as transfer printing, which eliminates water from the dyeing process.
4. Design garments and products with reusable components, such as trims and tags. Design the product so that trims and tags can be easily separated from the main body of the product at the end of its useful life to enable easy recycling. Establish collection system for these products, enabling collection, disassembly, and reuse.
5. Get your product Cradle-to-Cradle Certified. The Cradle-to-Cradle Certified TM Product Standard follows a multi-attribute, continuous improvement approach, offering a pathway to manufacturing healthy and sustainable items. The Standard rewards achievement in five categories and at five levels of certification. An accredited assessor will help to assess and optimize your product.
6. Develop garments that intentionally embrace the natural pilling of acrylic to extend the product's lifespan and divert waste from landfills.

9 http://www.epa.gov/ttnchie1/ap42/ch06/final/c06s09.pdf

10 Grose, Lynda and Kate Fletcher. Fashion & Sustainability: Design for Change. London: Laurence King Publishing Ltd, 2012.

11 http://www.OEKO-TEX.com

Elastane

Man-made fibre

The manufacturing process of elastane is highly chemical and is derived from petroleum, a non-renewable resource. Elastane is non-biodegradable, and will impede the biodegradability of any natural fibre it is blended with. Elastane blended with other fibres will obstruct recyclability. Efforts to address sustainability in these areas could help the overall positive influence of elastane on the environment.

Elastane

Elastane, also known by its trade name Lycra or Spandex, is a synthetic fibre renowned for its exceptional elasticity and stretch recovery properties. Elastane fibre production has consistently grown in recent years, reaching 1.16 million metric tons in 2021. This significant expansion, considering the production was approximately 0.8 million metric tons in 2017, underscores the sustained increase in demand. Although constituting around 1 % of the global fibre market in 2021, elastane fibre's continuous growth reflects its ongoing popularity and utilization.[1, 2] Elastane production involves a complex chemical process, that begins with the polymerization of a segmented polymer with alternating blocks of polyurethane and polyester.[3] The elasticity is controlled by the ratio between polyurethane and polyester which for the elastic fibres could be PU/PET (75/25) %. The spinning process produced a wide variety of fibres that can be blended with other fibres for specific applications.

Benefits

Elastane was produced as an alternative to the conventional natural fibres, since it can be stretched and reverted back to its original form, whereas other natural fibres cannot.

The practical or comfort benefits of elastane occur in the consumer use phase. Elastane can be stretched repeatedly – up to 500 % of its length – and consistently regain its initial form. It is lightweight, soft, smooth, offering unhindered mobility easy dyeing and resistant to abrasion, body oils and perspiration.

What makes elastane special is its compatibility with other fibres or yarns. Elastane fibres are included in textile applications where high elasticity and recovery are needed for the material produced, such as stretch denim, activewear and underwear. This allows for less stress on seams and help prevent garments from becoming loose-fitting in high stress areas such as the elbows or knees. This feature of elastane can prolong the product's lifespan and divert waste from landfills .[4] When used as the central filament core yarn with staple fibres such as cotton, elastane plays a vital role for the consumer by maintaining the shape and prolonging the life span of the product.

Elastane can be machine washable and drip-dried, depending on the other fibres it is combined with, thereby minimizing water and energy usage associated with consumer care and washing.

Potential impacts

Processing

Elastane provides significant advantages, but the production and related environmental issues needs careful consideration. The energy-intensive manufacturing process and non-biodegradable nature of the fibres are major concerns.

Many common solvents used in production of elastane are toxic. For instance, dimethylformamide (DMF) is a potent liver toxin and has been linked to a potential risk of cancer.[5]

The production of elastane emits hazardous pollutants into the air, including toluene and (2,4-toluene diisocyanate (TDI).[6] Toluene is found in gasoline, acrylic paints, varnishes, lacquers, paint thinners, adhesives, glues, rubber cement, airplane glue and shoe polish. Although not categorized as a carcinogen, chronic inhalation exposure to toluene and TDI in workers has caused significant decreases in lung function, and an asthma-like reaction.[7] Toluene levels of 500 ppm are considered immediately dangerous to life and health.[8]

Dyeing and finishing

Though dyeing of elastane is quite easy but certain types of dyes used are suspected carcinogens and mutagens, while other dyes are known to have a sensitizing effect on skin and should be avoided. If dye water is not treated properly, it can pollute

1 https://textileexchange.org/app/uploads/2022/10/Textile-Exchange_PFMR_2022.pdf
2 https://www.statista.com/statistics/1260343/elastane-fibre-production-worldwide
3 www.kpatents.com/pdf/applications/apn-4-05-03.pdf
4 www.nepis.epa.gov
5 Cohen, Allen and Ingrid Johnson. Fabric Science. New York: Fairchild Books, 2010.
6 Corbman, Dr. Bernard P. Textiles: Fibre to Fabric. New York: McGraw Hill Book Company, 975.
7 www.cdc.gov/niosh/docs/90-105/
8 U.S Environmental Proection Agency, "Economic Impact Analysis for the Proposed Spandex Production NESHAP," May 2000.

wastewater and harm aquatic ecosystem. So, it is important to treat dye water before releasing it into water treatment or sewer system.

MORE INFO: DYEING & PRINTING

End of use

Elastane's versatility and performance characteristics make it a suitable material across multiple industry applications, and it is used in a variety of different garments at different price points. It is produced from fossil fuel-based feedstocks just like most other synthetic fibres and considered non-biodegradable.[9] It has excellent durability and the potential to serve the customer to wear the garment for several years; however, it is often used in inexpensive, fast-fashion garments that are worn and quickly discarded.

Since elastane is often combined with biodegradable natural fibres, it will have a negative impact on the biodegradability and recyclability. Even a small portion of elastane, such as 2%, blended with 98% cotton, can make the garment non-biodegradable.

Optimize sustainability benefits

Bio-based elastane

In order to minimize the environmental impact of elastane, there are several innovative options available where bio-based feedstocks are utilized to produce bio-based elastane. For instance, today the company INVISTA offer the market a LYCRA® bio-derived spandex fibre, where approximately 70% by weight originates from a renewable source derived from dextrose obtained from corn.[10]

Genomatica is a company producing biobased 1,4-butandiol (BDO), used as precursor to the chemical that makes elastane fibres.[11, 12, 13]

MORE INFO – APPENDIX: WASTE TO ENERGY

Availability

OEKO-TEX® Standard 100 certified elastane is available.

Manufacturers and suppliers can be found.

Applications

Covered elastic yarn (covered with a spun or filament yarn to hide the elastane yarn): Can be used in heavyweight foundations, elastic bandages, and athletic supporters.[14]

Bare elastic yarn (monofilament elastane fibre): Are used in swimwear, athletic wear, lightweight foundation garments.[15]

Core spun yarns (central filament core with staple fibre): Can be used in active sportswear, stretch denim, and stretch chino.[16]

Innovation opportunities

1. Investigate alternative technologies for colouring synthetic fabrics, such as transfer printing, which eliminates water from the dyeing process.[17, 18]
2. Innovative and sustainable alternatives for elastane production such as using renewable feedstocks and increasing recyclability of the material.
3. Design garments and products with reusable components, such as trims and tags. Design the product so that trims and tags can be easily separated from the main body of the product at the end of its life to enable easy recycling. Establish collection system for these products, enabling collection, disassembly, and reuse.
4. Development of effective elastane blends with improved properties to expand its application areas further.

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Polyamide (nylon)

Man-made fibre

Polyamide's (PA) part of the global mill consumption is about 4,7 % in 2015.[1] The manufacturing process of Polyamide 6 and 6,6 is highly chemical and is derived from petroleum, a non-renewable resource. Also, the fibre and its resulting fabric are non-biodegradable. Efforts to address sustainability in these areas could help the overall impact of polyamide on the environment.

Polyamide

Polyamide 6, 6,6 and 6,10 are synthetic man-made fibres that are made/derived from a chemical process using petrochemical-based feedstock containing carbon, hydrogen, oxygen and nitrogen atoms. Depending on the distinct polymer building blocks, these various types of polyamides exhibit diverse properties enabling their utilization across different application areas.[1]

Benefits

Polyamide 6 and polyamide 6,6 share numerous fibre characteristics. They possess strong wear resistance, abrasion resistance, chemical resistance, heat resistance, are lustrous appearance, a with high melting point, and resilient.[2] Polyamide 6,6 has greater resilience, a higher melting point, and lower stain permeability compared to polyamide 6, making it ideal for carpets.[3]

The most notable characteristic of both polyamide 6 and 6,6 is versatility. Although originally developed as an "artificial silk," they have found diverse applications including garments, sheer hosiery, parachute cloth, backpackers' tents, bridal veils, musical strings, ropes, broom and toothbrush bristles, Velcro, and more.[4] Polyamide 6 and 6,6 blend well with other fibres, and their major contributions are strength and abrasion resistance.[2] Both polyamide 6 and 6,6 are machine washable, dry quickly, require minimal pressing, and maintain their shape well, minimizing water and energy usage associated with consumer care and washing.[4] Due to their durability and abrasion resistance, some polyamide 6 and 6,6 products have the potential to last and be worn multiple times, optimizing the energy and resources embodied in the product[5,6].

Potential impacts

Processing

The processing of polyamide 6 and 6,6 presents/implies a range of environmental and social concerns, including resource depletion from petrochemical feedstocks, energy-intensive manufacturing leading greenhouse gases emission, hazardous chemical releases, water consumption and waste generation. In order to minimize these issues, it is important to prioritize the eco-friendly production methods and maximize the recyclability of this material to make the whole nylon production cycle more sustainable.

Dyeing and finishing

Certain types of dyes are suspected carcinogens and mutagens, while other dyes are known to have a sensitizing effect on skin and should be avoided. Untreated dye water can negatively impact receiving water bodies and harm aquatic ecosystems if left untreated before its release.

MORE INFO: DYEING & PRINTING

Durable water repellents (DWR)

Durable water repellents (DWR) are applied to polyamide 6 and 6,6 garments and products to enhance breathability and water resistance. Fluorochemicals are commonly used in these water-repellent finishes and waterproof membranes (thin films or coatings attached to the back of fabrics to prevent water from passing through). Of particular concern are two fluorinated compounds: perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA), due to their persistent, bioaccumulative and toxic effects on the environment. The European Union has banned PFOS and has decided to ban PFOA and its derivates and precursors, effective from 2020.[7,8,9] Other fluorinated compounds are also proposed for restrictions.

MORE INFO: FINISHING

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4 Freinkel, Susan. PLASTIC A Toxic Love Story. New York: Houghton Mifflin Harcourt, 2011.
5 www.engr.utk.edu/~mse/Textiles/Nylon%20fibres.htm
6 www.atsdr.cdc.gov/csem/benzene/docs/benzene.pdf
7 www.patagonia.com/pdf/en_US/fluorochemicals.pdf
8 https://echa.europa.eu/sv/previous-consultations-on-restriction-proposals/-/substance-rev/1908/term
9 http://nipsect.dk/pfoa-to-be-banned-in-europe/

Consumer care and washing

Polyamide products are typically machine-washed. However, certain at-home detergents have been reported to have detrimental effects on humans and the environment, contributing to ozone depletion and polluting wastewater.

MORE INFO – APPENDIX: CONSUMER CARE & WASHING

End of use

Polyamide 6 and 6,6 fibres are made from a petroleum-based chemical feedstock and are considered non-biodegradable[7]. Their products are known for their durability, potentially lasting for many years. However, if discarded, they could remain in the landfill for decades.

MORE INFO – APPENDIX: BIODEGRADABILITY

Discarded polyamide products increase load on landfills, leading to potential land and water contamination and possibly toxic emissions into the air.[10]

When subjected to incineration, polyamide 6 and 6,6 releases substances, such as nitrogen oxide, formaldehyde, hydrogen cyanide and acrolein, which are toxic and may have carcinogenic properties.[11]

MORE INFO – APPENDIX: WASTE TO ENERGY

Alternatives to primary polyamide

Recycled polyamide

Using recycled polyamide offer two main ecological benefits: 1) it slows down the depletion of primary natural resources, and 2) it reduces textile waste building in landfills. Polyamide can be recycled into new versions of the same product or into entirely different products.

Post-consumer waste from used and discarded products and post-industrial waste from material collected during the product manufacturing can be recycled.[12]

Optimize sustainability benefits

Sustainability benefits can be optimized by:

- > Promoting the utilization of chemically recycled closed-loop polyamide 6.
- > Supporting the advancement of chemically recycled polyamide 6,6.
- > Exploring innovations in bio-based Polyamide 6, utilizing amino acids derived from dextrose fermentation as a sustainable alternative to petroleum.[13,14]
- > Research on non-toxic flame-retardant applications for polyamide.[15,16]
- > Advocating for the adoption of halogen-free flame retardants.
- > Exploring eco-friendly waterproofing methods for polyamide.
- > Encouraging the use of OEKO-TEX certified polyamide.[17,18]
- > Investigating water repellents free from PFOS and PFOA.

Exploring the utilization of waterproof membranes derived from renewable resources.

Availability

OEKO-TEX® Standard 100 certified polyamide is available.
Manufacturers can be found at: www.OEKO-TEX.com
Non-toxic methods of waterproofing and flame retardancy are available.
Recycled polyamide is available globally in United States, Europe, Slovenia, Croatia, China, Japan and Israel.[18,19]

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10 Grose, Lynda and Kate Fletcher. Fashion & Sustainability: Design for Change. London: Laurence King Publishing Ltd, 2012.
11 www.epa.gov/ttnchie1/le/acrylon.pdf
12 denr.sd.gov/des/wm/sw/documents/OpenBurningChemicalList.pdf
13 The Textile Dyer, “Concern over Recycled Polyester,” May 13, 2008.
14 www.oecotextiles.wordpress.com/2009/07/14/why-is-recycled-polyester-considered-a-sustainable-textile/#_ftn6
15 hrd.apec.org/images/a/aa/62.4.pdf
16 www.chemsystems.com/about/cs/news/items/PERP%200910_1_Caprolactam.cfm
17 www.OEKO-TEX.com
18 www.aquafil.com/en/about-us/worldwide.html
19 www.thecleanestline.com/2009/03/closing-the-loop-a-report-on-patagonias-common-threads-garment-recycling-program.html

Applications

The versatile properties of polyamide make it a useful material in diverse industries and applications. It can be used in jackets, lingerie, swimwear, exercise wear, hosiery, jackets, bedspreads, carpets, upholstery, tents, fish nets, sleeping bags, rope, parachutes, luggage.

Some companies are producing versions of mechanically recycled polyamide that are of almost equal quality to primary polyamide.

More sustainable options?

Non-toxic DWR (Durable Water Repellent Finish) methods If used and verified.
Non-toxic methods of waterproofing If used and verified.
OEKO-TEX® Standard 100 certified If verified and used.

Innovation opportunities

1. Investigate alternative technologies for colouring polyamide fabrics, such as transfer printing, which eliminates water from the dyeing process.[20]
2. Design garments and products with reusable components, such as trims and tags. Design the product so that trims and tags can be easily separated from the main body of the product at the end of its useful life to enable easy recycling. Establish collection system for these products, enabling collection, disassembly, and reuse.
3. Create in-store collections of polyamide 6 and 6,6 garments and products. Use fabrics from collected garments and products to innovatively redesign new products and prolong the lifecycle.
4. Work with partners to develop closed loop recycling of polyamide 6 and 6,6 fibres and infrastructure to label, collect, sort and purify garments.
5. Explore the unique aesthetics of recycled polyamide to encourage innovative design of products.
6. In the cases where recycled polyamide 6 and 6,6 affect the aesthetic of the garment, craft marketing messages to turn potential negatives into positives.
7. Explore alternative fibres in replacement of polyamide that utilize cleaner manufacturing process, enable easier recycling or are biodegradable.
8. Get your product Cradle-to-Cradle Certified. The Cradle-to-Cradle Certified TM Product Standard follows a multi-attribute, continuous improvement approach, offering a pathway to manufacturing healthy and sustainable items. The Standard rewards achievement in five categories and at five levels of certification. An accredited assessor will help to assess and optimize your product.
9. Be knowledgeable about the most environmentally impacted stages of the polyamide lifecycle. Work with partners to decrease impacts of these stages.
10. Get you product Bluesign Certified. The bluesign® system is built to eliminate harmful substances from the beginning of the manufacturing process and has requirements on chemicals and sets standards and controls on the production to get a sustainable product. The Bluesign is commonly used by outdoor product/garment companies.

20 www.triplepundit.com/2009/07/airdye-dyeing-fabric-without-water/


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Polyester (PET, PBT)

Man-made fibre

Finding innovations that mitigate the ecological impacts of polyester will not only reduce environmental impacts, but has the potential to influence the textile industry as a whole.

Polyester (PET, PBT)

Over the last 45 years, technical developments in production of polyester have improved the fibre's hand-feel characteristics, fineness, and overall quality. Polyester has emerged as the most favoured fibre worldwide, constituting approximately 54% of the global consumption in 2021. The annual production has been increased to 61 million tons in 2021 as compared to 57 million tons in 2020. This growth is driven, in part, by its extensive utilization in fast-fashion apparel, which is the most swiftly expanding segment of the fashion industry.[1,2,3,4]

Polyester is a synthetic, man-made fibre produced from crude oil (petroleum) through a process involving the breakdown of crude oil into petrochemical. These petrochemicals are then transformed into polyethylene terephthalate (PET) using heat and catalysts like antimony. Notably, this is the same type of plastic used in plastic soda bottles. But in care labels, the abbreviation "PES" is often used to indicate the content of PET-polyester.[5] There are also special types of polyester such as polybutylene terephthalate (PBT), which is most suitable for swimsuits where both stretch, and chlorine resistance are required.[6]

Benefits

Polyester fabrics offer several advantageous qualities, including availability, strength, resistance to stretching and shrinkage, resistance to chemicals, and durability against wrinkling, mildew, and abrasion. So, when polyester fabrics are used in robustly constructed garments, they have the potential to last and to be worn many times, optimizing the embodied energy and resources in the garment. See comment in 'Potential Impacts' for counterpoint to this benefit. Due to the versatile properties of the polyester fibre, which contribute to easy care, crease-resistant and to retain shape, it is also commonly used in blends with natural fibres such as cotton.

Polyester's positive attributes for clothing lie mostly in the consumer phase of its lifecycle, which accounts for 50-80 % of a polyester garment's total ecological footprint. Polyester garments are washed at low temperature and drip-dried, thereby minimizing water and energy use associated with garment care.[7]

Potential impacts

Processing

Petroleum, the main component in manufacturing polyester, is a non-renewable resource that leads to the destruction of natural habits through mining. That is to say that petroleum take millions of years to form and is currently being extracted from the earth for industrial uses faster than it can be replenished. The declining petroleum supply is the source of much debate – British Petroleum (BP) reports that there are 1,333 billion barrels still available to pump (enough for 40 years at current usage rates).[8] Other sources state that supply is overestimated and that reserves are about 30% lower than widely reported.[9]

The polyester manufacturing process is fully chemical-based, energy intensive and emits greenhouse gases into the environment10. Terephtalic acid (TA) or dimethyl terephthalate, along with ethylene glycol, are main components used in polyester production. This process releases emissions into the air and water, including substances like heavy metal cobalt, manganese salts, sodium bromide, antimony oxide, and titanium dioxide.[10]

Antimony is of particular concern, since it is a toxic heavy metal known to cause cancer under certain circumstances and is a suspected reproductive toxin9. It serves as a catalyst in the oxidation process during the polyester production. However, it is not essential for polyester production, and alternative non-antimony catalysts are also available. These alternatives are more costly, and many give a yellowness to the polymer.

Europe meets its oil consumption/needs by importing from foreign sources: 41 % from the Russian Federation, 26 % from Africa, 16 % from the Middle East—14 % comes from Europe itself—thus requiring transportation over long distances.[11,12] Fuel combustion emissions released by vehicles used to transport the oil causes pollution and CO_2 emissions.

Dyeing and finishing

Certain type of dyes are suspected carcinogens and mutagens, while other dyes are known to have a sensitizing effect on skin and should be avoided. Untreated dye water can negatively impact receiving water bodies and harm aquatic ecosystems if left untreated before its release. The release of microplastics from polyester textiles poses environmental pollution risks as these tiny plastic particles persist in ecosystems and can be ingested by aquatic life. Additionally, they can potentially enter the food chain, raising concerns about human health.

MORE INFO: DYEING & PRINTING

Consumer care/ washing

Polyester fabrics are typically machine washable; however, certain at-home detergents have been reported to have detrimental effects on humans and the environment, contributing to ozone depletion and polluting wastewater. Add some wording about release of microplastics.

MORE INFO – APPENDIX: CONSUMER CARE & WASHING

End of use

Polyester garments have the durability to last for several years, however it is typically used in inexpensive, fast-fashion garments that are worn and quickly discarded. Synthetic fibres are from a carbon-based chemical feedstock and are considered non-biodegradable.[13]

MORE INFO – APPENDIX: BIODEGRADABILITY

There are conflicting opinions about how long it takes for polyester to decompose, and estimates range from 40 years to 1000 years. This is because degradability is dependent upon several conditions including how much air, temperature and sunlight the fibre is exposed to.

Discarded polyester products increase load on landfills, contribute to water contamination and possibly toxic emissions into the air.[14] Release of microplastics/fibres by shredding during washing of synthetic clothing and textiles and discharge into the wastewater, is an identified source to microplastics found in oceans around the globe and in ice samples from arctic. This is an alarming and growing environmental problem, where polyester with its large market share contributes.[15,16,17]

MORE INFO – APPENDIX: WASTE TO ENERGY

Alternatives to primary polyester

Recycled polyester

Using recycled polyester fulfil two main ecological benefits: 1) it slows the depletion of primary natural resources, and 2) it reduces textile waste building in landfills. Polyester can be recycled and then used as a raw material for many different products. Post-consumer waste from used and discarded products and post-industrial waste from polyester collected during the product manufacturing can be recycled.[18,19]

Add some wording about PET-bottles being used as recycled polyester in textiles, but also that this will probably not be available with the coming EU-legislation where PET-bottles should loop back to the food industry instead, due to the high quality for food safety.

Biopolymer fibres – Polylactide (PLA)

Polylactide (PLA) is a renewable thermoplastic polymer. It is derived from plant starch, such as corn, sugar cane and sugar beet.[20] PLA is biodegradable, as it decays when exposed to heat and moisture. During decomposition, it split into carbon dioxide and water, which present no danger to the environment.[21,22]

PLA's ability to biodegrade comes as a result of that it is prone to hydrolysis and have a low melting point. These features could hinder PLA's ability to be suitable in some applications, such as the fabrics that needs to be ironed. However, efforts to address these drawbacks in PLA have recently been accomplished. NatureWorks LLC, who offer a PLA with the brand name Ingeo, has developed hydrolytic stabilizers that can be implemented in certain applications to prevent degradation outdoors.

Optimize sustainability benefits

Sustainability benefits can be optimized by:

> Promoting the use of chemically recycled polyester.
> Promoting the use of mechanically recycled polyesters from producers utilizing high-quality raw materials.
> Encouraging the adoption of antimony-free polyester.
> Promoting the utilization of polylactide (PLA).
> When using recycled polyester from PET bottles, ensure that the supplier is sourcing recycled bottles, not new ones.[20]
> Promoting the implementation of low-impact dye and bleaching processes. Advocating for the use of OEKO-TEX certified polyester.[23]

Availability

Partly due to the substantial volume of discarded soda bottles, mechanically recycled polyester is readily accessible to textile and apparel suppliers. Companies such as Freudenberg Politex in Italy, as well as REPREVE® and Poole Company in the United States, produce mechanically recycled polyester versions that are comparable in quality to virgin polyester due to their use of high-quality raw materials.

Chemically recycled polyester is gaining popularity, and the number of global companies providing fabrics made using this technology is increasing. The Japanese company Teijin was the pioneer in developing chemical recycling technology.

Eco Intelligent™, antimony-free polyester, is available through Victor Group in North America. Antimony-free titanium-based catalysts are offered by Johnson Matthey's catalyst Vertec and Teijin's "heavy metal-free" polyester chip.[24,25]

Polylactide (PLA) fibre is offered by NatureWorks LLC under the brand Ingeo.

Applications

Chemically recycled polyester fibres maintain the same quality as primary polyester fibres in perpetuity.

Mechanically recycled polyester fibres can be of almost equal quality to virgin polyester, depending on the quality of raw materials used. Some producers use low quality materials which result in low quality fibre.

Mechanically recycled polyester fibres can be blended with other fibres to give/generate strength and quality for applications in a variety of fabric constructions – activewear, intimates, outdoor wear, T-shirts, trousers, etc.

Polylactide (PLA) can be used for applications of bedding and apparel.

Innovation opportunities

1. Although creating different blends of recycled polyester with recycled cotton, organic cotton, etc., is good in the short term, however, these blends make it difficult to recycle at End of Use stage and create liabilities and waste. When designing fibre blends, consider what happens after End of Use.
2. Design garments and products with reusable components, such as trims and tags. Design the product so that trims and tags can be easily separated from the main body of the product at the end of its useful life to enable easy recycling. Establish collection system for these products, enabling collection, disassembly, and reuse.
3. Look for cross-sector marketing opportunities. For example, partner with a soft drink brand to use their PET bottles in fabrics, or partner with garment collection charity to establish a long-term collection facility where customers can drop their closed loop recyclable polyester garments.
4. Investigate alternative technologies for colouring polyester fabrics, such as Air-Dye, which eliminates water from the dyeing process.[22] Explore unique aesthetics achieved from using this process.
5. Design garments that are 100 % polyester, including trims, so garments can be chemically recycled easily at the end of use.
6. Design products so that non-polyester trims can be easily separated from the main body of the product at the end use, to enable easy polyester recycling.
7. Design 100 % degradable garments that are made from 100 % PLA and work directly with the fibre-producing company to ensure the performance and proper application. Create in-store take-back program for customers and partner with a local compost facility to ensure optimum conditions for garment to degrade properly.
8. Get your product Cradle-to-Cradle Certified. The Cradle-to-Cradle Certified™ Product Standard follows a multi-attribute, continuous improvement approach, offering a pathway to manufacturing healthy and sustainable items. The Standard rewards achievement in five categories and at five levels of certification. An accredited assessor will help to assess and optimize your product.
9. Get you product Bluesign Certified.[26] The bluesign® system is built to eliminate harmful substances from the beginning of the manufacturing process and has requirements on chemicals and sets standards and controls on the production to get a sustainable product. The Bluesign is commonly used by outdoor companies.


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Polyethylene (PE)

Man-made fibre

Polyethylene (PE) is a synthetic, manufactured plastic that is the most commonly used polymer in the world. It constitutes about one third of all plastics produced worldwide, and its applications are mainly bags, packaging and industrial uses.

Polyethylene (PE)

Polyethylene (PE) is a synthetic, man-made polymer that is the most commonly used plastic in the world. It constitutes about one third of all plastics produced worldwide, and its applications are mainly bags, packaging and industrial uses.

Both polyethylene and polypropylene are polyolefins (polyalkenes). They are difficult to dye depending on bereft of dye sites but can be coloured by the addition of pigments and dyes during the melt spinning process.[1] A major problem associated with the polyolefin-based fibres is the microplastics in the oceans. Currently about 60% of the plastic waste origination from post-consumer sources, primarily composed of polyolefins.[2]

Benefits

Polyethylene is tough, flexible, lightweight (some are featherweight), waterproof and easy to process.

There are three main types of polyethylene, including low-density polyethylene (LDPE), linear-low-density polyethylene (LLDPE) and high-density polyethylene (HDPE).[1]

Polyethylene is primarily available in fibre form as monofilament and multifilament, although it can also be produced as staple fibres, facilitating its blending with various types of natural and synthetic fibres. They are, for example, used for geotextiles, outdoor furniture, filter fabrics, industrial applications.

Products in these categories encompass a wide range of applications, such as dry-cleaning, and frozen foods; sandwich bags; shrink-wrap; squeezable bottles; coatings on milk cartons and hot and cold beverage cups; lids; toys; flexible tubing; plastic grocery bags; retail shopping bags; milk jugs; juice, detergent, and household cleaner bottles; safety protective clothing; and apparel/product bags for shipping.

Polyethylene is inexpensive. It costs less than a penny to manufacture 140 grams, and 0.06 to 0.13 SEK for a plastic bag.[3]

Potential impacts

Processing

The manufacturing process for polyethylene requires non-renewable resources and high-water usage. To produce 1 kg of high-density polyethylene (HDPE), for example, 1.5 kg of fossils fuels are required, and over 3 litres of water.[3]

Fuel released by vehicles used to transport oil and waste causes pollution and CO_2 emissions.[4]

End of use

Polyethylene's most substantial environmental impact is at its end of use stage. Despite its durability (plastic bags can hold more than 100 times their weight), polyethylene was not designed for longevity, but for immediate throwaway.

MORE INFO – APPENDIX: BIODEGRADABILITY

Carbon dioxide emissions are released when high-density polyethylene is incinerated. This could happen in countries that do not have access to more sophisticated disposal, recycling, and waste-to-energy methods.[5]

MORE INFO – APPENDIX: WASTE TO ENERGY

Alternatives to primary polyethylene

Recycled polyethylene

Using recycled polyethylene achieves two main ecological benefits: 1) it slows the depletion of primary natural resources, and 2) it reduces textile waste building in landfills. Polyethylene can be recycled into the same product or into entirely different products.

Post-consumer waste from used and discarded products and post-industrial waste from material collected during the product manufacturing can be recycled.[6]

1 https://www.ballyribbon.com/fibres/polyethylene/
2 PP-Presentation, Borealis, breakfast meeting, 170901 Västsvenska Kemi- och Materialklustret
3 www.plasticseurope.org/Documents/Document/20100312112214-FINAL_HDPE_280409-20081215-017-EN-v1.pdf
4 www.epa.gov/climatechange/wycd/waste/downloads/plastics-chapter10-28-10.pdf
5 www.naturalfibres2009.org/en/iynf/sustainable.html
6 The Textile Dyer, "Concern over Recycled Polyester," May 13, 2008.

Optimize sustainability benefits

Sustainability benefits can be optimized by:

- Encouraging the use of bio-derived polyethylene. Bio-based polyethylene is derived from renewable resources, such as sugar cane have a lower carbon footprint, and some are recyclable and compostable. There is no guarantee that products made from recycled polymers are manufactured with less harmful chemicals or contain less toxic additives.
- Encouraging the use of recycled polyethylene.

Availability

Recycled polyethylene is readily available globally.

Applications

(For fashion and textile industry)

Apparel shipping bags, shopping bags.

Innovation opportunities

1. Instead of "throwaway living," develop ways to reuse polyethylene for garment shipping of apparel and products to stores.
2. Investigate alternative fibres to replace polyethylene bags for garment product shipping. Look for innovations beyond replacing polyethylene bags with cotton or polyester bags with messages such as "not a plastic bag."
3. Create in-store collections of polyethylene bags. Redistribute bags to consumers.
4. Work with partners to develop closed loop recycling of polyethylene and infrastructure to collect and sort.
5. Increase awareness and participation of the public, and find simple, acceptable alternatives to polyethylene bag use.
6. Reward customers for reusing bags. Eye-catching signs raise awareness and encourage people to reuse bags.
7. Develop a 100 % compostable shopping bag that biodegrades in less than 2 months.
8. Design polyethylene products with reuse in mind in order to optimize resources embodied in the product.
9. Work with suppliers to advance the technology for bio-based plastics from organic feedstock.
10. Stop giving customers shopping bags to encourage them to bring their own.

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POLYPRO-PYLENE (PP)

Man-made fibre

Polypropylene (PP) is a long-chain synthetic polymer composed of at least 85 % by weight of ethylene, propylene or other olefin units. Polypropylene is a manufactured and man-made polyolefin fibre as polyethylene. When incinerated in a controlled process it only produce CO_2 and water.[1]

Polypropylene (PP)

Polypropylene's part of the global mill consumption in 2021 was about 2.7 %. The polypropylene fibre production increased slightly from 2.9 million tons to 3 million tons in 2021.[1] Due to the versatile properties of polypropylene, it is the second most widely used synthetic fibre after polyester. The polypropylene fibre can be found in several diverse applications such as carpets, ropes, wraps and bags, agro and geo textiles, filters, protective clothing and outdoor apparel.[2]

Benefits

Polypropylene's characteristics have been perfected over the years since it was originally developed in the 1950's. It has excellent durability, strength and resiliency while still have low density. Polypropylene has good resistance to ultraviolet degradation, stains and spilling, and excellent wicking action, which make this material great for carpets3. These features also eliminate the need for water and stain-repellent finishes.

Polypropylene's natural buoyancy also makes it perfect for high performance apparel such as wetsuits and swimsuits.

Polypropylene blends well with other fibres, and when used contribute with excellent wicking properties.[3]

Polypropylene can't be ordinary dyed in yarn or fabric state, instead pigments dyes are added to the polymer melt before the spinning process takes place. This means that the colour shade must be decided early in the design phase, but instead environmental benefits will be obtained as ordinary dyeing processes have much more environmental impacts.

Its low softening point encourages consumers to launder their products at low temperature washing and ironing, thereby minimizing water and energy use associated with consumer care and washing.[4]

Potential impacts

Processing

Typically, the production of polypropylene varies amongst different manufacturers. Individual manufacturers vary their processes to achieve certain properties such as dyeability, light stability and heat sensitivity.[5]

The manufacturing process for polypropylene requires non-renewable resources and high-water consumption and energy use.[6,7,8]

Fuel released by vehicles used to transport oil and waste causes pollution and CO_2 emissions.[9]

End of use

The most significant negative environmental impact of polypropylene occurs during its End of Use phase. Polypropylene, being non-biodegradable, contributes to the escalation of landfill waste and finds its way into oceans and other vast water bodies, posing a threat to aquatic organisms and the potential for contamination of our food and water sources.

A study conducted by Mark Browne, an ecologist from University College Dublin, showed that minuscule particles of acrylic, polyethylene, polypropylene, polyamide, and polyester have been increasingly identified within the northeastern Atlantic region. Furthermore, these microscopic fragments have been found on beaches in various locations including Britain, Singapore, and India. [10,11]

MORE INFO – APPENDIX: BIODEGRADABILITY

1 https://textileexchange.org/app/uploads/2022/10/Textile-Exchange_PFMR_2022.pdf
2 http://www.fibrevisions.com/About-Us/Sustainability/Sustainability-Throughout-Our-Product-Lifecycle.aspx
3 http://textileexchange.org/wp-content/uploads/2017/02/TE-Preferred-Fibre-Market-Report-Oct2016-1.pdf
4 Freinkel, Susan. PLASTIC A Toxic Love Story. New York: Houghton Mifflin Harcourt, 2011.
5 www.fabriclink.com/university/polyolefin.cfm
6 www.engr.utk.edu/~mse/Textiles/Nylon%20fibres.htm
7 Corbman, Dr. Bernard P. Textiles: Fibre to Fabric. New York: McGraw Hill Book Company, 1975.
8 www.plasticseurope.org/Documents/Document/20100312112214-FINAL_HDPE_280409-20081215-017-EN-v1.pdf
9 EPA. (1991) Chapter 6: Organic Chemical Process Industry retrieved from:
10 www.tech.plym.ac.uk/sme/mats324/mats324A9%20NFETE.htm
11 www.tech.plym.ac.uk/sme/mats324/mats324A9%20NFETE.htm

Alternatives to primary polypropylene

Recycled polypropylene

Using recycled polypropylene achieves two main ecological benefits: 1) it slows the depletion of primary natural resources, and 2) it reduces textile waste building in landfills. Polypropylene can be recycled into new versions of the same product or into entirely different products.

Post-consumer waste from used and discarded products and post-industrial waste from material collected during the product manufacturing can be recycled.

Availability

Recycled polypropylene is available from suppliers in Europe and China.
Bio-derived polypropylene is currently still at research stage and is not readily available.

Applications

High performance gear for backpacking/canoeing/mountain climbing, wetsuits, swimsuits, running/cycling clothing, inexpensive carpets, upholstery, industrial uses.

Optimize sustainability benefits

Sustainability benefits can be optimized by:

> Promoting the use of recycled polypropylene.
> Promoting the research on bio-based polypropylene. Bio-based polypropylene is derived from renewable resources, such as sugar cane. Bioplastics have a lower carbon footprint, and some are recyclable and compostable. There is no guarantee that they are manufactured with less harmful chemicals or contain fewer toxic additives. Also, plants used for bio-plastic feedstock can be grown without fertilizers and pesticides.[12,13,14]
> Promote OEKO-TEX certified polypropylene.[15]

Innovation opportunities

1. At the product design stage, consider what will happen to a polypropylene product at the End of Use stage of the lifecycle. Design products that address longevity, recyclability, biodegradability, disassembly for reuse, etc.
2. Work with partners to develop closed loop recycling of polypropylene products and infrastructure to collect and sort.
3. Look to suitable fibre alternatives for polypropylene that have more advanced technology and infrastructure for recycling and biodegradability, such as polyester and polylactide (PLA).
4. Work with suppliers to advance technology for bio-based plastics from organic feedstock.
5. Design polypropylene products with reuse in mind in order to optimize resources embodied in the product.
6. Get your product Cradle-to-Cradle Certified. The Cradle-to-Cradle Certified™ Product Standard follows a multi-attribute, continuous improvement approach, offering a pathway to manufacturing healthy and sustainable items. The Standard rewards achievement in five categories and at five levels of certification. An accredited assessor will help to assess and optimize your product.

12 www.epa.gov/climatechange/wycd/waste/downloads/plastics-chapter10-28-10.pdf
13 www.ecouterre.com/is-synthetic-clothing-causing-microplastic-pollution-in-oceans-worldwide/
14 www.prweb.com/releases/2012/2/prweb9194258.htm
15 www.OEKO-TEX.com

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Viscose made from wood

Man-made fibre

Viscose made from wood is categorized as a “manufactured” or “man-made” fibre created from cellulose found in trees. It is typically derived from spruce or pine (although any plants or trees can be used to make viscose, even cotton scraps) and is then chemically processed and regenerated to form a new polymer using the viscose process.

Viscose made from wood

Research projects are going on to see how textile waste of cellulose as is or in combination with wood-based material can be used for new cellulose fibres, either using the viscose process or in closed loop systems. Pulp made from cotton textile waste is now commercial.

"Modal" is also a type of viscose fibre, manufactured by using the viscose process, but the formula of the solvents used is modified to obtain higher wet strength of the fibre.[1]

The viscose process involves some harsh chemical. For this reason, it is important that the supplier has adequate water purification and chemical waste management. For instance, fibre producer Lenzing claims that their ECOVERO-process has lower water impact and lower CO_2 emissions than conventional viscose according to Higg MSI. New forms of viscose-type materials are emerging that have similar material characters as viscose but are produced using non-toxic processes and operate in a closed loop system where outputs are recovered, filtered and reused.

Today viscose represents more than 80 % of the global MMCF market, while lyocell stands for 4 % and modal for 3 %.[2] The two biggest producers of viscose is Lenzing and Birla Cellulose with production of pulp and/or fibres in Europe, India, China, Indonisia, Thailand, USA, Canada and Brazil, but other manufacturers upcoming in a growing market.

Benefits

Viscose has been on the market for quite some time. The viscose process was developed in the late 1800s as an inexpensive alternative to silk. Viscose has drapes well, is easy to dye, and is highly absorbent. It is a good conductor of heat, so it is a cool, comfortable fibre good for use in warm weather.

Viscose is also relatively inexpensive compared to other fibres and can be mixed in well with many fibres—viscose is sometimes used just to reduce cost, but also to give lustre, softness, absorbency or comfort.[1]

Potential impacts

Cultivation

Wood feedstock may be sourced from ancient and endangered forest. This has implications for biodiversity. FSC or PEFC certified means that the raw material is sourced from responsibly managed forests.

Processing

To transform for example wood-derived materials into a fabric, the cellulose must be separated from other compounds such as lignin, hemi cellulose. Sodium hydroxide (caustic soda) and sodium sulfide are commonly used to remove the lignin that binds the fibres together, and in some cases, bleach is required to whiten the pulp. In a complex process the pulp is steeped in caustic soda to produce alkali cellulose, which is then aged or oxidized before reacting with carbon disulfide to create sodium cellulose xanthate. This xanthate is dissolved in caustic soda to form a syrup-like spinning solution or "viscose," which can then be extruded through a spinneret to form viscose fibres.[3]

The viscose manufacturing process involves several toxic solvents and requires copious amounts of water. Wastewater effluents from processing must be properly treated to avoid contamination of surrounding water bodies. Air emissions caused by the viscose process include sulfur, nitrous oxides, carbon disulfide and hydrogen disulfide. Chronic exposure to carbon disulfide can cause damage to the nervous system in humans.[3]

Dyeing and printing

The dyeing process for viscose is a multi-step process that involves ample amounts of water at high temperatures (50°–95°C), salt, acetic acid and caustic soda. Mild peroxide bleach may also be necessary to remove residues of sulfur.

MORE INFO: DYEING & PRINTING

Consumer care/washing

Garments made from Viscose can be machine or hand-washed, sometimes dry clean can be appropriate due to delicacy of the fabric when wet.

Electricity and water use in the care of the garment can cause significant environ-

1 http://changingmarkets.org/wp-content/uploads/2017/06/CHANGING_MARKETS_DIRTY_FASHION_REPORT_SPREAD_WEB.pdf
2 Preferred Fibre & Materials Market report oct 2022, Textile
3 oecotextiles.wordpress.com/2009/08/19/348/

mental impacts. Certain chemicals used in dry-cleaning and at-home products have been reported to have detrimental effects on humans and the environment and contribute to ozone depletion and can pollute wastewater.
MORE INFO – APPENDIX: CONSUMER CARE & WASHING

End of use

After long use viscose can be mechanically recycled. A lot of research and development is ongoing regarding chemical recycling of MMCF including viscose.

Although there are claims that viscose is biodegradable, the ability is highly dependent on many conditions including disposal manner, humidity, temperature, UV exposure and presence of microorganisms. Remains from chemical treatments may be a risk leaving contaminations after the material has degraded.
MORE INFO – APPENDIX: BIODEGRADABILITY

Optimize sustainability benefits

Sustainability benefits can be optimized by:

> Only purchase viscose from suppliers who use raw materials sourced from responsibly managed forests registered in the Forest Stewardship Council (FSC) certification system and/or sourced from Programme for the Endorsement of Forest Certification schemes (PEFC) and Forest Stewardship Council (FSC) certified forests.

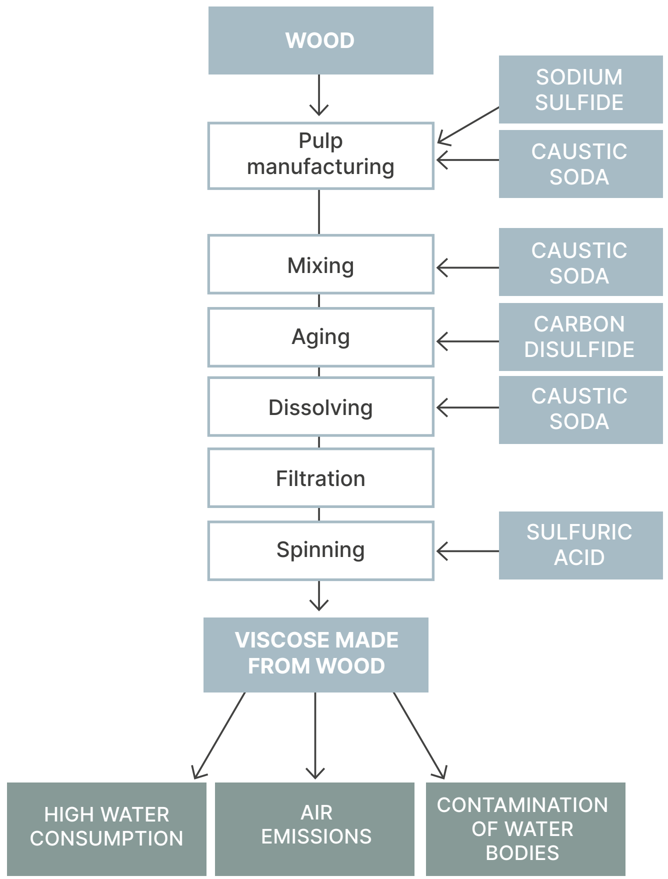
> Ask for information on renewable energy source through the entire supply chain.

> Check water source and wastewater treatment through the entire supply chain with special focus on fibre production and wet processes.

> Investigate viscose processing methods that use enzymes instead of chemicals.

> Lyocell can in many cases be used instead of viscose.

PROCESS FOR VISCOSE MADE FROM WOOD



Availability

In 2021 5,8 million tonnes viscose were produced. In total 7,24 million tonnes MMCF were manufactured of those Textile Exchange estimate that approximately 60-65% were FSC- and/or PEFC-certified.[2]

The two biggest producers of viscose are Lenzing and Aditya Birla (Cellulose)[4] with production of pulp and/or fibres in Europe, India, China, Indonisia, Thailand, USA, Canada and Brazil according to their webpages.

Applications

Viscose can be used in woven, knitted and non-woven textiles. The application area is wide, from technical textiles to garments and interior textiles.

More sustainable alternatives

PEFC-certified OR FSC-certified Must be verified and can be claimed on Point-of-sales items at retail.

OEKO-TEX® STePS certified If verified and used.

Innovation opportunities

1. Shift to existing material or fabrics with documented environmental road map when possible. These fabrics include fabric derived from organic cotton, recycled fabrics, hemp, flax and lyocell.
2. Use wood pulp from PEFC and FSC-certified plantations and produce the fabric with lyocell process.
3. Engage in sustainability projects regarding re-forestation, biodiversity, water management and recycling of viscose together with your supply chain.

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4 LENZING™ ECOVERO™: Sustainable Viscose Fibres For Fabrics

Unsplash/Franco Mariuzza

Viscose made from bamboo

Man-made fibre

Viscose made from bamboo is categorized as a “manufactured” or “man-made” fibre created from cellulose found in the bamboo plant. The fibres are derived from bamboo, which then processed and regenerated to form a new polymer using the viscose process.

Viscose made from bamboo

Benefits

Bamboo is a "rapidly renewable" resource, meaning that it grows quickly and can be harvested at least once a year.[1]

Fast-growing renewable fibres[2,3,4,5]

Fibre	Length	Timing
Bamboo	24 meters	40 days
Hemp	4 meters	3 months
Jute	1-4 meters	3-4 months
Flax	1 meter	3-4 months

Bamboo is a low maintenance crop that requires few chemical inputs during the growing season. It is mainly rain fed and can grow in diverse climates.

Due to its speedy growth and little input needed for growing, some say that using bamboo as an alternative to slower growing wood trees could help slow deforestation.[1]

Viscose from bamboo drapes well, is easy to dye, and is highly moisture absorbent. It is a good conductor of heat, so it is a cool, comfortable fibre good for use in warm weather.

Potential impacts

Cultivation

Some species of bamboo are highly invasive, meaning they take over natural vegetation.

Processing

To transform plant-derived materials into silky fabrics, the cellulose must be separated from other compounds (like lignin) in the bamboo stem. Sodium hydroxide (caustic soda) and sodium sulfide are commonly used to extract the lignin that binds the plant fibres together, and in some cases bleach is required to whiten the pulp. The pulp is steeped in caustic soda to produce alkali cellulose, which is then aged or oxidized before reacting with carbon disulfide to create sodium cellulose xanthate. This xanthate is dissolved in caustic soda to form a syrup-like spinning solution or "viscose," which can then be extruded through a spinneret to form viscose fibres.[6]

The manufacturing of viscose involves intensive chemical processes and requires copious amounts of water. Wastewater effluents from processing must be properly treated to avoid contamination of surrounding water bodies. Air emissions caused by the viscose process include sulfur, nitrous oxides, carbon disulfide and hydrogen disulfide. Chronic exposure to carbon disulfide can cause damage to the nervous system in humans.[6]

Dyeing and finishing[7]

The most common dyeing process for viscose made from bamboo is a multi-step process that involves ample amounts of water at high temperatures (50°-95°C), salt, acetic acid and caustic soda. Mild peroxide bleach may also be necessary to remove residues of sulphur.

MORE INFO: DYEING & PRINTING

Consumer care/washing

Viscose can be machine or hand-washed, sometimes dry cleaning can be appropriate due to delicacy of the fabric when wet.

MORE INFO – APPENDIX: CONSUMER CARE & WASHING

1 www.voanews.com/content/a-13-2006-08-29-voa51/323110.html
2 www.fao.org/economic/futurefibres/fibres/jute/en/
3 www.hempage.de/cms/
4 www.swicofil.com/products/003flax.html
5 www.decktowel.com/pages/how-linen-is-made-from-flax-to-fabric
6 oecotextiles.wordpress.com/2009/08/19/348/
7 textilefashionstudy.com/process-flow-chart-of-viscose-fabric-dyeing/

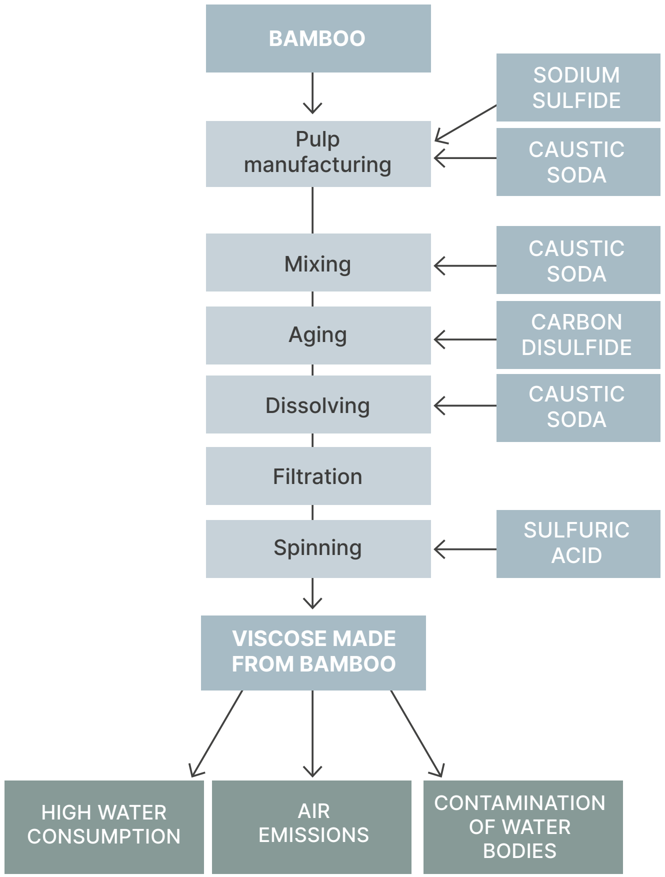
End of use

After long use bamboo viscose can be mechanically recycled.

Although it is claimed that bamboo viscose is biodegradable, however this is highly dependent on many conditions including disposal manner, humidity, temperature, UV exposure and presence of microorganisms. Remains of chemical treatments can cause contaminations when the material has degraded.

MORE INFO – APPENDIX: BIODEGRADABILITY

Process for viscose made from bamboo



Optimize sustainability benefits

- Acknowledge the difference between linen made from bamboo and viscose made from bamboo. Bamboo linen is bamboo bast fibres mechanically processed and not so common.
- Viscose made from bamboo employs a chemically intensive process with significant environmental and social impacts due to emissions to air and water during processing.
- Ensure that the bamboo viscose is made from FSC and/or PEFC certified bamboo and is verified as coming from certified sustainably harvested forests.
- Ask for renewable energy source through the entire supply chain.
- Check water source and wastewater treatment through the entire supply chain with special focus on fibre production and wet processes.
- Investigate alternative viscose processing methods. viscose-type materials are emerging and can be made through various types of processes. See Novel Cellulose-Based fibres.
- Lyocell made from Bamboo could be a better alternative. See Lyocell.[8]

Availability

There are few suppliers are currently offering viscose made from bamboo from PEFC and FSC certified plantations. Expressing higher interest in PEFC and FSC certification can influence the supplier's raw material sourcing strategy and lead to increase availability of responsibly sourced feedstock for viscose made from bamboo fabric.

Applications

Fabrics made from Bamboo derived from the Viscose or Lyocell process can be used in a variety of woven and knitted textile applications. Depending on the weight and construction of the cloth, these fabrics may be suitable for shirts, skirts, dresses, evening gowns, home furnishings and bedding.

Clarification and advantages

Viscose based on bamboo is being marketed strongly as an eco-friendly fibre. While the raw material is a rapidly renewable natural resource, fabrics made from bamboo viscose employs a highly pollutive process in its manufacture. The European Com-

8 http://www.lenzing-fibres.com/en/tencel/

mission has issued a directive on textile names, 2008/121/EC. This directive states how textile products should be marketed and sold in the EU. The name “bamboo” does not appear in this directive; therefore, it cannot be used for the purposes of compulsory description of fibre composition. The name “viscose” is included in this directive and should be used to describe the fibres corresponding to the definition: “regenerated cellulose fibre obtained by the viscose process for filament and discontinuous fibre” which includes viscose made from bamboo fibres.[9]

Some bamboo species grow approximately 24 meters within 40 days, as such it can be marketed as fast-growing renewable resource.

Low water footprint in cultivation

Bamboo can grow in different types of climates, rain fed is most common.

NOTE: There are companies claiming that bamboo is a natural antibiotic.
The Federal Trade Commission (FTC) in the U.S. notes that the chemical processing of bamboo viscose eliminates any of the plant’s antimicrobial properties.[10]

Innovation opportunities

1. Shift to existing more environmentally friendly materials when possible. Examples of materials are organic cotton, recycled fabrics, hemp, flax, and dissolving pulp from bamboo and hardwood plantations that are PEFC and FSC certified.
2. Use bamboo from PEFC and FSC certified plantations and preferably fibres made from lyocell process.
3. Get your product Cradle to Cradle Certified. The Cradle-to-Cradle CertifiedTM Product Standard is a multi-attribute for continuous improvement methodology that provides a path to manufacture healthy and sustainable products. The Standard reward achievements in five categories and at five levels of certification. An accredited assessor will help to assess and optimize your product.

9 eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:019:0029:0048:EN:PDF
10 ftc.gov/opa/2009/08/bamboo.shtm

Shutterstock

Lyocell

Man-made fibre

Lyocell fibres is made from cellulose originating from wood e.g. beech or eucalyptus and it has unique material properties that can be suitable for a variety of different applications. The manufacturing process for lyocell is a closed loop process, which makes it a more sustainable alternative to cotton, viscose and possibly other synthetics.

Lyocell

Benefits

Lyocell has a smooth fibre surface and round cross section. This fibrillar structure enables improved dye pickup and achieve vibrant colours and a slight sheen on the surface of the fabric while using less dye-stuff and less water throughout the dyeing process. In all applications, lyocell has good moisture wicking properties, good absorbency, is wrinkle resistant and has good drapability.

To transform hard wood into lyocell fabrics, the cellulose must be separated from other compounds in the wood such as lignin and hemi cellulose. The wood material is dissolved through a complex chemical process into viscous liquid, which is then extruded or spun to form fibres. The solvent used to transform the pulp into fibre is amine oxide (NMMO=N-Methyl-Morpholine-N-Oxide), which is considered non-toxic.

The brand named fibre TENCEL™ from Lenzing is today the most common lyocell fibre on the global market and 2017 the company launched Refibra®, a new lyocell fibre out of cotton scraps and wood cellolose.[1] The manufacturing process of the TENCEL™ lyocell fibre operates as a closed loop system, in which 99.8% of the solvent is recovered, filtered and reused and any remaining residues are decomposed in biological wastewater treatment plants.[2,3,4]

Lenzing also claim that the trees used in the feedstock for TENCEL™ lyocell are harvested from sustainably managed farms certified by the Forest Stewardship Council (FSC) or Programme for the Endorsement of Forest Certification (PEFC).[5] Lenzing has also confirmed that pulp used for the manufacture of TENCEL™ lyocell fibre is supplied from production locations that comply with the EU Timber Regulation.[4,5] New fibre brands from different manufacturers are continuously being introduced into a growing lyocell market.

Since the lyocell fibre absorbs and redirects moisture (i.e., sweat) fewer washing cycles may be needed, resulting in water and energy savings as well as reduced wear and tear that occurs with repeated laundering.

1 http://www.lenzing-fibres.com/en/tencel/

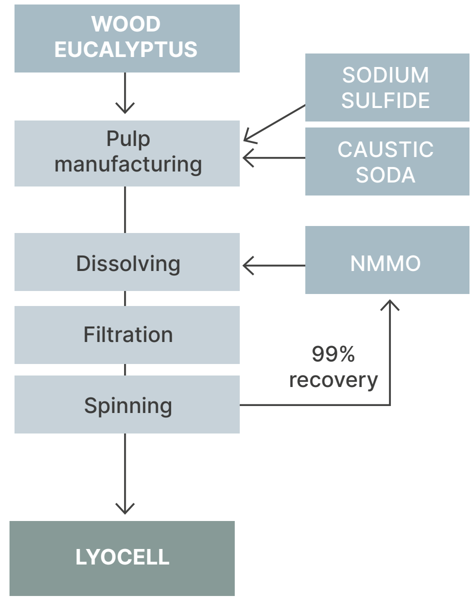
2 Textile Exchange "TENCEL® lyocell From Lenzing" March 2011

3 symposium.lenzing.com/fileadmin/template/pdf/lectures_speakersLCA_Li_shen.pdf

4 Dr. Bianca SCHACHTNER, personal communication, January 14, 2014.

5 ec.europa.eu/environment/forests/timber_regulation.htm

LYOCELL MANUFACTURING PROCESS



The dyeing process for lyocell can significantly reduce water consumption and dye and chemical use due to its good colour absorption when compared to other fibres.

Depending on the dyes and trims used, lyocell may be biodegradable if disposed under optimum environmental conditions (exposure to water, air, light).[4] Lenzing has reported in a Biodegradability Technical Bulletin that TENCEL™ lyocell fibres were found to have degraded completely after 6 weeks when composted.

Potential impacts
Currently, the solvents used for lyocell are derived from petrochemicals. However, the solvents are being recovered and reused.

Dyeing
Although the dyeing process for lyocell can significantly reduce water consumption and dye and chemical use due to its good colour absorption, the dyeing process still involves standard industry chemicals and water use.
MORE INFO: DYEING & PRINTING

End of use
After use lyocell can be mechanically recycled.
Although it is claimed that lyocell is biodegradable, the degradation is highly dependent on many conditions including disposal manner, humidity, temperature, UV exposure and presence of microorganisms. Remains from chemical treatments can leave contaminations in the degraded material.

Optimize sustainability benefits
- Ensure that lyocell fibre/fabric is made from FSC and/or PEFC certified wood and is verified as coming from certified sustainably harvested forests.
- Cross check with Lenzing that the fabric supplier is one of their supply chain partners.
- Ask for renewable energy source information through the entire supply chain.
- Check water source and wastewater treatment data through the entire supply chain.

Availability
Most of the lyocell made is sold under the TENCEL™ trade name. TENCEL™ lyocell is readily available and the fibre is produced at three production sites: Mobile, Alabama, USA; Grimsby, United Kingdom; and Heiligenkreuz, Burgenland, Austria.

Advantages
Since lyocell is derived from a natural renewable resource, and manufactured using a closed loop process it is considered a low impact fibre.

FSC-certified If lyocell from FSC-certified plantations is used, this can be claimed.

PEFC-certified If lyocell from PEFC-certified plantations is used, this can be claimed.

Biodegradable All fibres, yarns, trims and dyes used to manufacture the product or garment must also be biodegradable or alternatively be disassembled before disposal. This should be substantiated with documentation that the product can completely decompose into non-toxic material by being processed in a facility where composting is accepted.

Innovation opportunities
1. Design garments with lyocell used or inserted in high-perspiration areas of the garment, such as the underarm, to take advantage of its moisture absorbing and wicking properties.
2. Explore innovative design that use blends with lyocell preferable other bio-based fibres like organic cotton or recycled cotton.
3. Use tags and hangtags with information to encourage consumers and tumble dry and iron only when necessary.
4. Design the product so that hard parts and non-bio-based trims, tags, buttons, etc., can be easily separated from the main product at the end of its useful life. Create collection systems for the products.

Modal

Man-made fibre

The material properties for modal are similar to traditional viscose, however there are a few differences: the manufacturing process for Modal is less toxic and it has greater wet strength.

Modal

Modal is categorized as a "manufactured" or "man-made" fibre created from cellulose originating from hardwood trees like birch and oak. It is then chemically processed and regenerated to form a polymer by using a process similar to the viscose process.[1]

Benefits

Modal's key fibre characteristics are its extra softness and high wet strength. Fabrics made from Modal is machine washable, and can be washed in low temperature and drip-dried, thereby minimizing water and energy use associated with consumer care and washing.

Modal drapes well, is easy to dye, and is highly moisture absorbent.

Lenzing offers dope dyed modal using a process called Eco Colour. The company claim energy and water savings of up to 50% and that the CO_2 footprint is about 60% lower compared to conventionally dyed fabrics.[2]

Potential impacts

Dyeing and finishing

Not all colours can be used for dope dyeing, so traditional dyeing methods might have to be used. The dyeing process for modal is a multi-step process that involves ample amounts of water at high temperatures.

MORE INFO: DYEING & PRINTING

Consumer care/washing

Electricity and water use in the care of the garment can have significant negative environmental impacts. Certain chemicals used in at-home products have been reported to have detrimental effects on humans and the environment, contribute to ozone depletion and can pollute wastewater.

MORE INFO – APPENDIX: CONSUMER CARE & WASHING

End of use

After use modal can be mechanically recycled.

Although it is claimed that modal is biodegradable, the degradation is highly dependent on many conditions including disposal manner, humidity, temperature, UV exposure and presence of microorganisms. Remains of chemical treatments can cause contaminations in the degraded material.

MORE INFO – APPENDIX: WASTE TO ENERGY

Optimize sustainability benefits

> Ensure that modal fabric is made from FSC and/or PEFC certified wood and is verified as coming from certified sustainably harvested forests.
> If using TENCEL™ Modal, cross check with Lenzing that the fabric supplier is one of their supply chain partners.
> Ask for renewable energy source through the entire supply chain.
> Check for water source and wastewater treatment information through the entire supply chain.
> Use TENCEL™ Modal Eco Colour.
> In the programme Roadmap to Zero, the ZDHC foundation launched 4 guidelines applicable on modal; the ZDHC Man-Made Cellulosic Fibres (MMCF) Guidelines, the ZDHC MMCF Responsible Fibre Production Guidelines, the ZDHC MCF Interim Wastewater Guideline, and the ZDHC MMCF Interim Air Emissions Guidelines. These guidelines give suppliers producing MMCF unified criteria for measuring output indicators like wastewater, sludge, air emissions, and other process-related parameters. They also offer an aligned approach for the recovery of Sulphur and other compounds, as well as by-products generated during the production process. Fibre producers are expected to engage themselves in setting up a road map for continuous improvement defined by three levels of foundational, progressive and aspirational. Dissolving pulp production process will be considered at a later stage.[3,4]

1 https://sewport.com/fabrics-directory/modal-fabric
2 https://www.tencel.com/b2b/product/tencel-modal
3 Preferred Fibre & Materials Market report oct 2022, Textile Exchange
4 ZDHC: https://www.roadmaptozero.com/post/zdhc-man-made-cellulosic-guidelines-released

Availability

Modal is readily available.

Modal is often blended with cotton, wool or synthetic fibres and allow easy tone-in-tone dyeing.

Applications

Modal fibres are especially favoured for use in loungewear, sleepwear and undergarments. They can also be found in 100% form and blends with cotton, wool, silk and synthetic in apparel, outerwear and household furnishings.

Advantages

FSC certified and **PEFC certified** must be verified.

OEKO-TEX® STeP, EU Eco label and or Cradle to Cradle Material Health Certificate standard certified If used and verified.[5,6,7]

Innovation opportunities

1. Information on Hangtag and labelling/Point of sales (POS) would influence the consumer to take an active role in reducing environmental impacts of modal at the consumer washing stage.
2. Explain the difference between the viscose process and the production process used for TENCEL™ Modal on your website or point of sales materials.
3. Let the capabilities of TENCEL™ Modal Eco Colour guide your decision- making when it comes to colour choices.
4. Explore recycling options for 100% modal as a raw material for regenerated cellulose fibre production.

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5 www.OEKO-TEX.com

6 https://eu-ecolabel.de/fileadmin/user_upload/Documents/PG016/Sonstiges/textile_factsheet_en.pdf

7 https://c2ccertified.org/the-standard/material-health-certificate

Part 4: Novel & biobased fibres

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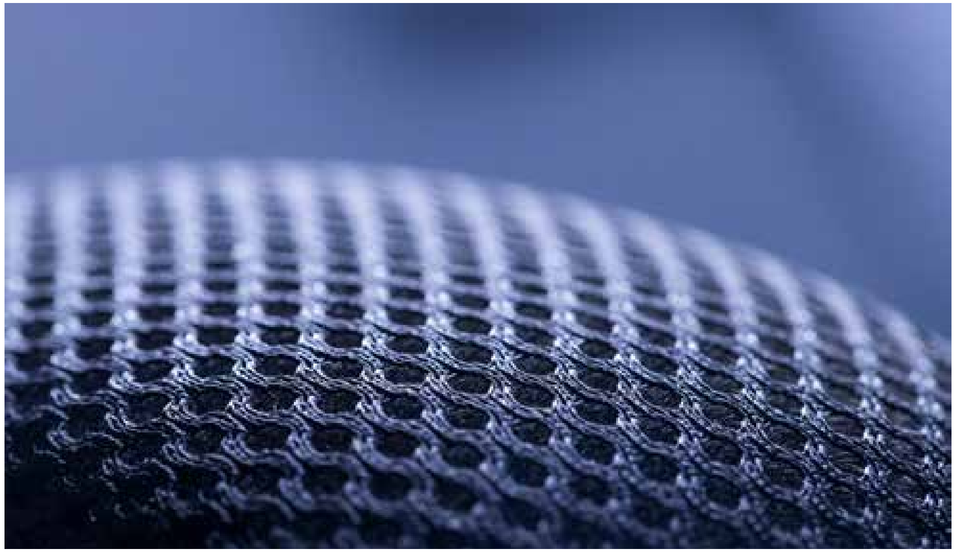


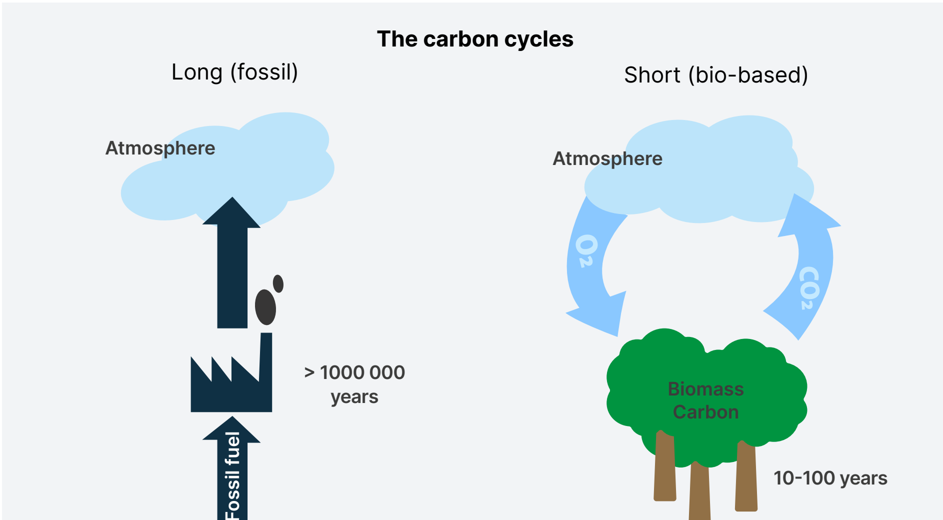
Introduction

In order to address the global environmental challenges, the large-scale production of biodegradable plastics with equivalent properties to synthetic counterparts is an urgent need. Although bioplastics counts for less than 1% of the 367 million tons of annual plastic production, their market is steadily growing due to rising demand and need for use in advanced applications. Recent data, from European Bioplastics and Nova-Institute, project global bioplastics production capacity to rise from 2.42 MTn in 2021 to approximately 7.59 MTn in 2026. This hike mark the first timethe market share of bioplastics' in global plastic production will exceed 2%.[1]

Sustainability efforts within the textile and fashion industry necessitates operating within the finite boundaries of our planet's capacity to generate raw materials for fibres and to assimilate the waste generated by industrial processes and garment disposal. Bio-based synthetic fibres, often referred to as "green fibres," "eco-fibres," or "sustainable fibres," are derived from renewable biological sources such as plants, agricultural crops and bio-waste, rather than non-renewable fossil fuels. For conventional oil-based fibres such as polyesters and polyamides (often called nylons), there is an imbalance between the pace of raw material extraction and the rate of natural regeneration (approximately one million years for crude oil). On the other hand, bio-based feedstocks can produce polyester and nylon fibres exhibiting almost similar properties as fossil based, yet with a significantly shorter regeneration cycle (roughly ten to on hundred years). This shift can substantially alleviate the carbon burden imposed on the environment.

Origins and types of bio-based fibres

A diverse array of bio-based fibres exists already, with appropriate properties and applications. Natural fibres like cotton, hemp, flax, and jute have been used for centuries. However, recent advancements have generated innovative bio-based fibres, including those derived from agricultural waste (e.g., wheat straws, banana stems, corn, bagasse), bio-polymers (e.g., polylactic acid – PLA, polyhydroxyalkonates – PHA), and regenerated cellulose fibres (e.g., lyocell, vicose). Natural fibres and new biopolymers are part of the broader movement towards biomaterials and bioeconomy, where resources are harnessed from nature in a regenerative and responsible manner, which will ultimately reduce the carbon footprint of the fibres as well as products made from these fibres. The carbon cycle of oil and biomass is illustrated below.[2]



RISE IVF

1 RISE IVF

2 http://www.european-bioplastics.org/news/multimedia-pictures-videos/

The European Bioplastics organization has described the potential configuration of closed loop for bioplastics, which can be seen in the figure below.[3]

source: European Bioplastics

Production processes of bio-based fibres

The production of bio-based fibres most often involve complex processes such as agricultural practices, chemical processes, and material engineering. These steps comprising fibre production are dependent on the bio-based feedstocks used such as, extraction or regeneration of fibres from agricultural wastes and wood materials, as well as the cultivation of microorganism under controlled conditions. In general, the fibre production includes steps such as feedstock cultivation, fibre extraction, polymerization, fibre spinning and textile fabrication. The properties of produced fibres can be precisely controlled and modified to align with specific end-user needs or applications.

Properties and advantages of bio-based fibres

Bio-based fibres offer a compelling range of properties that make them attractive for various applications. They can be engineered to exhibit specific characteristics such as strength, durability, moisture-wicking, and thermal insulation, making them suitable for textiles, nonwovens, composites, and more.

One of the most significant advantages of bio-based fibres lies in their reduced environmental impact. Unlike synthetic fibres derived from petroleum, bio-based fibres are sourced from renewable feedstocks. This inherent connection to nature leads to lower greenhouse gas emissions, reduced dependence on finite resources, and decreased ecological footprint. Additionally, bio-based fibres often have a smaller carbon footprint compared to their conventional counterparts.

Furthermore, the biodegradability of many bio-based fibres presents a solution to the growing issue of plastic waste. When disposed properly, these fibres degrade naturally within short time in landfills or ecosystems. Biodegradability of bio-based polymers align with the principles of a circular economy, where materials are designed to be reused, recycled, or returned to the biosphere.

Challenges and future aspects

Although bio-based fibres offer a significant potential, several challenges need to be addressed before their widespread adoption. The cost of production remains to be a key consideration, as bio-based fibres can be more expensive to produce than conventional synthetic fibres. However, ongoing research and technological advancements are expected to drive down costs.

Another challenge lie in achieving consistent quality and performance across different batches of bio-based fibres e.g., PLA vs bio-based-PET. Variability in feedstock sources, processing methods, and polymerization techniques can impact the final material properties and suitability for specific applications.

3 Sustainable Material Guide for apparel companies (Modint)

New bio-based polymers

In recent years, extensive research efforts have been undertaken to explore bio-based alternatives to conventional synthetic fibres derived from fossil fuels. Through utilization of bio-based feedstocks and innovative production techniques, a potential exists to create alternatives to nearly all traditional synthetic fibres, including polyester, polypropylene, nylon, polyethylene, and elastane. These alternatives often exhibit properties that are comparable to those of their synthetic counterparts. Notable examples of such alternatives encompass PLA, PHA, PHB, and bio-based nylon, among others.

Some Commercial biopolymer fibres:

LACTIC ACID

PLA(Polylactide), is a bio-based synthetic fibre that share similar properties with polyester, making it a strong contender in the market. PLA is derived from renewable sources such as corn, sugarcane, and sugar beet, as well as from waste generated by the agro-food industry.[4] Some commercial fibres are:

> Ingeo® (NatureWorks)[5]
> BIOFRONT® (Teijin)[8,9]

CASEIN (MILK)

Casein, a protein-based substance naturally found in milk, is renowned to function as a main element in the production of protein-based fibres. Fabrics produced from casein fibres exhibit a gentle and silky texture, making them exceptionally comfortable against the skin. Some examples are:

> QMILK® (QMILK) Fibre from non-food milk.[5]
> MIKROFIL® (CRESPI), a yarn from organic milk.[6]

SUGARS (GLUCOSE)

Sugars, derived from renewable sources such as corn, sugarcane, and other biomass, are utilized to produce biobased-fibres. One example is Sorona® (Dupont) 37 % of the polymer is out of renewable plant-based sources. It is a fibre to be compared with Polyamide 6 and 6,6.[9]

SOYA BEAN

Soybean fibre, also known as soy fibre or soybean protein fibre, is a type of textile fibre derived from the protein-rich byproduct of soybean processing, known as soybean cake. This innovative and sustainable fibre is created by extracting the protein from soybean cake and processed into a latex/solution that can be spun into fibres and yarns that later can be used to weave or knit fabrics. When blended with other fibres soybean fibres can enhance e.g. smoothness and lustre, minimize shrinkage, and give easy care properties.[15] Harvest SPF Textile Co.,Ltd is one of the producer of these fibres.[16]

POTATO STARCH

Bio-based textile fibres based on potato starch, a carbohydrate-rich component of potatoes, is an emerging innovation within the field of sustainable textile materials. After extraction and modification of starch from potatoes, conventional fibre spinning techniques can be used to produce the fibres. The obtained fibres can be used for example in raincoats, blankets etc.[13,14]

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4 https://www.natureworksllc.com/What-is-Ingeo
5 https://www.qmilkfibre.eu/?lang=en
6 http://www.mcrespi.com/en/milkofil-latte/
7 https://www.plasticstoday.com/content/teijin-now-marketing-film-and-sheet-grades-its-heat-resistant-bioplastic/31495184216596
8 http://news.bio-based.eu/silk-crepe-kimonos-made-with-teijins-biofront/
9 http://sorona.com/

Shutterstock

CASTOR OIL

Castor oil, sourced from the castor bean plant (Ricinus communis), serves as renewable feedstock to produce bio-based polyamide (nylon). The process of producing textile fibres from castor oil involves steps such as, extraction of castor oil from castor beans, polymerization of castor oil into suitable polymers, fibre spinning and finally the production of textiles production. Some commercial fibres are:

> Castlon® (Unitika Fibre) from Rilsan®Polyamide 11 Resin (ARKEMA)[9, 10,11]

SEAWEED

Among other cellulose-containing alternative plants, seaweed is a promising and renewable source that can grow in cold water, requires no arable land, fresh water, irrigation, or toxic fertilizers. Due to its natural benefits, it acts as an active source to a cellulose based fibre manufactured by the lyocell-process. When fabrics produced from these fibres are worn, nutrients are released from the seaweed, facilitated by the moisture from the body. The fibres give a smooth and silky texture to the fabric.

> SeaCell® (Smart Fibre AG), Produced at Lenzing AG, Austria is one example.[13]

10 http://news.bio-based.eu/silk-crepe-kimonos-made-with-teijins-biofront/
11 https://naturalpolymers.wordpress.com/2011/11/16/a-bio-fibre-designed-with-arkemas-rilsan-polyamide-11/
12 https://www.unitika.co.jp/e/products/fbtx-bis/clothes.html
13 http://www.smartfibre.de/en/fibres/seacelltm/ Lhttp://www.equilicua.com/Recursos/lookbook_leyre_ingles.pdf
14 https://www.babongoshop.nl/en_GB/a-39227591/equilicua/picknickblanket-made-from-biodegradable-plastic/
15 http://www.fibre2fashion.com/industry-article/5924/soybean-fibres-a-review?page=1

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Polylactide (PLA)

New biobased fibre

Polyactide (PLA) is mainly made from sugars derived from corn, though any abundantly available sugar, such as wheat, sugar beets or sugarcane could also be used. PLA is a new class of polymer that is biodegradable under optimum conditions. Ingeo from NatureWorks LLC is a readily available brand name of PLA.[1]

Polylactide (PLA)

Polylactide (PLA), derived from lactic acid, is a renewable thermoplastic polymer. It is sourced from plant starches like corn, sugarcane, and sugar beet etc. PLA is biodegradable and decomposes as a result of exposure to heat and moisture. This decomposition results in the formation of carbon dioxide and water, which pose no environment harm.[2,3]

PLA's ability to biodegrade is a result of its hydrolysis and low melting point. These features could hinder PLA's ability to be suitable in some applications, such as outdoor fabrics or fabrics that needs to be ironed. However, recent advancements have addressed these limitations. NatureWorks LLC, who offer a PLA with the brand name Ingeo, has developed hydrolytic stabilizers that can be implemented in certain PLA's for use in for example outdoor garments to avoid premature degradation.

Benefits

Polylactide (PLA) is a bio-based thermoplastic polymer that is composed of at least 85% by weight of lactic acid ester units derived from naturally occurring sugars (corn, sugar beets, wheat, rice, potatoes etc) and can be converted into fibres by conventional melt spinning process.[3,4]

PLA is made from renewable raw material only. Therefore, it is widely acknowledged as the most significant biobased and biodegradable material, finding extensive utilization in industries such as food packaging, transport, textiles and electronics.

Polylactide has excellent properties such as, resiliency, outstanding crimp retention and good wicking ability. It has good thermal insulation characteristics, breathability, high UV protection and excellent hand and drape properties.[4] PLA has natural resistance to staining, low odour retention, and can be machine-washed and dried, and garments made from PLA don't need to be ironed.

Polylactide is fully biodegradable (if component parts of the garment are also made from PLA), under optimum composting conditions.

The use of PLA could allow Europe to reduce its reliance on foreign sources of fossil fuels. Europe cover the oil consumption/needs by importing from foreign countries such as the Russian Federation, Africa and the Middle East (only 16.7 % of the oil consumed comes from within Europe, (2016)).[5,6]

Potential impacts

Processing

Land degeneration/leaching due to too intensive farming/ exploitation to fulfil human needs for food, fibre, and fuel has led to the degradation of more than 25% of the world's agricultural land, pastures, woodlands, and forests.[7]

Polylactide a relatively new to the market and requires further development to enhance its performance attributes, price, and scalability. For instance, proper heat setting is not always achievable, resulting in PLA fabrics having a relatively low melting point. This can also impact dimensional stability during storage, transportation, dyeing, ironing, transfer printing, and other processes.[8]

End of use

Polylactide is biodegradable, but only under certain conditions. For example PLA will not biodegrade in landfills. It PLA requires a balance of oxygen, moisture, aeration and steady temperatures of 49-60°C, an environment that is typically found in industrial composting facilities. Under these conditions, it usually takes 10 to 22 months for PLA to decompose. Home compost heaps do not provide the required combination of temperature and humidity to trigger decomposition.[8]

Furthermore, PLA cannot be discarded into the regular PET recycling bin because it can contaminate PET in the recycling process. There is currently no standard system for differentiating PLA plastics from for example PET.

1 http://www.swicofil.com/harvesttextile.html
2 https://www.aitex.es/portfolio/phbtex-textile-production-from-biopolymers/?lang=en
3 www.natureworksllc.com
4 Freinkel, Susan. PLASTIC A Toxic Love Story. New York: Houghton Mifflin Harcourt, 2011.
5 Cohen, Allen and Ingrid Johnson. Fabric Science. New York: Fairchild Books, 2010.
6 "Monthly and cumulated Crude Oil Imports (volumes and prices) by EU and non EU country," 2012.
7 ec.europa.eu/energy/observatory/oil/import_export_en.htm
8 Doran, "International Workshop on Assessing the Sustainability of Bio-Based Products," 2003.

When used in combination with non-renewable alternative plastics, PLA cannot be claimed as biodegradable.

MORE INFO – APPENDIX: BIODEGRADABILITY

Optimize sustainability benefits

Sustainability benefits can be optimized by:

> Connecting to or developing an infrastructure(s) to collect and process compostable fibres.
> Labelling garments for consumers to identify composting routes for biodegradable fibres, to ensure they remain separate from degradable and non-degradable synthetic fibres.
> Using non-genetically modified, organically grown feedstock.
> Checking colour matching, as dark colours can be difficult to achieve.
> Ensuring that requirements are met in terms of light and colour fastness.

Availability

Ingeo, a brand name for polylactide, is readily available from NatureWorks LLC.

There are also sources in Belgium, Italy and the United Kingdom producing polylactide for non-woven.

Applications

Due to the diverse properties of PLA, it can be used in a wide range of applications such as, pillows, comforters, mattress pads, performance activewear, fashion apparel, outdoor furniture as well as in non-woven, such as diapers.

Advantages

Biodegradable, for polylactide to biodegrade effectively, it must be disposed of in an industrial composting facility. Proper disposalafter use is crucial, and explicit/developed infrastructure is necessary for post processing. Claiming ”biodegradable” cannot be made without thorough investigation and communication in these aspects. To earn the ”biodegradable” label, documentation is necessary that the product can fully decompose into non-toxic materials.

Innovation opportunities

1. Design completely biodegradable garments where all fibres and component parts compost fully and safely.
2. Partner with composting facilities to guarantee effectiveness of composting ability.
3. Design garments and products with reusable components, such as trims and tags. Design the product so that trims and tags can be easily separated from the main body of the product at the end of its life to enable easy recycling. Establish collection system for these products, enabling collection, disassembly, and reuse.
4. Communicate to customers proper route of disposal.
5. Get your product Cradle-to-Cradle Certified. The Cradle-to-Cradle Certified™ Product Standard follows a multi-attribute, continuous improvement approach, offering a pathway to manufacture healthy and sustainable items. The Standard rewards achievement in five categories and at five levels of certification. An accredited assessor will help to assess and optimize your product.

Polyhydroxy-alkonates (PHAs)

New biobased fibre

Polyhydroxyalkonates (PHAs) represent a category of bio-based polyesters, renowned for their potential use in thermoplastics and their inherent biodegradability. This characteristic makes them an ideal candidate for replacing traditional plastics in reducing impact on the environment.[1]

Polyhydroxyalkonates (PHAs)

PHAs are naturally occurring biopolymers and can be extracted through a fermentation process utilizing different carbon-based feedstocks, including organic food waste, methane gas and captured CO_2.[2] With the technological advancements in processing made, more than 150 different types of PHAs have been identified until now, out of which polyhydroxybutyrate (PHB) is most prominent due to its properties similar to conventional petroleum-based plastics such as polypropylene.[3]

Benefits

PHA exhibit several favourable characteristics, including a small pore size that facilitates efficient recycling, a high volume-to-surface ratio, as well as biodegradability and biocompatibility. Recently, PHA has attracted significant attention due to its numerous advantageous such as, ease of processing, strong resistance to UV radiation, insolubility in water, ability to naturally degrade, compatibility with living organisms, and thermal and mechanical properties similar to conventional plastics.[4] These qualities make PHA's suitable candidates for replacing materials like polylactic acid, polyethylene terephthalate, bio-based polyamide, and other bio-based materials that don't naturally[5] degrade. These materials are used in various fields like farming, food, packaging, and fabrics. Depending on the environmental conditions, microbial activity, polymer composition and areas of application areas, PHAs can degrade withing a span of few weeks to several years, depending on the conditions, generate lower greenhouse gas emissions compared to conventional plastics, contributing to a reduced carbon footprint.

PHA/PHB have good compatibility with other bio-based materials such as PLA, so blends made from these materials can generate additional properties and can be used for broad range of applications such as packaging.[6]

Challenges

Even though PHAs have many benefits compared to man-made materials, their use for commercial purposes have been restricted due to their weak physical and mechanical properties limiting their use for commercial purposes because of lack of critical/needed characteristics, difficulties for use in regular thermal processes because they degrade at relatively low temperatures, and are expensive to produce. The poor characteristic of PHB to handle heat and water makes it hard to use in normal methods for making plastic products (like extrusion, injection molding, and 3D printing)7. The conventional melt spinning techniques for fibre production is usually not applicable for PHA/PHB due to the long exposure to higher temperature resulting in rapid and significant molecular weight loses, colour changes (from white/yellow to brow), and loss of critical mechanical properties.[7]

Though PHA/PHB are sustainable alternatives to fossil fuel-based materials but large-scale production of these materials, cost-effectiveness and consistent properties are the major challenges to be sorted.

1 Tania P-S., Vincent O'F., Piet N.L.S, "Polyhydroxyalkonate bio-production and its rise as biomaterials of the future", Journal of Biotechnology, 348 (2022).
2 https://fashionforgood.com/our_news/fashion-for-good-launches-the-renewable-carbon-textiles-project/
3 R. Mitra, T.Xu, H.Xiang, J. Han, "Current developments on Polyhydroxyalkonates synthesis by using halophiles as a promising cell factory", Microb. Cell Faactories, 19 (2020).
4 R. Dwivedi, R. Pandey, S. Kumar, D. Mehrotra, "Polyhydroxyalkonates (PHA): role in bone scaffolds", J. Oral Biol. Craniofac. Res. 10 (2020).
5 V. Sharma, R. Sehgal, R. Gupta, "Polyhydroxyalkonate (PHA): Properties and Modifications", Polymer 212(2021).
6 https://www.packnet.se/article/view/1047260/pha_tar_plats_i_premiumforpackning_for_kosmetika?ref=newsletter&utm_medium=email&utm_source=newsletter&utm_campaign=daily
7 V. Kumar, R. Sehgal, R. Gupta, "Blends and composites of Polyhydroxyalkonates (PHAs) and their applications", Eur. Poly. J. 161 (2021).

Optimize sustainability benefits

The sustainability benefits can be optimized by:

- > Increasing production volume through innovative production techniques while minimizing production costs.
- > Optimizing fibre properties by incorporating alternative fibre spinning methods, such as solution dry and wet spinning techniques.
- > Modifying the inherent properties of PHA/PHBs during production to make them suitable for textile applications.
- > Enhancing biodegradability through microbial and environmental activities.

Availability

Due to the high cost and low production volume, the supply of PHA/PHB is still limited. The NewLight and Mango Materials are major producers of PHA/PHB from greenhouse gases.[8,9] FAHION FOR GOOD have launched a project recently[2] in order to find the use for PHA/PHB in the fashion industry.

Applications

The use of PHA/PHB are expanding over time, thanks to their diverse properties comparable with both conventional bio-based and fossil fuel-based materials. They find their applications in packaging, agriculture, pharmaceuticals, textiles, automoti-ve, and electronics sectors.

Innovation opportunities

1. Enhance the material properties during the production steps making PHA/PHB more suitable for the fibre production and hence, for textile applications.
2. Optimize the fibre spinning methods such as melt spinning and solution spinning processes in order to increase the mechanical properties.
3. Design completely biodegradable garments where all fibres and component parts compost fully and safely.
4. Partner with composting facilities to guarantee effectiveness of composting ability.
5. Design garments and products with reusable components, such as trims and tags. Design the product so that trims and tags can be easily separated from the main body of the product at the end of its useful life to enable easy recycling. Establish collection system for these products, enabling collection, disassembly, and reuse.
6. Communicate to customers proper route of disposal.
7. Get your product Cradle-to-Cradle Certified. The Cradle-to-Cradle CertifiedTM Product Standard follows a multi-attribute, continuous improvement approach, offering a pathway to manufacture healthy and sustainable items. The Standard rewards achievement is set up in five categories and at five levels of certification. An accredited assessor will help to assess and optimize your product.

8 https://www.newlight.com/
9 https://www.mangomaterials.com/

Unsplash/Olena Bohovyk

Novel Cellulose-base Fibres

New biobased fibre

Traditional methods like the viscose process use carbon disulfide, which is a toxic solvent, and sulfuric acid, which requires careful handling. The lyocell process, on the other hand, uses NMMO (N-methylmorpholine N-oxide), which is less toxic but still require high temperatures for dissolution.

New technologies are developed to produce novel cellulose-based fibres with sustainability in mind.

Cellulose Carbamate-based Fibre

Cellulose carbamate fibre is a type of regenerated cellulose fibre that is produced by modifying cellulose using urea or urea derivatives. The process generally involves converting the cellulose into a carbamate derivative, which can be more easily dissolved to form a solution. This solution is then extruded through spinnerets into a coagulation bath to form fibres.

The key benefit of using cellulose carbamate in fibre production is that the process usually requires fewer harsh chemicals than other regenerated cellulose fibre production methods like the viscose or Lyocell process. As a result, cellulose carbamate fibres can be seen as more eco-friendly alternative.

Furthermore, the presence of carbamate groups in the cellulose structure can impart specific properties to the fibres, such as improved elasticity, moisture absorption, and affinity to dye. These characteristics make cellulose carbamate fibres suitable for a variety of textile applications, ranging from clothing to home textiles like bed linens and upholstery.

Despite these advantages, it's worth mentioning that the production of cellulose carbamate fibres still entail complexities and costs, particularly in optimizing the process for large-scale manufacturing and ensuring consistent quality of the fibres.

Modifying recycled cotton fibres with urea can make it possible to regenerate them using the cellulose carbamate process. The spinning of fibre from cellulose carbamate dope occurs in an acidic bath, employing a process similar to the viscose method. Cellulose carbamate is a stable compound that can be stored for long periods of time, making it easier to transport and spin.[1]

Cotton cellulose derived from used textiles maintain a high degree of polymerization (DP), making it suitable for regeneration into new fibres. Infinited Fibre Co (IFC), a spin-off from VTT, pioneered this technology.

Notable Features

> Cellulose carbamate process offers an alternative route for creating regenerated cellulose fibres with potentially lower environmental impact and distinct functional properties.

> Recycled cotton is a resource for cellulose carbamate fibre.

Collect recycled cotton textiles

Raw Material Preparation
Textiles are torn and bleached to prepare them for chemical treatment.

Chemical Treatment
The cotton is treated with urea to form cellulose carbamate

Dissolution
The cellulose carbamate is dissolved in a sodium hydroxide solution to form a spinning dope

Spinning Dope Formulation
The dope may also contain various additives and nano-fillers to enhance fibre properties

Spinning
The spinning dope is extruded through spinnerets into an acidic bath, similar to the viscose process

Coagulation
The fibre starts to coagulate and solidify in the acidic bath

Post-Processing
Process: Washing, stretching, other treatments
Output: Final fibre with desired properties

1 https://nousfibreconsulting.com/production-of-man-made-cellulose-fibres-in-the-cross-roads/

Fibres obtained by cold alkaline solution

A cold alkaline process (Modified alkaline process) would involve using a cold, basic (alkaline) solution to dissolve the cellulose from wood pulp. It has several advantages, such as reduced climate impact, reduced chemical demand and reduced toxicity compared to traditional methods.

The environmental benefits arise from using non-toxic solvents and the potential for closed-loop production, where all the solvents and water used can be recycled.

However, the specifics of the process – like which alkaline chemicals are used, how the solution is prepared, and how the fibres are ultimately spun – would determine its feasibility and efficiency.

Tree To Textile AB has patented methods for turning cellulose into fibres. The patents are based on using the physico-chemical method, which has been developed for producing cellulose fibre based on wood pulp. This is achieved by injecting an aqueous cold alkaline spin-dope solution or suspension into an alkaline spinning bath.[1]

Based on the company's patented methodologies, the production process begins with the preparation of a cellulose slurry. This slurry is a well-balanced blend of several key ingredients: a cold aqueous solution of sodium hydroxide, and an activated cellulose that has undergone prior treatment.[2]

The spinning solution, commonly referred to as ”spin dope”, contains sodium hydroxide.

Polymer additives can have role in the fibre-making process, particularly in enhancing the mechanical strength and elongation of the final fibres.[3]

The processing of this spin dope is not restricted to any particular technique. However, it can be carried out by any established method known in the field for dissolving cellulose in a cold alkali solution. This flexibility in production allows for potential optimization and scale-up.

Notable Features

- Eco-Friendliness: The methodology appears to prioritize environmental sustainability, utilizing cold alkali solutions.
- The process includes a recovery system for water and chemicals.
- The production cost is low. It is designed to have low energy demand and low chemical consumption, at least 33% energy, at least 80% lower water usage, and at least 70% less chemicals than conventional viscose process.
- Customization: The technique allows for the inclusion of various additives, offering the capability to produce specialized fibres.
- Flexibility in production allows for potential optimization and scale-up.
- The method provides an innovative and potentially more sustainable way to produce high-quality regenerated cellulose fibres.

Wood pulp

Raw Material Preparation
Input: Wood pulp
Process: Physico-chemical treatment
Output: Activated cellulose

Preparation of Spin Dope
Inputs: Activated cellulose, sodium hydroxide
Process: Dissolution in cold alkali
Output: Spin Dope

Spinning
Input: Modified Spin Dope
Process: Injection into spinning bath
Output: Coagulated fibre

Coagulation Bath
Inputs: Diluted sodium hydroxide, optional salts and compounds
Process: Coagulation of fibre
Output: Regenerated cellulose fibre

Post-Processing
Process: Washing, stretching, other treatments
Output: Final fibre with desired properties

1 https://treetotextile.com/
2 https://nousfibreconsulting.com/production-of-man-made-cellulose-fibres-in-the-cross-roads/
3 “Regenerated cellulosic fibres spun from an aqueous alkaline spindope”, World International Intellectual Property Organization, WO2018169479 A1.

Fibres obtained by ionic liquids process

Ionic liquids are essentially salt in a liquid state, often at room temperature, and have the ability to dissolve a variety of polymers, including cellulose. The process offers several advantages over conventional methods, such as being more environmentally friendly, efficient, and versatile.

Notable Features

- Solvent recycling: one of the major benefits of using ionic liquids is that they can be easily recycled, significantly reducing the environmental impact of the process.
- Reduced harmful emissions: unlike volatile organic solvents, ionic liquids don't evaporate, which reduces harmful emissions into the atmosphere.
- Superior dissolution: ionic liquids can dissolve a variety of biopolymers, not just cellulose, offering flexibility in raw material selection.
- Quality and consistency: the high degree of control over the dissolution and spinning process allows for consistent and high-quality fibres.
- Energy efficiency: the process is generally more energy-efficient compared to traditional methods, mainly because of the lower temperatures required and the solvent recycling capabilities.
- Customization: by selecting specific ionic liquids or by mixing them, researchers can tune the properties of the fibres for specific applications.
- Environmental compliance: the ionic liquid process aligns well with the push for greener, more sustainable textile manufacturing methods and tend to be compliant with environmental regulations.
- Material versatility: beyond cellulose, ionic liquids can be used to process a variety of materials, including proteins, synthetic polymers, and more, opening up avenues for new types of fibres.
- The Ionic liquid cost limit the scale-up of the process, hence the need to recover them.

Cellulosic or other polymer-based materials

Raw Material Preparation
Input: Raw Cellulose/Polymer
Action: Cleaning, refining
Output: Prepared Cellulose/Polymer

Dissolution in Ionic Liquid
Input: Prepared Cellulose/Polymer
Action: Mixing with Ionic Liquid
Output: Homogeneous Solution

Homogenization
Input: Homogeneous Solution
Action: Stirring/Mixing
Output: Fully Homogenized Solution

Spinning
Input: Fully Homogenized Solution
Action: Extrusion through Spinneret
Output: Spun Fibres in Coagulation Bath

Washing and Recovery
Input: Spun Fibres in Coagulation Bath
Action: Washing and Ionic Liquid Recovery
Output: Washed Fibres + Recovered Ionic Liquid

Post-Processing
Process: Washing, stretching, other treatments
Output: Final fibre with desired properties

Fibre from Microfibrillated Cellulose

Microfibrillated cellulose (MFC) is composed of aggregates of cellulose microfibrils. These microfibrils have a small size, which results in a high volume and a large surface area. MFC is produced through a homogenization process. The diameter of microfibrillated cellulose (MFC) fibres falls within the nanometer range, specifically 20 to 60 nm, while their length spans the range of micrometres and can vary depending on the method used to produce it. MFC is composed of a bundle of 10–50 microfibrils. They exhibit both amorphous and crystalline parts and present a web-like structure usually stored as water suspensions.[1,2]

An innovative process developed by Spinnova® enables the production of a high-concentration aqueous dispersion (MFC) comprising both pulp fibres and micro-fibrillated cellulose.[3]

Remarkably, this method eliminates the need for a dissolving step and directly yields to textile fibre. The process include the use of a specialized nozzle that induces turbulent flow, enhancing the binding between the cellulose molecules.[3]

The process is highly versatile and can accommodate various sources of cellulose, such as soluble cellulose, paper pulp, and even cereal straws.

Notable Features

> No dissolving process and coagulation.
> The technology allow for raw material from a broad spectrum of sources, from paper pulp to cereal straw, making it resource-efficient.
> It is an exceptionally innovative, non-traditional and advanced process.
> The MFC fibre has unique properties compared to regenerated cellulose fibre.
> This method can be used for making micro fibrillated fibres from protein and wool-based materials.[4]

MFC Production Process
Raw Material Preparation Input: Various sources of cellulose (e.g., soluble cellulose, paper pulp, cereal straw)
High-Concentration Aqueous Dispersion Process: Combine pulp fibres and micro-fibrillated cellulose
Specialized Nozzle Process: Induce turbulent flow with a specialized nozzle
Gel Formation Output: Formation of a strong gel
Drying Process: Drying of the gel Output: filament

1 P.A. Larsson, A.V. Riazanova, G. Cinar Ciftci, et al. Towards optimised size distribution in commercial microfibrillated cellulose: a fractionation approach. Cellulose 26, 1565–1575 (2019). https://doi.org/10.1007/s10570-018-2214-4

2 N. Lavoine, I.Desloges, A. Dufresne, J Bras. 2012. Microfibrillated Cellulose - Its Barrier Properties and Applications in Cellulosic Materials: A Review. Carbohydrate Polymers. 90. (2012). doi:10.1016/j.carbpol.2012.05.026

3 https://spinnova.com/

4 "Method and apparatus for manufacturing a staple fibre based on natural protein fibre, a raw wool based on the staple fibre, a fibrous yarn made of the staple fibre, a non-woven material made of the staple fibre and an item comprising the staple fibre, World International Intellectual Property Organization, WO 2018/149950 AI.

Paper yarns

Paper yarn is a type of yarn that is made from paper strips by a twisting process. This process has been used for centuries in Japan, where it is known as "washi". Paper yarn has recently been highlighted as a new material suitable for textiles.

The process of making paper yarn is simple: moist wood pulp is cut into fine strips and then spun into yarns. The thickness of the yarn depends on the size of the strips used:

> Textiles: home décor items like curtains, rugs, and upholstery.
> Fashion: garments, it is usually blended with other yarns (such as linen) for added strength.
> Crafts: popular in scrapbooking, weaving, and other craft projects.
> Packaging: sometimes used in specialty packaging due to its unique texture and appearance.
> Industrial uses: occasionally used in technical textiles where high tensile strength is not a primary concern.

The paper yarn has some limitation Limitations due to:

> Moisture sensitivity: unless specially treated, it is sensitive to moisture and may degrade more quickly when wet.
> Cost: the production process can be more labor-intensive, which often make it more expensive than other types of yarn.
> Limited applications: limitations of certain properties result in that paper yarns are not a direct substitute for traditional yarns in many applications.

Shutterstock

Raw Material
Wood, Recycled Paper, or other Cellulose Sources

Pulp Preparation
Pulping Process, Chemical Treat-mentsWashing and Cleaning

Paper production

Cutting to strips

Spinning/Twisting

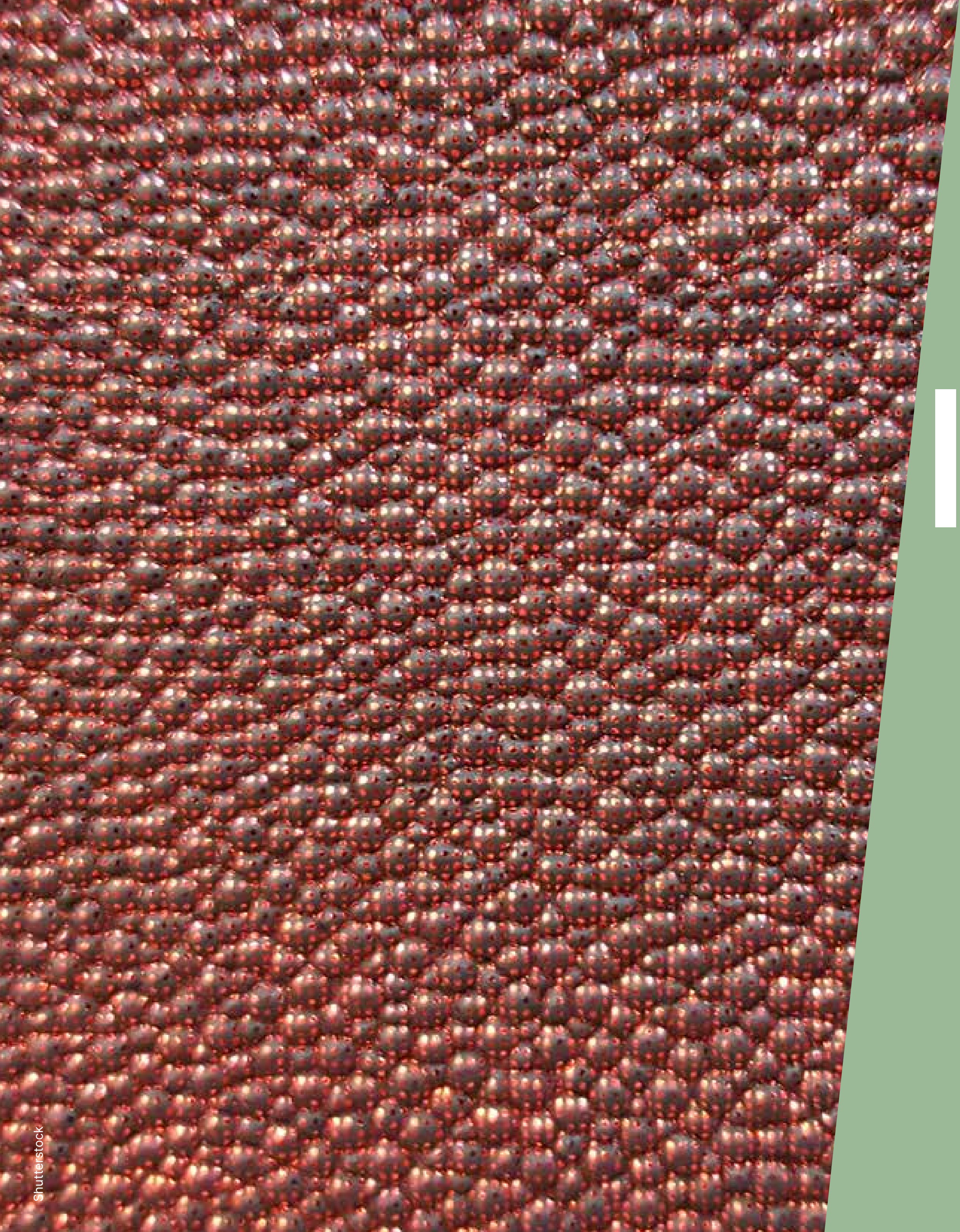
Post-Processing

Fungal threads / yarns[1]

While several types of cellulose-based man-made fibres are already found in the market, other type of bio-based man-made fibres are still under development. One example of such innovative fibre is fungal thread that is spun from the fibrous fraction of fungal cells i.e., fungal cell wall. Structurally fungal thread contains biopolymers such as chitin and chitosan that are the building blocks of fungal cell wall. Filamentous fungi can be cultivated low-cost organic material such as food waste in bioreactors, in a scalable bioprocess (submerged cultivation). Recently, a continuous thread has been spun from fungal cell wall. The obtained thread has shown promising aspects for medical applications, such as biocompatibility against skin cells, wound healing effect, and antibacterial properties. The potential of fungal thread for other textile applications yet must be explored. Fabrication of renewable fungal thread, in an environmentally friendly process, from abundant food waste opens up new possibilities for creations of sustainable man-made fibres.

As an innovative material obtained from a sustainable source, the impacts and benefits of fungal threads is yet to be studied.

1 https://www.hb.se/en/research/research-portal/projects/sustainable-fungal-textiles-a-novel-approach-for-reuse-of-food-waste/



Imitation Leather

Man-made fibre

There are several types of synthetic alternatives to genuine leather. More common materials, including thermoplastic polyurethane (TPU), polyurethane laminate (PUL) and polyvinyl chloride (PVC), are often used for jackets, handbags, shoes and upholstery, and were developed as inexpensive alternatives to leather. These materials are man-made synthetic products.

Benefits and potential impacts

	Descriptions	Benefits	Impacts
Thermoplastic polyurethane (TPU)	Heat bonding lamination process where no solvents are necessary. Two types of TPU are common: polyester based and polyether based.	Can be waterproof and weigh lessthan genuine leather. • Can be constantly reused,which is why it's often used fordisposable diapers. • Could be considered "animalfriendly" since it is not derivedfrom the hide of a cow. • These products have the visualaesthetics of genuine leather, butat substantially less cost.	• Less durable than genuine leather. • The base material used to form polyurethane compounds is aby-product of the oil refining process. • Almost all commercial grade polyurethanes availableare based on two different isocyanates: TDI (toluenediisocyanate) and MDI (methylene bisdiphenyl diisocyanate). • TDI is considered a volatile organic compound (VOC) and has acute and chronic effects on humans. • Not biodegradable. • Not recyclable.
Polyurethane laminate (PUL)	A polyurethane coating is laminated onto fabrics such as polyester or cotton, and uses solvents in a chemical bonding process.	• Durable, waterproof, flexible. • Can be constantly reused. • These products have the visualaesthetics of genuine leather, butat substantially less cost. • Could be considered "animalfriendly" since it is not derived from the hide of a cow.	Impacts are the same as TPU above.
Polyvinyl chloride (PVC)		• Polyvinyl chloride (PVC) is aversatile plastic that can take on avariety of characteristics – rigid,filmy, flexible and leathery – with relatively limitless applications. • Could be considered "animalfriendly" since it is not derivedfrom the hide of a cow. • These products have the visualaesthetics of genuine leather, butat substantially less cost.	• Less durable than genuine leather. • Dioxin (the most potent carcinogen known), ethylenedichloride and vinyl chloride are emitted during theproduction of PVC and can cause acute and chronic healthproblems, including cancer, endocrine disruption, andreproductive and immune system damage. • Chemical stabilizers are necessary in the creation of PVC,including lead, cadmium and organotins. Phthalates areused to soften PVC. Certain phthalates have been banned inthe European Union, such as DEHP, BBP and DBP, and areknown to cause acute and chronic health problems, and arepossible carcinogens. • During use, dioxins and phthalates can leach, flake or outgasfrom PVC over time, again emitting dioxin and heavy metalsinto the air, water and land. • Fibre is less breathable than polyurethane. • Not biodegradable.

Optimize sustainability benefits

- Promote suppliers who use alternatives to PVC.
- Promote suppliers who use water-based solvents for Polyurethane laminate (PUL).
- Investigate “vegan leathers” made out of polyester or polyamide microfibre, which could allow them to be recyclable.
- Consider using 100% genuine leather that utilizes low-chrome tanning, non-chrome tanning or vegetable tanning processes.

Availability

Vegetable, low- or -no-chrome tanned leather is readily available.
Water-based solvents for PUL are currently being researched.
Microfibre made out of synthetics, such as polyester, are readily available.

Applications

Chrome tanning still provides the softest quality leather most suitable for high end clothing.

Vegetable tanned leather is applicable to bags, belts and some shoes.

Laminated leather is applicable for belts, shoe soles and furniture upholstery, though it could be creatively applied to bags.

Microfibre for leather substitutes made out of polyester is applicable for shoes, handbags and upholstery.

Microfibres for leather substitutes made out of 100% chemically recycled polyester is available through Toray in the United States.

More sustainable options

Vegetable tanned leather or “naturally tanned” leather If vegetable or naturally tanned. post-consumer recycled leather If from used garments.

100% recyclable If polyester or polyamide microfibres are used, and an infrastructure to collect products and garments is in place.

NOTE: Simply saying “vegan leather” is not enough to substantiate sustainability claims, since these processes are generally derived from petroleum and can be both toxic and carry a significant climate impact.

Innovation opportunities

1. At the product design stage, consider what will happen to imitation leather products at the End of Use stage of the lifecycle. Design products that address longevity, recyclability, biodegradability, disassembly for reuse, etc.
2. Explore innovative products made from imitation leather that specifically address toxicity during production and use.
3. Work with partners to develop closed loop recycling of imitation leather products.
4. Design products where all materials and component parts are fully and safely recyclable. Partner with textile recycling facilities to guarantee effectiveness of recycling ability. Set up infrastructure to collect used or obsolete products. Communicate the proper route of disposal to consumers through Point-of-sales (POS) and hangtags.
5. Use recycled leather collected from tanneries to create modular accessories or patchwork pieces; or use in trims on garments.

Other substitutes to genuine leather

PU SPLIT LEATHER

PU split leather, also known as “PU split,” comes from the same hide as 100% genuine leather. The hide is prepared and tanned. Since the hide is too thick to use on its own, it is split into layers: the top layer is of the highest quality, and is considered pure leather. The lower layer, called “split,” is also considered 100% genuine leather and looks like suede. For the processing of PU split leather, the tanner applies a thin layer of polyurethane (PU) with foil or extrusion that hardens on top. A hair cell pattern can be embossed on the PU layer so that it looks like genuine leather. PU coated split leather is not considered 100% leather.

BONDED LEATHER

Bonded leather also comes from the same hide as 100% genuine leather. The hide is prepared and tanned. Small pieces of leather that are cut away from the final usable piece are combined with composite materials and spread out in sheets. Foil is put on top to resemble the top layer of leather. Bonded leather is to 100% genuine leather as particle board is to wood. Bonded leather is not considered 100% leather.

Biobased imitation leather

Biobased imitation leather, which completely or partly is made from renewable plant-based materials is expected to be more environmentally friendly than the synthetic imitation leather. While some of the biobased imitation leathers already exist in the market, research is ongoing to develop innovative imitation leather with higher content of renewable materials. Generally, two different approaches are followed to develop biobased imitation leather:

1) Plant based biomass (such as fibres of pineapple and cactus leaves, or apple waste from juice or cider production) are mixed with a polymer such as polylactic acid or polyurethane to form a composite that serve as a base material for the imitation leather. Presence of the waste derived renewable plant-based materials in this composite results in a more environmentally friendly composite compared to natural leather, which is used for different applications in the fashion industry. Presence of the synthetic polymers which binds the plant-based fibres means that the obtained imitation leather is still not 100% biobased. Sometimes, plant-based biomass, such as bark from cork oak trees are used to prepare thin sheets, and a fabric backing, such as a cotton fabric, is applied to the sheets. The sheet is then used as the base material for imitation leather.

2) In the second approach a web of interconnected nano or microfibres is created during cultivation of microorganisms and is used as a base material for creation of imitation leather.

   Bacterial nanocellulose is an example of such a material, which is a porous knit-like mat of cellulose nano-fibres obtained in the fermentation process of cellulose producing bacteria. Formation of bacterial cellulose often takes several weeks.

   Another example is fungal mycelium, which is a network of branched microfibres of fungi. Often solid-state cultivation under controlled condition of temperature and humidity is used to grow fungi on a plant-based and nutrient rich substrate to form a cohesive network of fungal microfibres around the substrate residues. Formation of mycelium network through solid-state fermentation also often takes several weeks.

Submerged cultivation is an alternative method for fungal growth that shorten the cultivation times to a few days. In this method, the fungal biomass is grown as dispersed mycelium and therefore is not directly harvested in the form of a sheet. therefore, a wet laying process is used to form sheets from fungal biomass. Both bacterial nanocellulose and fungal mycelium sheets need to undergo some post-treatment processes to enhance the material flexibility, strength, and durability. This can include treatments with vegetable tannins, applying plasticizers, surface coating with a reinforcement layer, or using fabric backing (which can be based on synthetic or natural fibres).

While some of the biobased imitation leather already is in the market, and used in garment and accessories, footwear, automotive and furniture applications, research is still ongoing in order to optimize the sustainability aspects of these materials by reducing the share of the non-renewable phases and enhancing the material performance to make it compatible with natural leather.

Part 5: Technical and high-performance fibres

Introduction

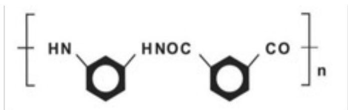
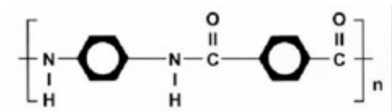
High-performance fibres, also known as technical fibres, have played a key role in the development of many technical textile applications. These fibres have been engineered with properties such as high tensile strength, high-modulus or to withstand extreme temperatures or resist chemicals.[1]

Aramid fibres

Aramids or aromatic polyamides is a group of synthetic high-performance fibres. There are two types of aramids, p-aramid and m-aramid made from slightly different building blocks. As a result, the fibres have different properties as shown in table 1. The most common trade names for p-aramid fibres are Kevlar® by DuPont, Twaron® by Teijin Aramid, Heracron® by Kolon Industries and Taparan® by Yantai Tayho Advanced Materials. Well known trade names for m-aramids fibres are Nomex® by DuPont and Newstar® by Yantai Tayho Advanced Materials.

Aramid kevlar.
Photo by Shutterstock.

TABLE 1. Typical fibre properties of aramid fibres[2]

Property	m-aramid	p-aramid
Tenacity (mN/tex)	485	2030-2100
Initial modulus (N/tex)	7,5	49–75
Elongation at break (%)	35	1.3-3.6
Decomposition temperature (°C)	415	550
Chemical structure		
CO_2 footprint	n.a	8.7 kg CO_2 -eq/kg*

*From the manufactures' leaflets of Twaron®

Benefits

P-aramid fibres are known for their exceptional high strength and impact resistance and commonly used in applications where low weight is desirable. In addition, p-aramid exhibits high heat and flame resistance, good chemical resistance, and high cut resistance. As a result, applications made from p-aramid fibres can contribute to energy efficiency, as they can reduce the overall weight.

M-aramid fibres showcase remarkable high-temperature resistance and stability. These fibres have led to the creation of materials tailored for specific industrial heat-resistance applications. When used in personal protective clothing (PPC) they contribute to enhanced durability and safety of humans working for instance in the fire brigade. When M-aramid based fabrics are exposed to flame or a high heat source, they undergo a process known as

1 Fei, B. (2018). High-performance fibres for textiles. In Engineering of High-Performance Textiles (pp. 27-58). Woodhead Publishing.
2 Hearle, J.W.S (2021) High performance fibres, Ed, CRC Press: New York, p. 35

thermal degradation. As a result, the fabric begins to shrink when it comes in contact with a high heat source and produce a thick char, which act as the thermal barrier.[3] Due to their inherent flame and heat resistance, the fibres do not need to be treated with harmful flame-retardant chemicals, which can emit harmful substances into the environment. Fabric composed of m-aramid fibres are also noted for their chemical resistance. Compared with p-aramid fibres, m-aramid fibres have lower tensile strength and higher elongation resulting in a fabric with a softer hand feel.

Both p-aramid and m-aramid fibres are associated with durability. As a result, applications made of aramid fibres are longevity and can thereby reducing the need for frequent replacement.

Potential impacts

Petroleum-based feedstock: Aramid fibres are made from non-renewable petrochemicals which in general are considered as no good for the environment as this contributes to environmental pollution due to its high carbon emissions.

Production process: The production of aramid fibres is energy intensive. It involves complex chemical processes, including the use of hazardous substances. Some of those substances are sulfuric acid ($H2_{S}SO_{4}$), caustic soda (NaOH), N-Methyl-2-pyrrolidone (NMP), Dimetyletanamid (DMAc), dimetylsulfoxid and tetrahydrofuran (THF), which all are commonly used in the chemical industry.[4] When not handling these chemicals properly and if discharged untreated they can pollute the environment near the manufacturing site.

Health issues: Some solvent used to produce m-aramid fibres like NMP is reprotoxic.[5]

Dyeing: Aramid fibres are inherently difficult to dye. However, meta-aramid fibres can be dyed with the help of a dyeing accelerate, a so-called carrier, which allow the dyestuff to penetrate the fibre. Many carriers, e.g., benzyl alcohol, benzylaldehyde, acetophenon, used to dye m-aramid are associated with numerous health issues as well as environmental concerns.[6]

Non-biodegradable: Aramid fibres are non-biodegradable, which means they persist in the environment for a long time when discarded. During production and when in use, aramid fibres can shed microfibres and thus contribute to the pollution by/spread of microplastics.

End-of-use: Recycling options for aramid fibres are still limited, why they mostly end up in landfills or incineration facilities at the end of their life cycle.

Availability

OEKO-TEX® Standard 100 certified aramids both types, p-aramid and m-aramid, are available. Manufacturers can be found at: www.OEKO-TEX.com[7]. Teijin Aramid has developed a p-aramid fibre, Twaron®, using a small fraction of recycled feedstock[8]. General Recycled™ are offering mechanical recycling of post-consumer aramid fabrics. They can weave and knit with aramid yarn containing up to 15-20% post-consumer fibres.[9]

3 Shaker, K., Nawab, Y. (2020). Fibres for Protective Textiles. In: Ahmad, S., Rasheed, A., Nawab, Y. (eds) Fibres for Technical Textiles. Topics in Mining, Metallurgy and Materials Engineering. Springer, Cham. https://doi.org/10.1007/978-3-030-49224-3_4

4 Jassal, M., Agrawal, A. K., Gupta, D., & Panwar, K. (2020). Aramid fibres. Handbook of Fibrous Materials, 207-231.

5 Substance Information - ECHA (europa.eu)

6 Opwis, K., Celik, B., Benken, R., Knittel, D., & Gutmann, J. S. (2020). Dyeing of m-Aramid fibres in ionic liquids. Polymers, 12(8), 1824.

7 www.OEKO-TEX.com

8 First industrial-scale production of Twaron® using recycled material (teijinaramid.com)

9 General Recycled gives new life to FR industrial workwear - PCIAW®

Applications

M-aramid fibres are widely used in the manufacturing of fire and heat resistant clothing for firefighter, oil refinery workers, military, police personnel and racing suits. P-aramid fibres are best known for being used in bullet-resistance vest and vehicles, automobiles tires, mooring lines, and in the telecommunications industries.

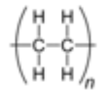
Innovation oppertunites

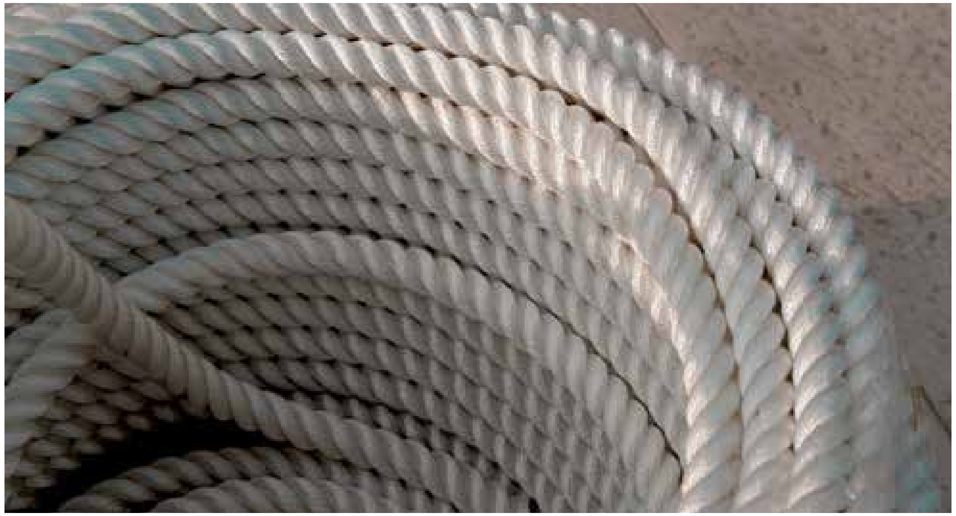
> Use dope-dyed aramid fibres to avoid that toxic carrier residuals from dyeing ends up in the environment through the wastewater.
> When blending p-aramid with m-aramid use the same colour tone to avoid miscoloured/frosty surface appearance after washing. This will increase the longevity of the fabric or garment.
> Use aramid fibres when both heat resistance and weight reduction of the final product is important.
> Design products and garments that are easy to dismantle for recycling and avoid fibre blending to allow the industry to become circular.
> Invest in recycling technologies for aramid fibres.
> It is also further encouraged that manufacturers of aramids are calculating and communicate the carbon footprint of their fibres.

UHMWPE Fibres

UHMWPE stands for Ultra-high Molecular Weight Polyethylene. It is a thermoplastic material and is chemically identical to other polyethylenes such as low density and high-density polyethylene (LDPE and HDPE) but has a much higher molecular weight. UHMWPE is known for its exceptional strength and durability in relation to its weight.[1] Some typical properties of UHMWPE fibres can be found in table 2 below. Two well-known trade names of UHMWPE fibres are Dyneema® by Avient former DSM and Spectra® by Honeywell.

TABLE 2.
Typical fibre properties of UHMWPE filament yarns[2]

Tenacity (mN/tex)	Initial modulus (N/tex)	Elongation at break (%)	Chemical structure
2600-3700	75-120	2.9-3.8	



Shutterstock

1 Hearle, J.W.S (2021) High performance fibres, Ed, CRC Press: New York, p. 62
2 Hearle, J.W.S (2021) High performance fibres, Ed, CRC Press: New York, p. 69

Benefits

High-strength-to-weight ratio: UHMWPE fibres are exceptionally strong, even stronger than steel on a weight-for-weight basis. This makes the material ideal for applications where high strength is essential and weight needs to be minimized.

Low-density: UHMWPE fibres have low density, which is beneficial in industries like aerospace, where reducing weight is critical for fuel efficiency and performance.

Abrasion resistance: UHMWPE fibres have excellent abrasion resistance.[3] Products made from the fibres will therefore last longer and requires less frequent replacement.

High UV resistance: UHMPWE fibres have high resistance to UV and is therefore a most suitable fibre to use in application exposed to sunlight. The material's lifespan will not be affected and thus the frequency of replacement can be reduced.

Potential impacts

Petroleum-based feedstock: UHMWPE fibres are derived from petroleum-based feedstock, which raises concerns about their contribution to greenhouse gas emissions during the production process.

Production process: The production of UHMWPE fibres typically involves a process known as gel spinning which requires the use of solvents. Paraffin oil[4] (also known as mineral oil or liquid oil) and decalin are commonly used solvents. If the solvents are released into the environment, they can have adverse effect on ecosystems. They are not readily biodegradable and their persistence in water bodies or soil may lead to environmental contamination.

Non-biodegradable: Like other synthetic fibres, UHMWPE fibres are non-biodegradable and can shed microfibres during production and use, contributing to microplastic pollution in the environment.

End-of-use: While UHMWPE fibres are recyclable, the recycling process can be complex and costly. The availability of recycling facilities for these fibres are unfortunately limited.

Availability

Clariter has developed a technology where they can chemically recycled UHMWPE into applications such cleaning agent, degreasers, paint, and speciality wax.[5] However, recycled fibres are still not available to purchase for commercial use. Avient offer UHMWPE fibres under the name Dyneema® made from feedstock sourced from bio-based raw materials.[6] According to the manufactured themselves the bio-based Dyneema® emits five metric tons less CO_2 per metric ton fibre produced compared to conventional Dyneema®.[7]

Applications

UHMWPE fibres are used in a variety of industrial applications such as ropes, bullet-resistance vest, cut resistance gloves etc. The fibres are also often used to make fabrics stronger which is a key feature in garments such as cycling jersey and motorcycle protection.

3 Ultra-High Molecular Weight Polyethylene Fibre (honeywell.com)
4 Substance Information - ECHA (europa.eu)
5 Clariter
6 Bio-Based Dyneema® Fibre
7 brochure-bio-based-dyneema-fibre (1).pdf

Innovation oppertunites

- To maximize the sustainable benefits of UHMWPE fibres, it is essential to invest in efficient recycling technologies and develop renewable sources of feedstock.
- Exploring alternatives to offer a biodegradable UHMWPE could be a sustainable solution in applications such as fish lines to minimize issues related to ghost fishing and microplastic pollution.
- When strength is a limiting factor of other materials, UHMWPE is a good alternative. As the use of the yarn can reduce the weight of a final product is yet to be explored in many other applications, such as composites for transportation vehicle, or further as kites[8] to harness wind to use for transport ships etc.

8 Seawing - (airseas.com)

Carbon Fibres

Carbon is a high-performance fibre made from precursor fibres such as polyacrylonitrile (PAN) or from petroleum pitch. Carbon fibres has gained popularity primarily due to their properties such as exceptional heat resistance, strength-to-weight ratio, fatigue resistance and absorbing vibration. The fibres final properties vary depending on its starting material and process of manufacturing.[1,2] They are most common offered as a high strength type or as a high modulus type as shown in table 3 below. Some trade names are DIALEAD™ and Pyrofil™ by Mitsubishi, HexTow® by Hexcel and TORAYCA® by Toray.

TABLE 3.
Typical properties of carbon fibres

Fibre Type	Precursors	Tensile strength (MPa)	Tensile Modulus (GPa)	Elongation (%)
Standard modulus	PAN	3,530 – 4,900	230 – 240	1.5-2.0
High modulus	PAN	3,530 – 4,900	230 – 240	1.5-2.0

Obtained from the manufacturing leaflet of Torayca®[3]

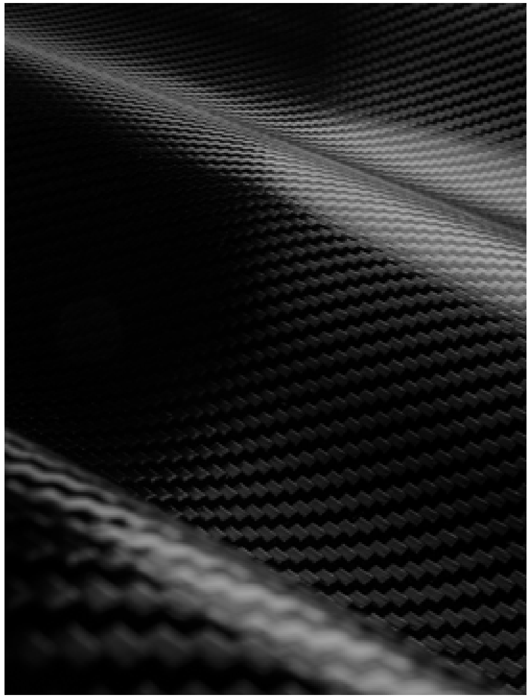
Shutterstock

1 Newcomb, B. A. (2016). Processing, structure, and properties of carbon fibers. Composites Part A: Applied Science and Manufacturing, 91, 262-282.

2 MInus, M., & Kumar, S. (2005). The processing, properties, and structure of carbon fibers. Jom, 57, 52-58.

3 Carbon-Fiber-Selector-Guide.pdf (toraycma.com)

Benefits



Strength-to-weight-ratio: Carbon fibres have a matchless strength-to-weight ratio, making them incredibly strong yet lightweight. This advantage is especially valuable in applications where weight reduction is critical, such as in the aerospace and automotive industries.

Stiffness: Carbon fibres are exceptionally stiff, providing excellent rigidity and stability to structures. Good stiffness can contribute to longevity since the need for repairs and replacements can be reduced, and eventually leading to reduced waste and resource consumption.

Fatigue resistance: Carbon fibres have good fatigue resistance enabling them to endure repeated loading and unloading without deteriorating and deforming overtime provided that the fibres are loaded in the fibre direction.[4] This is an advantage in applications such as sail constructions since it enables the creation of lightweight, stiff, and durable sails that will perform and last overtime.

High temperature tolerance: Carbon fibre has high temperature resistance allowing the material to keep their mechanical properties at elevated temperatures.

Corrosion resistance: Carbon fibres are highly resistance to corrosion, unlike metals. Carbon fibre-reinforced polymer (CFRP) materials are therefore a good alternative to steel reinforcement to improve the durability and safety of structures used in coastal areas with saltwater exposure.[5]

Potential impacts

Energy-intensive production: The manufacturing of carbon fibre is energy-intensive, involving high temperatures and chemical treatments. This can contribute to significant carbon footprint during production.[6] It is claimed that carbon fibre consumes 14 times more energy during manufacturing compared with steel.[7]

Production process: During the production process different chemicals are used. If they are not handled or discarded correctly, they can pose health risks to workers and can release harmful emissions during production. These chemicals are solvents used during the polymerisation of the PAN precursor yarn, catalyst to initiate reactions or oxidizing agents to improve the handling of the yarn.[8]

Petroleum based feedstock: The most common used precursor material to make carbon fibres is PAN followed by petroleum pitch which is based on non-renewable resources.

Non-biodegradable: Like other high-performance fibres and synthetic fibres, carbon fibres is non-biodegradable and can therefore shed microfibres during production and the use phase, contributing to the microplastic pollution.

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4 Mirdehghan, S. A. (2021). Fibrous polymeric composites. In Engineered Polymeric Fibrous Materials (pp. 1-58). Woodhead Publishing.

5 Vijayan, D. S., Sivasuriyan, A., Devarajan, P., Stefańska, A., Wodzyński, Ł., & Koda, E. (2023). Carbon Fibre-Reinforced Polymer (CFRP) Composites in Civil Engineering Application—A Comprehensive Review. Buildings, 13(6), 1509.

6 MInus, M., & Kumar, S. (2005). The processing, properties, and structure of carbon fibers. Jom, 57, 52-58.

7 Isa, A., Nosbi, N., Che Ismail, M., Md Akil, H., Wan Ali, W. F. F., & Omar, M. F. (2022). A review on recycling of carbon fibres: methods to reinforce and expected fibre composite degradations. Materials, 15(14), 4991. 25 Bhat, G. (Ed.). (2016). Structure and properties of high-performance fibers. Woodhead Publishing.

8 Isa, A., Nosbi, N., Che Ismail, M., Md Akil, H., Wan Ali, W. F. F., & Omar, M. F. (2022). A review on recycling of carbon fibres: methods to reinforce and expected fibre composite degradations. Materials, 15(14), 4991.

End-of-use: Carbon fibre recycling is complex and not as established as recycling of other high-performance fibres. One method used to recycle carbon is a process called pyrolysis. During pyrolysis the material is exposed to elevated temperatures to decompose the composite matrix material and then recover the carbon fibre. The recovered carbon fibre can then be reused in non-critical structures or components.

Availability

Recycling of carbon fibres is still an evolving field, and there are challenges related to the quality of the recycled fibres, cost-effectiveness, and the scalability of recycling processes.[9]

Applications

The use of carbon fibre is almost exclusively as reinforcement in composites. In the aerospace and automotive industries carbon fibres are used for manufacturing parts such as the wings, fuselage sections, racing car bodies, interior elements etc. In sporting goods, they can be found in application such as golf clubs, sails, and tennis rackets. The civil engineers are using carbon fibre in constructions work as bridges and highway support columns.

Innovation oppertunities

> It is essential to consider trade-offs and make conscious decisions when choosing carbon fibres for various applications since alternative materials might offer comparable performance with lower environmental impact. A Life Cycle Assessment (LCA) is recommended to conduct of a product to evaluate its environmental impact from raw-materials to end-of life.

> Alternative renewable resources as precursor yarn are needed. Rayon was used in the past and lignin have been identified as an attractive source. However, more research needs to be conducted before lignin can compete with the properties achieved when using PAN.

> Scrap material (cut waste) is already recycled through mechanical recycling into nonwovens. Scrapped carbon fibres can also be explored in other applications that could benefit from the properties of carbon fibre.

> As the recycling technology and methodologies continue to advance, the potential for broader adaption of recycled carbon fibres in various industries can increase.

9 Isa, A., Nosbi, N., Che Ismail, M., Md Akil, H., Wan Ali, W. F. F., & Omar, M. F. (2022). A review on recycling of carbon fibres: methods to reinforce and expected fibre composite degradations. Materials, 15(14), 4991.

Part 6:
Wet processing

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Pre-treatment

Wet processing

Scouring & bleaching. Treatments that are done before dyeing or printing to improve fabric's water absorbency, cleaniness and whiteness are collectively called pretreatments.

Pre-treatment

Pretreatment is necessary to remove natural impurities from fibres such as dirt, seed materials, waxes, and natural colours (grey or yellowness). Pretreatments also help to make the fibre clean and water absorbent which are necessary for the next processes e.g. dyeing, printing, and special finishing processes. Common pretreatment processes include desizing, singeing, scouring, bleaching and heat-setting. However, not all the pretreatments are necessary for all types of fabrics. It depends on the type of fibre (natural or synthetic), fabric type (woven or knitted) and end-use of the fabric.

Desizing can be important for woven fabrics if 'sizing' coating has been used on warp threads. Desizing is used to remove the sizing materials (starch, gelatin etc.) and thus to make the fibres more water absorbent. This process step to remove sizing use a lot of hot water and detergents.

Singeing is the process used to remove unwanted protruding fibres from fabric surface. By removing such fibres, the fabric surface becomes smoother, cleaner and thus help to prevent pilling. This process is more common for fabrics made with fibres of short length. Singeing is done by passing the fabrics quickly over a flame or hot metal surface to burn out the protruding fibres and followed by washing. Thus, this step consumes high amount of energy such as gas or electricity.

Mercerising is a process used to increase tensile strength, dimensional stability and lustre cotton-based textiles. This process can also improve dye uptake of cotton and thus reduce dyestuff consumption. Mercerising can be carried out on yarn in hanks, woven and knitted fabric. There are several methods of mercerising, among them mercerising with tension and caustic soda (sodium hydroxide) are most common. Ammonia based mercerising are rarely used.

Scouring & bleaching

The aim of scouring and bleaching is to make the textile fabric or yarn cleaner and whiter. Traditionally, scouring and bleaching processes are done in two separate steps. Nowadays, there is a tendency to combine the two steps which can help to reduce the use of water, chemicals, energy and processing time.

Scouring

Fabric and yarns made from plants and animal sources may contain impurities like dirt, soil, seed and leaves particles, fat and wax etc. Synthetic fabrics may get oil marks during weaving or knitting. These impurities are cleaned during scouring to ensure better absorbency of water (hydrophilic) and chemicals for later processing steps. Conventional scouring process involves washing the cellulose-based textiles with soda, salt and detergents near boiling temperature of water. More advanced and environment friendly scouring can use enzymes (e.g. pectinase)[1] and plasma[2] treatment to reduce the water and energy usage.

Scouring steps for silk and wool fabric are known as degumming and carbonizing (pre-scouring), respectively. Raw silk filament contains a gum-like substance (sericin) which is removed during the degumming process by using soap solutions. In carbonizing process, the raw wool is cleaned by using mechanical combing and acid treatment. Wool scouring creates a lot of grease as a by-product and wastewater. Enzyme-based alternatives are available for both conventional degumming and carbonizing processes.

Bleaching and stripping

Natural fibres have a yellowish or greyish colour which is removed by the bleaching process. After bleaching fibres become whiter which is desirable for good dyeing and printing effects. This is especially important for colouring fabrics with lighter shades as they need to have a perfectly white background. Obviously, only bleached fabrics and garments can be sold as white colour items.

Removing colours from an already dyed fabric is called stripping and this is a separate process though it is often confused with bleaching. Stripping colour from a dyed fabric can be done partially or fully. Partial stripping is done to give the garment a vintage or faded design look such as on vat/indigo dyed denims. Full stripping can be done on a faulty coloured fabric to make it paler and then re-dye. Both bleaching and stripping include the use of extensive amount of chemicals and affect the textile quality e.g. strength, hand feel.

Different type of chemicals is used for the industrial bleaching and stripping processes. Common bleaching chemicals are oxidizing agents like hydrogen peroxide and stripping chemicals are reducing agents like hydrose. However, these chemicals

1 Sawada K, Tokino S, Ueda M, Wang XY, Journal of the Society of Dyers and Colourists 1998, 114,(11):333-336.
2 Marcandalli B, Riccardi C, in Plasma Technologies for Textiles, (Eds:Shishoo R.) Woodhead Publishing:282-300. 2007.

can be used for textile whitening as well. Normally, chemicals used for textile stripping are more aggressive than the bleaching chemicals. Since bleaching is a common process for all natural fibres, therefore some of the chemical and alternative bleaching methods are discussed below.

Chemical bleaching

Hydrogen peroxide

Nowadays, cotton and similar cellulose-based textiles are often bleached with hydrogen peroxide. This bleaching process is often done in higher pH (using soda) and under high temperature conditions. If necessary, cotton blends, wool and silk are also bleached using hydrogen peroxide but in lower concentrations. Hydrogen peroxide is economical, readily available and can be used for a wider range of fibres. It is safer than chlorine-based bleaching.

Impacts on environment

Hydrogen peroxide bleaching requires high temperatures, additional or helping chemicals and good washing after bleaching step which makes it a resource-intensive process. Hydrogen peroxide is relatively unstable during storage and requires chemical stabilizers like sodium silicate, magnesium salts which are strong water polluters.

Hydrogen peroxide bleaching can be done using a wide range of machine set-ups, including cold pad-batch, under steaming conditions and in a long chemical bath. Hydrogen peroxide can be used at lower temperature and pH compared to other bleaching chemicals and thus use less resources however it can result in less whiteness.

Chlorine derivatives

Chlorine-based bleaching chemicals are more aggressive than hydrogen peroxide and therefore these can ensure a greater bleaching effect. Some examples of such chemicals are sodium hypochlorite, chlorite/chlorate and chlorine dioxide gas. However, their use in industrial process is in decline due to ecological concerns.

Sodium hypochlorite bleaching process needs high pH but low temperature (about 30°C). It can be used to achieve a permanent white substrate or to remove colour from already dyed substrate (striping). This bleaching process can be done in different machine set-ups such as in batch (e.g. overflow, jet, jigger, winch beck), semi-continuous (pad-batch) or continuous mode.

Chlorite/chlorate is still used for synthetic fibres, cotton, flax and other cellulosic fibres, often in combination with hydrogen peroxide.

Chlorine dioxide gas works better on synthetic and less water absorbent (hydrophobic) textiles e.g. bast fibres such as flax, hemp. It can give better whiteness and cause less damage to the textiles. This gas is mixed into water to form the bleaching chemical and thus expensive to produce. Compared to other chlorine-based chemicals chlorine dioxide has less environmental impacts.

Impacts on environment

Chlorine is a halogen compound that in higher concentrations may harm aquatic life, human health and environment in higher concentrations. It can break down organic materials, accumulate in soil and affect our food chain. Wastewater coming from the sodium hypochlorite bleaching process can form complex compounds which are suspected to be carcinogenic (skin cancerous). Bleaching with a high concentration of hypochlorite may cause chlorine emission in air. Appropriate personal protection and care is necessary when working with the bleaching chemicals. Chlorine bleach can affect the fabric strength as well.

Alternative and emerging technologies for pretreatments

Ozone

Ozone (O_3), a molecule composed of three oxygen atoms, is a powerful oxidizing agent used in various applications in the textile industry. It is thermodynamically unstable and cannot be stored or transported and therefore must be generated on-site. Ozone is typically produced by passing oxygen through a corona discharge or UV radiation.

Ozone has diverse applications including bleaching, stripping, fading effects, wastewater treatment, odour removal, disinfection, and improvement of dyeing processes.[3] It offers several advantages such as high efficiency, reduced water and energy consumption, and eco-friendliness. Ozone reacts with chromophore groups and breaks chemical bonds responsible for colour in textile fibres. This oxidation process helps to remove or decolourize dyes. However, there are challenges related to equipment costs, safety measures, and potential fabric damage when implementing ozone-based processes in textiles.

Enzymes

Enzymes are proteins extracted from natural sources e.g. plants, fungi and animals. They are used in several wet processing like desizing, scouring and bleaching as an alternative or in addition to synthetic chemicals. Enzymes are biodegradable and friendlier to environment as they can be used at lower temperature, pH and concentrations compared to synthetic chemicals. However, the desired effects of most enzyme treatments are milder and thus economic feasibility of replacing synthetic chemicals with enzymes in industrial scale is not yet favorable.[4]

The most widely used desizing method for starch-based sizing agents is enzymatic desizing using amylases enzymes. They can rapidly break down starch into soluble materials which then removed by a hot wash process. Amylases from bacterial sources are the preferred enzymes due to their high efficiency.

Enzymatic scouring of cotton fabrics began in the 1990s as a more environmentally friendly alternative. Cellulases were found to be particularly suitable for this process, along with some other enzymes such as pectinases, proteases, lipases, and their mixtures. Pectinases are efficient in removing pectin, proteases target proteins, lipases act on oils and fats, and xylanases degrade hemicellulose. These enzymes selectively target specific impurities without causing any significant damage to the cotton fibre. The selection of enzymes is based on factors such as optimum pH and temperature, process time, and desired product quality.

Enzymes can also be used to help the bleaching processes due to their effectiveness and environmental advantages. However, certain misconceptions exist regarding the role of enzymes in bleaching mechanism. Enzymes like pectinase, lipase, or cellulase can help bleaching by improving fabric's water absorbency (giving scouring effect) but these enzymes have limited effects on whitening. Effective bleaching requires oxidizing agents and oxidation processes. Enzymatic bleaching can be achieved through three separate mechanisms: in situ generation of hydrogen peroxide, in situ generation of peracetic acid, and direct or indirect electron transfer using laccase enzymes. Therefore, the enzymes used for bleaching must follow any of these mechanisms.

Glucose oxidase (GOD) is an enzyme that generates hydrogen peroxide during the oxidation of glucose. It has been studied for bleaching of cotton fabrics, and it was found that oxygen aeration and high temperature and alkaline conditions can enhance enzyme's activity.

Cellobiose dehydrogenase (CDH) is another enzyme capable of generating hydrogen peroxide in situ. Certain mixtures of enzymes have been commercialized to assist bleaching process e.g. Gentle Power Bleach (GPB), PrimaGreen EcoWhite developed by Genencor/Danisco and Huntsman company.

Laccases are multi-copper enzymes that can oxidize various aromatic compounds. They have been tested for bio-bleaching of cotton and have shown potential in enhancing whiteness when combined with chemical bleaching. However, the efficiency of laccase-assisted bleaching alone is not sufficient, and require additional chemical bleaching steps.

Plasma technology

Plasma is known as the fourth state of matter, consisting of ionized gas with equal numbers of positively charged ions and free electrons. It is highly reactive and can be used to modify the surface properties of materials. Plasma technology finds applications in diverse industries, including textiles, automotive, medical, and electronics. In textiles, it is utilized for improved colouration, surface cleaning, and functionalization.[5] Plasma treatment offer several advantages over traditional wet processes, such as reduced water and chemical usage, shorter processing times, and contributes to environmental sustainability.

Plasma is created by applying energy to a gas, causing the gas atoms to release electrons and become ionized. Various methods, such as radiofrequency, microwaves, or corona discharge, can be used to generate plasma. Plasma treatment is employed in the textile industry to enhance the surface properties of fabrics. It helps improve

3 Ayşegül K, in Textile Industry and Environment, (Eds:Ayşegül K.) Rijeka IntechOpen:Ch. 2. 2018.
4 Andreaus J, Colombi BL, Gonçalves JA, dos Santos KA, in Advances in textile biotechnology, Elsevier:185-238. 2019.
5 McCoustra MRS, Mather RR, Textile Progress 2018, 50,(4):185-229.

dye absorption, adhesion, and wettability, leading to better printability and reduced pilling. Different fibres are treated with specific gases during plasma processing such as oxygen, nitrogen and inert gasses. This technology can be used to coat or deposit gaseous particles onto textiles as well. One major limitation of the technology is that the achieved effects are not permanent in nature (significantly declines with time and exposure to air). Therefore, more research is necessary to improve its potential.

Plasma technology is considered sustainable due to its eco-friendly nature, allowing for reduced chemical consumption, and energy efficiency. It aligns with the industry's increasing focus on environmentally friendly practices and reduces the ecological footprint of textile production. However, there is a lack of research and interest from industry to make this technology widely available. Suitable process conditions to treat various textiles fibres and structures are yet to be established.

Limited adoption of plasma technology in the textile industry is due to the costs of equipment and maintenance. There is lack of awareness and technical knowledge about applications and customization for plasma treatment of different textiles. Often, industry management are satisfied with existing wet processing infrastructure and are not willing to change to drastically newer technologies.

Technology availability

- Hydrogen peroxide is widely available globally.
- Chlorine derivatives are widely available but only used in exceptional needs.
- Ozone is relatively expensive, and the equipment is not widely available.
- Enzyme pretreatment technologies are readily available globally.
- Plasma equipment is available upon order request.

Innovation opportunities

- Design clothes and textiles that do not require extensive bleaching or whitening. Promote products that come in natural colours.
- Highlight alternative bleaching methods used by your company on a basic garment item.
- Find ways to combine several pretreatment steps.
- Evaluate possibilities of recovering and reusing of the chemicals after any treatment.
- Develop graphic symbols for hydrogen peroxide, ozone, enzyme, etc. for use in communication with the customer.

Optimize sustainability benefits

Opportunities	Considerations
Look for design opportunities to avoid bleaching.	Lighter, brighter shades need to be well bleached before colouring. Darker shades need less bleaching.
Promote suppliers who use alternate scouring and bleaching processes such as enzymes, plasma, or ozone.	Investment, availability and knowledge of these technologies.
Innovate and promote aesthetic values of textiles pretreated with alternate techniques.	Compare expected final effects with conventional pretreatment techniques.
Promote methods of combined scouring and bleaching steps to reduce water, chemical, energy usage, and processing time.	There can be a possibility of local variations and fastness issues of the alternate effects.
Promote suppliers who use low-temperature peroxide bleach processes, such as pad-batch systems.	Some fibre types and expected colour shades may require only scouring or to treat them separately.
Avoid chlorine bleaching as much as possible.	Pad-batch bleaching process is notably slower and needs considerable factory space for long durations.
Partial peroxide bleaching followed by mild chlorine treatment can reduce its use.	Demand for chemicals and required whiteness level need to be considered.
Promote proper wastewater treatment.	Setting up wastewater treatment plant is costly and water cleaning again needs the use other chemicals and biological agents. Thus, it is better to minimize chemical use from the beginning of textile processing.

Dyeing & printing

Wet processing

The goal of adding colour to a textile substrate is to produce and appealing, level, fast colour on a product at a reasonable cost with good performance and minimal environmental impact.

Dyeing & printing

Colourants

Colour is an important part of our culture and identity. Similarly, the colour of a fabric or garment greatly influences its appeal and marketability. Right colour, pattern, or print can be the only factor on buyer's purchasing decisions. A product with good fibre and fabric quality but having an unattractive colour may make it unmarketable. On the contrary, a poor-quality fabric can be sold out easily based only on its attractive colour features. Aside from its attractiveness, colour fastness is important to define the quality of products. Fastness means if the colour particles (dyes or pigments) are well fixed on the textiles and the ability of colours to not change over time or use. Products with poor fastness can become faded, bleed and stain colours on other textiles due to several reasons such as washing, sweat, sea water, sun light, rubbing and crocking etc.

Colour is a visual sensation or feeling to our brain. The actual particles or substances used to make something colourful are called colourants. Textile colourants are generally two types i.e. dyes and pigment. Dyes are smaller in size, water soluble and have substantively (attraction) to bond with many fibres. Comparatively, pigments are larger in size, less or not water soluble and have no substantively to fibres, however they produce a brighter colour appearance than dyes. Thus, one needs to choose between dyes and pigments depending on several factors such as fibre type, brightness, shade, fastness, end effect, machinery, cost etc.

Before the industrial revolution, textile colourants were limited to natural dyes and pigments obtained from plants, insects and minerals etc. Today we mostly use synthetic colourants that are formulated in a laboratory. The first synthetic dye was developed in 1856 and by the early 20th century, a wide range of synthetic dyes was readily available. Compared to natural colourants, the synthetic alternatives come in wide variety of shades, they are more consistent, have good fastness, are readily available and cheaper. About 10-50% of the dyes and pigments used in current textile industry ends up in the wastewater, which mean about one million tons.[1] Unfortunately, a large part of this wastewater is not treated or cleaned before releasing to the drainage system.[2]

It is a delicate process to add colours on a textile substrate e.g. fibre, yarn, or fabric. Variations in final colour result can be caused by irregularities in substrate structure, any defects, or impurities from previous processes and how many pre-treatments were done. Successful dyeing and printing require well knowledge and control of the chemistry between fibres and colourants. Dyes are either chemically reacted or trapped inside the fibre matrix to fix on textiles. Pigments attach on textiles with the help of another chemical i.e. binding agent.

Natural colourants

Natural colourants are extracted or collected from sources like plants, lichens (fungus and algae), mushrooms, insects, mollusk (oysters, snails) and minerals. Most dyes come from various parts of a plant such as roots, fruits, bark or leaves are used to extract colour materials. Variations in geographical location, climate and season at the sourcing of the colourant may cause colour variations even for the same type of plant. It is challenging to grow, produce and extract natural colours to meet current industrial scale demand with a reasonable cost and quality when compared to synthetic colourants.

A summary of common natural dyes

Colour effect	Chemical group	Source examples
Red	Anthraquinoid	Madder plant, lac insect (Laccifer lacca), Cochineal insect
Yellow/green	Flavonoids and tannin	Henna plant, pomegranate fruit, weld plant (Reseda luteola)
Brown	Naphthaquinoid, flavonoid	Black walnut, Clutch (wood extract of Acacia tree)
Blue	Indigoids	Indigo plant

Most natural colourants are now fixed or bonded to fibres by help of an additional chemical called mordant (or, tannin for cellulose). Mordants are usually a metal salt (aluminium or iron) that helps to make the natural dyes insoluble inside fibres.

1 Farah Maria Drumond C, Gisele Augusto Rodrigues de O, Elisa Raquel Anastácio F, Juliano Carvalho C, Maria Valnice Boldrin Z, Danielle Palma de O, in Eco-Friendly Textile Dyeing and Finishing, (Eds:Melih G.) Rijeka IntechOpen:Ch. 6. 2013.

2 Wastewater Recycling in Textile Industries. Earth.Org Ltd. Available at: . Accessed 26 July 2023.. Accessed 26 July 2023.

Protein fibres (especially wool) are easier to dye with natural colours, compared to cellulose fibres.

Natural dyes can be classified in two ways: i) Based on chemical groups (scientific name of the plant) ii) Dye class i.e. if the dyes are fixed with help of another chemical (mordant or tannin).[3]

Natural colourants have limited variety in their colour palette. Several colours need to be mixed to get a specific final colour effect. Slight shade variation occurs for each new batch of colour extraction and dyeing session. Therefore, colour repeatability and consistency is challenging. Use of mordant regulates proper fastness of natural dyes in textiles. However, fastness properties of natural colourants are inferior to synthetic colourants due to lack of strong chemical or mechanical bonding to fibres. Therefore, use of natural colourants are currently limited to artisan and niche design house products.

Potential Impacts

In the past, harmful chemicals were used for by dyers (or in dyeing) such as lead acetate, chromium and arsenic to achieve desired colour effect but now better and less harmful alternatives exists e.g. non-metal based mordant. It is important to avoid use of extra chemicals together with natural colourants to improve the final effect or fastness.

To extract a small quantity of dyes a good amount plants or insects are necessary. Therefore, it can influence crops production and wildlife if produced in large quantities.

It is important to think about the longevity and sustainability of the product. If the colour fades or leaches out after using and washing for several times then the cost and effort of producing the dyes will not be worthy.

Synthetic colourants

Synthetic colourants or dyestuffs are produced or synthesized through several levels of chemical reactions. The raw materials used to produce synthetic dyes are primarily derived from petrochemicals, which are obtained from crude oil. The main components used in the synthesis of synthetic dyes are aromatic hydrocarbons, such as benzene, toluene, and xylene, which serve as the starting materials. They are produced in a wide variety of shades with unlimited range of colour palette. Synthetic colourants are chemically designed in such a way that they can fix with fibres strongly. Therefore, their fastness properties are better than natural colourants.

Synthetic dyes are generally classified in two ways:

> **Chemicals class:** Azo, anthraquinone, phthalocyanine, vat dyes etc.
> **Dye-fibre bonding way:** Reactive dyes, disperse dyes, acid dyes, direct dyes, pigment dyes etc.

Synthetic dyes come in a numerous of variations, offering specific attributes like high light fastness, washability, and resistance to external factors. Within each dye class, manufacturers produce numerous variations to cater the diverse demands of fashion and textile applications. The global market for synthetic dyes and pigments in the textile industry estimated to be worth billions of dollars annually.

Different dyes are chosen based on the type of textile fibre. For instance, acid dyes are commonly used for protein fibres like wool and silk, while disperse dyes are suitable for polyester, nylon, and acetate fibres. Reactive dyes are preferred for cotton and other cellulosic fibres due to their excellent colour bonding. There are also some special or advanced application dyes such chromic and fluorescent dyes. Chromic dyes can change the appearance from one colour to another when trigged by certain stimuli i.e. change of pH, light source, temperature etc. Fluorescent dyes can improve colour visibility (reflex) or become visible only under certain condition such as exposure to UV light.

Potential Impacts

Despite their widespread use, the production and application of synthetic dyes raise environmental concerns. Synthetic colourants are difficult to remove from fibres and wastewater therefore creates great challenges on recycling and ultimately polluting the environment.

Reactive dyes are widely used for natural fibres like cotton however, they require use of large amount of salt and soda for proper effect. Disperse dyeing was previously done with the use of harsh synthetic carrier chemicals however, nowadays it is done with the help of energy demanding high-temperature and pressure processes. Acid

3 Boutrup J, Ellis C, The art and science of natural dyes: principles, experiments, and results. Schiffer Publishing, Limited. 2018.

dyes are considered less harmful than other classes of dyes, but their production may involve toxic substances. Direct dyes are cheaper and easy to apply with good colour fastness however, some direct dyes may contain heavy metals or other harmful chemicals that can leach into the environment if not managed correctly.

REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals) is a regulation set up (instituted) by the European Union that aims to protect human health and the environment from the risks posed by chemicals. For synthetic dyes used in textiles, REACH compliance is essential to allow import and use within the European Union market. Manufacturers and importers must ensure that the dyes meet the regulatory requirements, which include proper labelling, safe handling, and providing safety data sheets to downstream users.

Innovation opportunity

- Developing non-toxic dyes that do not contain harmful chemicals or heavy metals. These dyes should also be biodegradable, minimizing their impact on the environment when they eventually are disposed.
- Exploring and promoting the use of plant-based and natural dyes derived from renewable resources and that have lower environmental impacts compared to synthetic dyes.
- Designing dyes that have excellent light fastness properties, reducing the need for frequent re-dyeing and prolonging the colour durability of textiles.
- Utilizing biotechnology to develop dyes through sustainable and eco-friendly processes, reducing the need for harsh chemicals and hazardous intermediates.
- Potential of locally available natural dyes should be explored for better sustainability. Instead of looking for a specific colour effect, dyes from locally grown sources should be utilized.

Dyeing process

Purpose of dyeing is to ensure proper penetration of colourants well inside fibres with minimum or no change of hand feel. Difference between dyeing methods or end effects can be thought in several ways as below.

- **Dyeing styles:** The appearance after dyeing like solid (same colour everywhere), resist patterns (tie-dye, batik) or space dyed (several colours appearing side-by-side).
- **Stage of dyeing:** Depending on which stage or form the textile is coloured by e.g. fibre dyeing, yarn dyeing, fabric dyeing and garment or product dyeing.
- **Mechanism or chemistry of dyeing:** Reactive, disperse, acid or pigment dyeing

Textiles are dyed in fabric form as it is more stable, faster, easier to control, and more economic than the other forms. Fibres or filaments can be dyed in staple form (natural based) and during spinning (synthetic and regenerated). **Fibre or yarn dyeing** is used to produce fancy or stripe like effects. Different techniques of yarn dyeing are hank or skein dyeing, package or cone dyeing, rope dyeing and warp beam dyeing. They are chosen based on yarn source, quality, strength and end-use. **Bobbins injection dyeing** is a method of colouring different parts of a same bobbin with several colours. **Fabric dyeing** procedures are different based on fabric structure (woven or knit), fibre content (pure or blend) and machine setup (batch or continuous). **Garments colouring** is done to give special, worn-out or casual design looks. Garments dyeing replicate a washing process with colourant by using a paddle or rotary drum type machine.

The goal of a dyeing process is to ensure that maximum amount of colourant are well fixed with the textiles. Important control factors of dyeing chemistry are pH, temperature, time and use of helping or auxiliary chemicals (salt, dispersing, levelling chemicals etc). Selection of proper machinery, colourant concentration, water amount (liquor ratio) and proper movement of textiles during colouring process are also important. As low amount as possible of water, chemicals and energy should be used for a sustainable dyeing process with the possibility to recover and reuse resources.

Dyeing machines

Machine setup for dyeing can be broadly classified into two main types: batch dyeing and continuous dyeing. Each setup has its unique characteristics and is suitable for different production requirements.

Batch dyeing is a traditional dyeing method where a specific quantity of fabric or yarn is dyed in a closed vessel or container. The dye liquor is added to the vessel along with the textile material, and the dyeing is carried out until the desired colour is achieved. This process allows for better colour consistency and flexibility in dyeing smaller batches of textiles. Examples of some processes for batch dyeing machines are winch dyeing, jig dyeing, package or beam dyeing and jet dyeing.

Continuous dyeing is a modern and more automated dyeing method where the fabrics or yarns continuously pass through the dyeing machine. The dyeing process progress continuously as the material moves through the machine, allowing for large-scale and continuous production. Pad-Steam machines are most common continuous machine setups that utilizes a padding process to apply dye liquor to the textile material continuously. The dyed material is then subjected to steam to fix the colour quickly.

Both batch and continuous dyeing processes have their advantages based on factors such as the production volume, type of fabric or yarn, and required colour consistency. While batch dyeing provides better colour control for smaller quantities, continuous dyeing offers higher production efficiency for larger volumes of textiles and faster production speed.

Potential impacts of dyeing

The impacts of textile dyeing processes are influenced by several factors. Firstly, the choice of dyes used in the process can play a significant role. Some dyes may contain toxic substances or heavy metals, and their colour fastness properties may contribute to environmental concerns. Secondly, the auxiliary agents present in the dye formulations, which include chemical additives, can also have implications on the environment based on their composition and biodegradability. Moreover, basic chemicals like alkali, salts, reducing agents, and oxidizing agents used in the dyeing process can contribute to environmental issues depending on their properties and the way they are disposed. Lastly, contaminants present on the fibres, such as residues of pesticides in wool or spin finishes on synthetic fibres, may end up in the dyeing process, further impacting the overall environmental footprint.

Dyeing processes involving synthetic dyes, pose significant harmful impacts on the environment, ecology, and society. Certain dyes, like disperse dyes, contain toxic aromatic compounds that harm aquatic life and have a sensitizing effect on human skin. The use of dyeing carriers, often employed in the industry, poses further threats. The extensive use of salt in textile dyeing processes to improve dye absorption leads to the generation of large quantities of saline wastewater, causing environmental damage to water bodies and soil.

The chemicals used in dyeing, including heavy metals and toxic compounds, can contaminate soil and pose health risks to workers and nearby communities. Moreover, the energy-intensive nature of dyeing contributes to greenhouse gas emissions and climate change, exacerbating the global environmental crisis. Improper management of waste generated during dyeing further adds to environmental contamination, filling landfills and releasing harmful substances into the environment.

More research, innovative techniques and sustainable alternatives are available to mitigate the environmental impact of textile dyeing processes. However, widespread adoption of new more environmentally friendly dying processes faces challenges, including resistance to radical changes from traditional practices.

Printing

Textile printing and dyeing are two distinct methods of adding colour and designs to fabrics. While dyeing involves immersing the entire fabric in a dye bath to colour it uniformly, printing allows for precise and localized application of colours and patterns. Printing provides greater design flexibility and creativity compared to dyeing. Several colours can be added on fabric during the same session of printing. Printing allows to make more complex designs and detailed patterns. This makes printing a preferred choice for creating unique and visually appealing textiles. Compared to dyeing, printing reduces water and chemical consumption since only targeted areas of the fabric are coloured. This leads to a reduction in wastewater generation and positive environmental impact. Additionally, printing offers shorter production times, lower energy consumption, and a more cost-effective method for textile decoration.

Printing steps

The textile printing process typically involves several steps.

- Fabric pre-treatment to remove any impurities and whitening (scouring, bleaching)
- Making the print paste by mixing the dyes or pigments with thickeners and other chemicals
- Applying the design by using a chosen printing style and method (see below)
- Drying and fixing the colours by using heat, steam and other chemicals (if necessary)
- Optional after-treatment and washing to improve fastness depending on used dyestuff and pigment

Above steps can vary based on the used colourant type i.e. dyes or pigment.

Printing with pigments

Pigment printing has gained significant importance, particularly for cellulose fibres. Main advantage is that pigments can be applied to almost all types of fibres and substrates. Pigment printing pastes contain thickening agents, binders, and other auxiliary additives like fixing agents, plasticizers, and defoamers. Bonding or fixing of colourants is done with help of a binder chemical however it can affect the hand feel.

The fabric is dried after applying the printing paste, and the pigment is typically fixed by using warm air, though some formulations may allow for fixation at room temperature over a few days. A significant advantage of pigment printing is the possibility to skip subsequent washing which is a requirement in most other printing techniques.

Printing with dyes

Printing with dyes involves preparation of complex and variable pastes. Paste preparation is determined by dye class (reactive, vat etc.), fibre type, fabric structure and weight, printing *style* and *method*, and fixation methods.

Dye pastes contain not only the dye but also several auxiliaries with specific functions. Some of these auxiliaries include oxidizing agents like m-nitrobenzenesulphonate, sodium chlorate, and hydrogen peroxide, reducing agents such as sodium dithionite, formaldehyde sulphoxylates, and thiourea dioxide, as well as discharging agents, and substances with a hydrotropic effect like urea. Additionally, there are dye solubilizers like glycerine, ethylene glycol, butyl glycol, and thiodiglycol, along with resisting chemicals, and defoamers like silicon compounds and organic esters.

The preparation of the pastes for printing is a critical step, as several different pastes (often between 4 to 10) may be required to print a single pattern. To minimize wastage and measurement errors, modern plants use automatic stations for dosage and software to precisely measure and mix the required amounts of chemicals. Filtering the printing pastes before application is also a common practice in printing houses to prevent blockages in the screens and printheads followed by unwanted cleaning or washing steps.

Styles of printing

In printing, design or patterns can be in three manners or styles:

> **Direct print:** Colours of the pattern directly added on fabric (like drawing)

> **Discharge print:** Colours are removed (discharged) from an already coloured fabric to create patterns of white or new colours

> **Resist print:** Pattern created by blocking (resist) some parts of the fabric by a knot/tie or chemically

Direct print is the easiest and most common form of industrial printing. Discharge printing require more control as a background colour is removed with a strong chemical or a new colour. There is a potential risk of fabric damage as well if not have full control of the process. Resist printing is more common for speciality design and artisans' works as it require more manual attention and precision. Control of the desired pattern and making finer lines are difficult in resist printing.

Methods of printing

The print paste or ink can be added to textile surfaces using various equipment or methods to achieve a desired pattern or design impression. Common methods include the use of a block, a screen or a printhead (digital) for this purpose. Exclusive techniques such as printing yarns or warp threads also exists for special end uses.

> **Block printing:** A traditional technique where hand-carved wooden blocks are dipped in dye and pressed onto the fabric to create repetitive patterns. It is labour intensive and used for small scale production or artisan works.

> **Screen printing:** This traditional method involves pushing the colour paste through a mesh-like screen, with certain areas blocked to create a pattern, onto the fabric. This method creates sharp and well-defined patterns. This is the most used printing method in current industry. There are several varieties of screen printing, starting from manual flatbed screens to automated flat and rotary screen printers.

> **Roller and rotary screen printing:** These are continuous printing processes that allows efficient and rapid application of designs onto fabrics. The technique involves the use of cylindrical screens or rollers engraved with the desired pattern or design. Each colour of the design requires a separate roller with the corresponding pattern. Rotary printing can be used with a variety of fabrics, both natural and synthetic, making it a versatile method for various textile applications. This printing method is widely used for high-volume production of frequent or repeating design orders. It has higher initial setup and engraving costs. Additionally, the complexity

of changing designs (rollers) makes it less ideal for small batches or custom designs.

- **Digital printing:** Utilizing advanced inkjet technology, digital printing allows for high-resolution and detailed designs directly printed onto the fabric. Complex designs and unlimited colour variations are created using the computerized technique. It does not need any intermediate block, screen, or paper preparation so it is faster and more efficient than traditional printing methods. Consumption of chemicals, water and energy are low in this method. Both large and small volume orders can be inkjet printed. There is a growing interest from industry to adopt digital printing for replacing traditional dyeing and printing methods.

- **Heat Transfer Printing:** In this process, designs are first printed onto transfer paper using a digital inkjet printer and then transferred to the fabric using heat and pressure. This method is particularly suitable for synthetic fibres such as polyester, nylon, and polyamide by using disperse dyes. Generally, transfer printing gives good hand feel and fastness properties. This method can be applied on both small single fabric pieces or on larger scale production however quite energy consuming process.

Potential impacts of printing

There are several emission sources from traditional printing processes such as printing paste residues, wastewater from screen and roller cleaning, harmful volatile organic compounds (VOC) produced during drying and fixing.

Printing paste residues are generated during the printing process due to various reasons, including incorrect measurements and the practice of preparing excess paste to avoid shortages. Equipment and containers used in printing also accumulate paste residues during colour changes, necessitating cleaning. Dry capture systems are commonly employed to remove paste residues before rinsing with water, reducing water contamination. Sample or pattern preparation on production machines can also lead to significant residues.

Wastewater can come from final fabric washing after fixation, cleaning application systems in printing machines, colour kitchen equipment, and belts. Cleaning-up operations of screens and rollers can contribute significantly to the total pollution load as well. Main water pollutants are unfixed dyes, urea (hydrotropic agent), ammonia (used in pigment print), thickeners (polysaccharides, carboxymethyl cellulose), and binders (polyacrylates) etc.

Heat treatment

After the dyeing and printing processes, the fabrics or yarns need to undergo several heat and moisture treatments e.g. steaming, drying and curing. The aim is to achieve proper fixation of dyes and pigments. Steaming and drying are essential steps in textile finishing ensuring colour fastness and improving overall quality. These processes help in removing excess moisture, setting the colours, and enhancing the physical properties of the textile materials.

Drying in general is a high-energy demanding step. It is usually achieved by combination of mechanical squeezing or water-extraction and then, heating up thermally or by radiation. Heat can be transferred to the fabric in several ways and machines such as air convection, direct contact with heated metal surface, infrared radiation and radio frequency are used.

Steaming and drying methods can be adapted to various types of fabrics and yarns, including cotton, wool, silk, synthetic fibres, and blends. The specific requirements for each material, such as temperature, steam duration, and drying time, vary based on its composition and intended use. Traditional steaming and drying processes can be energy-intensive, leading to higher operational costs and emit volatile chemicals causing environmental impacts. To address sustainability concerns, many textile manufacturers are exploring energy-efficient and eco-friendly alternatives. Advanced technologies, such as microwave-assisted drying and infrared steaming, offer the potential to reduce energy consumption and processing times, contributing to a more sustainable textile industry.

Innovation & improvement of textile dyeing & printing

Below are some general suggestions for innovation to improve textile dyeing and printing:

- Investigate methods to recover and recycle dyes from wastewater and textile waste, reducing the need for new dye production and minimizing waste generation.
- Innovate low-temperature dyeing processes that require less energy, thereby reducing the environmental footprint of dye application.
- Explore smart dyeing technologies that allow precise and controlled application of dyes, minimizing wastage and improving colour uniformity.
- Minimize printing paste losses in rotary-screen printing by reducing the volume of the supply system and improving paste recovery.
- Explore computer-assisted systems for recycling printing pastes in textile finishing

mills to reduce waste.
- Consider the advantages of digital printing techniques for short-run production and the avoidance of printing paste residues.
- Investigate techniques to reduce or eliminate the use of urea in reactive printing pastes, such as controlled addition of moisture by foaming or spraying.
- Opt for more environmentally friendly options in printing pastes, phasing out water-in-oil thickeners and hydrocarbons in favour of sustainable alternatives.
- Research and adopt eco-friendly printing techniques that utilize natural dyes and pigments derived from plant-based sources, reducing the reliance on synthetic and potentially harmful chemicals.
- Explore the use of digital design software and 3D printing technologies to create intricate and detailed textile patterns, allowing for greater creativity and customization while minimizing material waste.
- Investigate the development of waterless or minimal-water printing processes, which can significantly reduce water consumption and wastewater generation.

Emerging and alternative technologies for coloration

Below are some emerging and alternative technologies to contribute for more sustainable and improved textile dyeing and printing practices.

NATURALLY COLOURED COTTON

Naturally coloured cotton is the result of genetic diversity within the cotton plant species (Gossypium). Various indigenous cotton varieties and landraces across different regions exhibit natural colours, reflecting their adaptation to diverse environmental conditions. The use of naturally coloured cotton dates back thousands of years, with historical evidence indicating that cultivation and utilization by ancient civilizations existed such as the Inca and Maya. These cottons may have shades ranging from cream to brown, red, and green, with potential for other colours like purple and mauve. Efforts over the last two decades have involved crossbreeding cotton in diverse colours to expand colour variety and enhance fibre quality.

One of the significant advantages of naturally coloured cotton is its potentially reduced impact on the environment. By avoiding the need for synthetic dyes, the cultivation of naturally coloured cotton can lead to a reduction in water and chemical usage, making it a more sustainable choice for textile production. It can be cultivated without the use of genetically modified organisms (GMOs) and synthetic pesticides, contributing to a healthier ecosystem and supporting biodiversity.

Naturally coloured cotton fibres often exhibit excellent colour fastness to washing and sunlight. Blending coloured cotton with white cotton is a common way to improve quality, reduce costs, and ease processing, even though this may dilute the colour intensity. Strength can be increased by plying multiple yarn ends together, although this adds cost.

Despite environmental benefits and unique properties, naturally coloured cotton remains less common in the global cotton market compared to traditional white cotton. It is particularly valued for its use in niche markets, such as premium and luxury textiles. The cultivation of naturally coloured cotton requires specialized knowledge and expertise, and the production is currently limited in scale. Ongoing research and breeding efforts are focused on improving naturally coloured cotton varieties, including enhancing fibre strength, yield, and colour variety.[4]

DYEBATH REUSE

Dyebath reuse can be a solution to reduce waste from textile dyeing industry. It can reduce water consumption, minimizing wastewater generation, and improving overall environmental performance. Traditionally, dyeing processes involve immersing textiles in a pool or bath containing dyes, water and various other chemicals. After dyeing, the dyebaths contain residual dye and chemicals, making them potential sources of pollution if not properly managed. In dyebath reuse, instead of disposing of the dyebaths after each dyeing cycle, they are recycled and reused for subsequent dyeing processes. Implementing dyebath reuse practices can result in cost savings for textile manufacturers. Reusing dyebaths reduces the need for fresh dye and chemicals, saving on raw material costs. Reusing dyebaths can also lead to energy savings, as the reheating of large volumes of fresh water for each dyeing cycle is avoided.

Nevertheless, dyebath reuse is not without challenges. Reusing dyebaths may result in dye exhaustion, affecting colour uniformity and overall dyeing performance. With each reuse, dyebaths may accumulate contaminants from the previous dyeing cycles, leading to colour variations or unintended colour shifts. Careful monitoring and maintenance are required to avoid cross-contamination.

4 Rathinamoorthy R, Parthiban M, in Handbook of Ecomaterials, (Eds:Martínez LMT, Kharissova OV, Kharisov BI.) Cham Springer International Publishing:1499-1519. 2019.

Despite these challenges, dyebath reuse is a promising approach in the textile dyeing industry to improve sustainability and reduce environmental impact. Manufacturers must adopt best practices, optimize dyeing parameters, and invest in proper monitoring and maintenance systems to make the most of this eco-friendly technique.

PLASMA-ENHANCED DYEING AND FINISHING

Plasma technology can be used for not only surface pre-treatment but also to improve dyeing and finishing effects. Plasma-based processes can reduce water and chemical usage, as well as enhance colour fastness and product durability. Plasma treatment eliminates the need for harsh chemicals typically used in dyeing and finishing processes. Instead, it relies on the activation of gas molecules to create plasma, which then interacts with the textile surface.

Plasma-enhanced dyeing and finishing processes generally require less energy compared to traditional methods. The plasma activation occurs at relatively low temperatures, reducing the energy consumption during the treatment phase.

Plasma treatment modifies the textile surface at a nano-level, creating a strong bond between the fabric and the dye. This improved adhesion results in enhanced colour fastness and durability of the dyed fabric, making it more resistant to fading and washing.

Plasma-based dyeing and finishing is compatible with a wide range of fibres and textiles, including natural fibres like cotton, wool, and silk, as well as synthetic fibres such as polyester and nylon. It offers a versatile solution for the entire textile industry. Research is going on to utilize plasma for overcoming the limitations of natural dyeing.[5]

SUPERCRITICAL FLUID DYEING

Supercritical fluid dyeing is an environmentally friendly dyeing technique that shows promising potential enough for revolutionizing the textile industry. In this process, supercritical fluids, specifically supercritical carbon dioxide ($scCO_2$), are used as the dyeing medium instead of conventional water-based dyeing systems. It also allows for the recycling and reuse of carbon dioxide, making it a more sustainable alternative to conventional dyeing.

Supercritical fluids are substances that exist above their critical temperature and pressure, resulting in unique properties that make them efficient and versatile for various applications. Here, carbon dioxide is pressurized to a level above its critical point, where it behaves both like a liquid and a gas, allowing dyes to penetrate textile fibres easily. This results in better dye penetration and fixation leading to improved colour fastness and reduced dye wastage.

The super critical fluid dyeing process occurs at a lower temperature compared to conventional water-based dyeing, which helps to reduce the energy consumption and processing time significantly. Unlike water-based dyeing processes that use a range of chemicals to facilitate dye uptake, supercritical fluid dyeing requires fewer chemicals, leading to a reduction in the overall environmental impact.

Supercritical fluid dyeing can be applied mainly to synthetic fibres, especially polyester and it’s blends due to similarity in hydrophobic nature between $scCO_2$ fluid and polyester. Some research efforts are ongoing to enable dying of natural fibres like cotton, silk, and wool using this technique as well.[6] Industrial scale application and machine availability are at an early stage and there are only a few companies manufacturing these machines.

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Coloured fabrics.

Despite many advantages, there are some challenges associated with supercritical fluid dyeing. The technology is still in the early stages of development, and the cost of implementing and maintaining supercritical fluid dyeing equipment can be relatively high. However, ongoing research and advancements in the field are expected to address these challenges and make supercritical fluid dyeing a more commercially viable option in the future.

5 Haji A, Naebe M, Journal of Cleaner Production 2020, 265:121866.

6 Abou Elmaaty T, Abd El-Aziz E, Textile Research Journal 2018, 88,(10):1184-1212.

FOAM DYEING

In foam dyeing, the dye is applied in the form of a stable foam, eliminating the need for a large amount of water typically used in conventional dyeing methods. This process involves formation of a foam solution containing the dye and auxiliaries, which is then applied to the fabric surface. The foam acts as a carrier for the dye, ensuring a more uniform and controlled distribution of the dye on the fabric, leading to improved colour consistency and reduced waste compared to conventional dying. Foam dyeing reduces the overall dyeing time, resulting in higher production efficiency and energy savings.

The process is particularly suitable for dyeing fabrics with fancy patterns (marble effect) with high-quality requirements. Research work used mostly cotton, especially denim yarn dyeing using foam technology.[7] However, there are ongoing efforts to make foam dyeing suitable for synthetic fabrics as well. Similar to supercritical fluid technology, foam dyeing has limited availability for industrial use, and the technology is not yet widely applied.

SPRAY OR NOZZLE DYEING

Spray dyeing is an innovative technique that offers precise, efficient, and more eco-friendly colour application to textiles. This technology allows for a controlled and localized deposition of colour, and it is significantly different from traditional dyeing methods, such as exhaust bath or pad dyeing. Unlike traditional dyeing methods that involve large volumes of water and energy-intensive processes, spray dyeing requires minimal water usage. It can significantly reduce the time required for colour application compared to conventional dyeing methods.

The heart of the technology lies in the spray nozzles. These nozzles are designed to create fine and controlled jet streams of colour liquids to be sprayed onto textiles. The nozzles can be adjusted to set spray angle, droplet size, and spray intensity. This technology uses a liquid colourant that is stored in a reservoir and sprayed onto fabrics with consistent flow and pressure of the nozzles. A software precisely controls the pattern and intensity of colour deposition. After the colourant is applied, the fabric may undergo a drying and fixation process involving steam and heat.

Spray dyeing can be applied to various textiles; however, ensuring compatibility with different fabric types, blends, and finishes is crucial. Researchers and manufacturers need to address issues related to fabric behaviour during the dyeing process. Continued advancements in equipment design and functionality are essential for future widespread implementation.

Currently, there are only a few companies who are developing spray or nozzle-jet dyeing equipment such as imogo AB (Sweden), RotaSpray GmbH (Germany) and Alchemie Technology (UK).

Other notable textile colouring technologies under development includes laser based dyeing and infrared radiation assisted dyeing. These technologies are mainly used in smaller laboratory scale and research, or design project works.

7 Hoque E, Acharya S, Shamshina J, Abidi N, Textile Research Journal 2023, 93,(1-2):486-501.

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Finishing

Wet processing

Finishing applications, such as water, stain and odour repellents and flame retardants can greatly improve the performance of garments and textiles.
These finishing applications, however, have been the source of much debate due to their bioaccumulative effects on people and the environment.

Finishing

Common finishing

Most of the industrially used fabrics undergoes several common finishing steps for adding or correcting the quality, aesthetics, and feeling such as brushing, compacting, and shrinkage control.

Brushing is an effective technique employed to improve the texture and feel of fabrics. By gently brushing the fabric surface, fibre ends are raised, creating a soft and slightly textured finish. This technique is particularly suitable for fabrics like cotton, wool, and flannel, where a plush, luxurious feel is desired. Brushing enhances the aesthetic appeal of these materials, making them ideal for cold-weather clothing and cozy home textiles.

Compacting, or calendaring, is a crucial process for improving fabric surface uniformity and smoothness. It is commonly applied to both woven and knitted materials. By passing the fabric through a nip of heated rollers or plates, under controlled pressure, the fabric's structure is compacted, leading to reduced thickness and enhanced dimensional stability. Fabrics made from synthetic fibres like polyester and nylon often benefit from compacting, as it provides a sleek appearance and improved draping properties.

Sanforizing is essential for preventing excessive post-wash shrinkage in fabrics. It is a pre-shrinking process that involves the controlled application of moisture, heat, and mechanical action to the fabric. Fabrics prone to shrinkage, such as cotton and denim, greatly benefit from sanforizing. By ensuring that the fabric retains its intended dimensions, sanforizing contributes to garments and textiles maintaining their original shape and size, providing durability and long-lasting fit.

Heat-setting finishing is used to enhance fabric's resistance to wrinkles, making it an ideal choice for garments that require a smooth and polished appearance. Additionally, this finishing contributes to the fabric's ability to retain its shape and maintains its original form over time. Heat-setting is particularly advantageous for thermoplastic synthetic fibres like polyester and nylon, as well as for blended fabrics. During heat-setting, textiles are exposed to very high temperatures (~150-200°C) for a specific duration, typically surpassing the glass transition temperature of the fibres. This controlled heat treatment stabilizes fabric's dimensions and improves its physical characteristics.

Easy-care finishing

Easy-care chemical finishing are often applied to cellulose-containing fibres to give similar qualities of their synthetic counterparts like polyamide and polyester. These treatments give attributes commercially marketed such as easy or less washing, resistance to creasing, and reduced need for ironing. Easy-care finishing agents, often referred to by various names like resin-finishing, wash-and-wear, or wrinkle-resistant. The mechanism behind the function of these agents involves the creation of cross-links between cellulose molecules, decreasing the fabric's propensity to wrinkle under wet and dry conditions. Easy-care chemicals can be made of various ingredients such as:

> Cross-linking agent – often contains urea, melamine, formaldehyde
> Catalyst – magnesium chloride, ammonium salts
> Additives – softeners, water repellents, surfactants etc.

Most of these chemicals are harsh and thus their environmental impact must be carefully considered to align with sustainability practices.

Water repellents

The ability to repel water ensures that fabrics, and the user stay dry, maintaining their appearance and functionality under wet conditions. In addition to resistance to water absorption, enhancing textiles' durability, comfort, and performance under different conditions are also expected from this finishing. However, achieving effective water repellence without violating environmental concerns is a challenge that the textile industry continuously strives to overcome.

Nowadays, several types of water repellent treatments are utilized in the textile industry. Durable Water Repellents (DWRs) are commonly used as treatments that provide long-lasting water repellence to fabrics. DWRs are often based on fluorocarbon chemistry, which raises environmental concerns due to its persistence and potential bio-accumulative effects. Currently, the most pronounced name in water repellent technical textiles is GORE-TEX where polytetrafluoroethylene (PTFE) is the main component used for water repellent properties.[1]

Few alternatives to traditional fluorocarbon-based treatments exist today, one example is SympaTex which is a membrane made of hydrophilic polyether-ester block

1 Loghin C, Ciobanu L, Ionesi D, Loghin E, Cristian I, in Waterproof and water repellent textiles and clothing, Elsevier:3-24. 2018.

copolymer.13 More of similar solutions are needed to address the environmental impact and regulatory restrictions associated with the use of fluorinated compounds. For example, nano-scale coatings can be applied to fabric surfaces to create a hydrophobic layer, making the fabric water repellent.[1] These coatings can be engineered to balance performance and environmental considerations.

Innovation opportunities

- Explore alternative non-fluorochemical surface finishing materials, such as silicones, polyurethane (PU), and waxes. While these coatings have recyclable properties individually, though they can hinder the overall recyclability when combined with dissimilar base substrate. However, there is potential for enhanced recyclability if these finishes are applied to a substrate made from the same or similar material.
- Explore the use of nano-scale hydrophobic coatings that can be applied to fabric surfaces. These coatings can be designed to create a water-repellent barrier without the need for large quantities of chemicals.
- Investigate and develop water repellent coatings derived from renewable and bio-based sources, such as plant extracts, natural waxes, or biopolymers. These bio-based alternatives can provide effective water repellence and reduce the dependence on petrochemical-derived chemicals. Emphasize the use of biodegradable polymers or materials that have minimal impact on ecosystems and aquatic life.
- Design water-repellent finishes that do not hinder or affect recyclability of textiles. Ensure that the treatment can be easily removed during recycling processes without leaving harmful residues, contributing to a more circular and sustainable textile industry.

Stain repellents

Stain repellent finishes are applied to textiles to provide resistance against stains, soil, and grease. These finishes often involve the use of fluorochemicals, which can be effective in repelling stains but raise health and environmental concerns. There is a push to avoid the use of fluorochemicals due to their negative impact. Finding non-toxic, biodegradable alternatives for stain repellent finishes aiming to balance functionality with environmental sustainability is a key innovation area.

Innovative solutions are essential in the transition towards more sustainable stain repellent finishes. One approach is to explore the use of non-toxic, biodegradable alternatives to fluorochemicals. Natural compounds, such as plant-derived materials, could be utilized to create effective stain repellent finishes without the harmful effects associated with fluorochemicals.

Biocides & antimicrobials

Biocides, also known as “antimicrobials” or “antimicrobial pesticides,” play a crucial role in controlling and stopping the spread of harmful microbes such as bacteria, fungi, and viruses.[2] This finishing treatment can be based on synthetic chemicals or by the use of another microorganism. Such finishing agents are valuable for various applications, such as preventing odour caused by the breakdown of sweat, inhibiting microbial growth, and enhancing hygiene in textiles. However, the use of biocides and antimicrobials raises important considerations related to health, environment, and sustainability.

Carpet production industry often uses biocides to impart lifetime protection against textile pests, known as mothproofing agents based on synthetic pyrethroid or halogenated diphenylurea derivatives. Synthetic pyrethroids in general are reported to have be non-hazardous to humans but may have high aquatic toxicity. Halogenated dyphenylurea derivatives may exhibit less aquatic toxicity but is less biodegradable.[3] Common antimicrobial agents used in textiles include silver, triclosan, triclocarban, and organotin. Each of these agents serves a specific purpose in preventing microbial activity.

In general, all synthetic chemical-based biocides give rise to environmental concern when they are discharged as wastewater because of their toxicity to aquatic life.

Innovation opportunities

- Promote use of fibres that have natural resistance to microorganisms such as wool
- Avoid or decrease the use of biocides, but when needed explore bio-based alternatives such as chitosan or antibacterial enzymes.

2 Biocides: Essential Tools that Prevent Harmful Microbial Growth. American Chemistry Council, Inc. Available at: . Accessed 2023-08-14.. Accessed 2023-08-14.

3 Le Marechal AM, Križanec B, Vajnhandl S, Valh JV. Textile finishing industry as an important source of organic pollutants. Paper presented at: Organic pollutants ten years after the Stockholm convention-environmental and analytical update2012.

Flame retardants

Flame retardants in textiles serve as critical components to enhance the fire safety of various products. There are essential distinctions to be made between durable and non-durable flame-retardant treatments, each offering unique benefits based on their application and longevity.

Durable flame retardants react with the fibres at a molecular level, resulting in permanent fire retardancy properties. This characteristic makes them suitable for products that require long-lasting fire protection. Once applied, durable flame-retardant finishes endure multiple washing cycles and maintain their efficacy over time. In contrast, non-durable flame retardants, while effective at providing flame resistance, are not permanently bonded to the fibres. These treatments can be removed by washing, limiting their suitability to products that are not frequently washed or after washing can be re-treated with retardants.

Flame retardant agents operate through different mechanisms based on their chemical composition.[4] Within the textile industry, the following chemical classes are commonly used for flame-retardant treatments. Inorganic flame retardants can enhance the fire resistance of textiles by incorporating elements such as phosphorus, nitrogen, or boron, which contribute to reducing flammability.[5] Halogenated organic compounds such as chlorine or bromine that interfere with the combustion process and act as fire inhibitors. However, there are growing environmental and health concerns associated with halogenated flame retardants, leading to regulatory restrictions regarding their use in certain regions. Organo-phosphorus flame-retardants function by forming a protective char layer when exposed to heat or flames, effectively insulating the underlying material from further combustion. Organo-phosphorus compounds are widely used in flame-retardant treatments due to their efficacy and relatively low environmental impact compared to some halogenated compounds.

In the search for more sustainable and environmentally friendly flame-retardant solutions, researchers and the textile industry are exploring alternative formulations. The focus is on reducing the use of certain halogenated compounds with potential ecological impact while maintaining the necessary level of fire protection. Innovations in flame-retardant chemistry aim to strike a balance between fire safety, durability, and sustainability, ensuring that textiles meet stringent safety standards while minimizing potential environmental concerns.

4 Salmeia KA, Gaan S, Malucelli G, Polymers 2016, 8,(9):319.
5 Özer MS, Gaan S, Progress in Organic Coatings 2022, 171:107027.

Anti-felting finishing

Anti-felt treatments in textiles are essential processes designed to prevent or minimize the undesirable phenomenon of felting, which occurs primarily in woollen and animal fibre textiles. Felting is the matting and interlocking of fibres due to mechanical action, heat, moisture, and friction during washing, causing the fabric to shrink and lose its original structure.

The primary objective of anti-felt treatments is to enhance the dimensional stability and durability of woollen textiles, making them more resistant to felting and shrinking. These treatments help maintain the original appearance, texture, and size of the fabric, ensuring that it retains its intended shape and structure after repeated use and washing.

There are various methods and chemical treatments used for anti-felt finishes, each with their own mechanisms and benefits:

> **Chlorine** based treatment: It is the oldest anti-felting method where a chlorine-releasing oxidising agent works on the scales of the cuticles and changes the external structure of the fibre chemically. Sodium hypochlorite or sodium salt dichloroisocyanurate could also be used as oxidising agents. However, this technique is rarely used now due to environmental and health concerns of active chlorine.

> **Resin** based treatments: Polymer and silicone-based resins are commonly used in anti-felt finishes to create a protective layer on the surface of the fibres. These resins form cross-links between the wool fibres, making them more resistant to the forces that cause felting. This method improves the fabric's ability to withstand the mechanical stresses and changes in moisture during washing. Cationic polymers are the most suitable for this treatment. Silicone-based resins can create a hydrophobic (water-repellent) layer on the fibres' surface, reducing their tendency to absorb water and swell. This hydrophobic barrier helps prevent the fibres from intertwining and felting, maintaining the fabric's original structure.

> **Combined or Hercosett** process: The Hercosett process, is a combination of chlorine pretreatment and application of a polyamide-epichlorohydrine resin, is a long-standing method used for anti-felting finishing of wool. It offers cost-effectiveness and reliable effects, making it widely utilized for wool in various forms, including

loose fibre, combed top, yarn, and fabrics. However, this process generates effluents with high COD (chemical oxygen demand) and AOX (absorbable organic halogens), attributed to both oxidants and the resins. Alternative resins with reduced environmental impact have been developed, such as polyethers and cationic aminopolysiloxanes, but none of these matches the comprehensive results of the Hercosett process. Despite environmental concerns, effectiveness of Hercosett process makes it the preferred choice in the industry. Efforts towards developing more sustainable options should address these environmental issues while aiming to achieve comparable results.

Sustainable alternatives of anti-felting finishing

In the strive for finding sustainable textile finishing, researchers and the industry continue to explore innovative and eco-friendly anti-felt treatments. The goal is to develop solutions that not only provide effective anti-felt properties but also align with environmentally conscious practices, reducing the use of harmful chemicals and minimizing the ecological impact of the finishing process. Some of the emerging technologies for this purpose are below.

> **Ozone** (O_3) can be used in the chlorine-Hercosett treatment set-up with some modifications for wool treatment. Ozone treatment has some advantages, like etching cuticle edges without affecting bulk properties or dyeability of wool fibres. It provides excellent shrink-resistance, especially in continuous aqueous or gaseous ozone treatments. Patagonia and other commercial wool apparel manufacturers use the Ozone/Hercosett method for a more eco-friendly and sustainable shrink-resist treatment for wool.[6]

> **Enzymes** such as protease can be used to modify the surface structure of wool fibres, making them less prone to felting.[7] Enzymatic treatments break down the scales on the wool fibres, reducing the opportunity for interlocking and matting.

> **Radiation** treatments, involving energy waves like UV, gamma, X-ray etc., are utilized to modify fibre characteristics. UV radiation, particularly in the UV-A region, is employed for making wool fibres shrink-resistant. These treatments create hydroxyl radicals that can lead to macromolecular chain degradation of wool scales.[6]

> **Plasma** treatment, are considered be eco-friendly as they produce no effluent. This technique have been investigated for making wool fabric shrink-resistant. Different plasma generators, such as corona discharge and dielectric barrier discharge, have been are used. The corona discharge is the earliest technique used for this purpose. Plasma treatments modify both the surface topography and the chemistry of the wool fibres, by creating hydrophilic groups. The application of non-polymerizing gases in low-pressure plasma treatment modifies the outer layer of wool fibres, and argon/helium plasma provides excellent, durable shrink-resistance, especially when processed under low temperatures. Both low-pressure and atmospheric pressure plasma processes have been explored, each having its advantages and suitability for continuous wool treatment.[6]

6 Hassan MM, Carr CM, Journal of advanced research 2019, 18:39-60.
7 Li W, Zhang N, Wang Q, Wang P, Yu Y, Zhou M, Fibres and Polymers 2021, 22,(11):3045-3054.

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Garment Washing

Wet processing

In addition to improving or softening the hand-feel of products, garment washing affects the aesthetic of the product, often by imparting a ”worn in” or ”aged” appearance. Garment washing has become an indispensable tool for apparel designers to manipulate garment aesthetic and to impart unique decorative effects, particularly for denim.

Garment Washing

The terms ”garment wet processing”, ”garment finishing”, or just ”garment processing” are used interchangeably to describe various techniques aimed at altering the garment's hand-feel or aesthetics. ”Garment washing” primarily involves water and chemicals, while dry procedures are used for localized effects like sandblasting, hand sanding, brushing, and cutting. Wet garment washing uses different chemicals for abrasion, decolourization, and softening, leading to variable results within a garment and between garments mainly due to several factors e.g., fabric density. Denim products are given the most intensive wet treatments, but similar techniques are now applied to other types of woven bottoms, woven tops, and even knit garments.

Two primary types of equipment for garment washing are side-loading horizontal washers (belly washers) and front-loading rotary washer/extractors. Rotary washer/extractors offer more options to control wet treatments, including advanced liquor ratio control (amount of used water and chemicals), heating, and chemical systems, leading to better waste minimization. Large open-pocket tumble dryers are commonly used to dry apparel after washing, with modern units having sophisticated controls, such as moisture sensors, to minimize energy consumption.

Steps of garment washing

Desizing and scouring

In the case of woven denim products, the initial step is de-sizing to remove sizing agents applied to the warp yarns, such as starch or polyvinyl alcohol (PVA). Enzymes like amylase are commonly used to break down starch molecules for easier removal. Other "top finishes" on fabrics, like lubricants, can be removed through garment scouring, typically accomplished by rinsing with suitable detergents. A combination of light scouring and desizing results in significant softening of denim garments.

Wet abrasion

This technique aims to create a natural-looking worn-out and faded effects on the garment, ranging from slight to pronounced levels. A classic approach is ”stonewashing”, which involves tumbling wet garments with pumice stones or other abrasive elements. Variations in water quantity, stone size, tumbling duration, and mass ratio of stones against garments yield diverse effects. Sometimes, stones are pre-soaked in oxidative chemical solutions (bleach) to enhance the decolourization effect, leading to specific design outcomes. Stone treatment is less preferred now due to health and environmental concerns.

Enzymes like cellulase can be employed to accelerate abrasion effects or replace the need for stones altogether. Following wet abrasion, a quick rinse is performed to remove any residual dyestuff or dust from the abrasive materials.

Colour removal

Bleaching or stripping process is used to lighten the overall colour of the garment, for example, to remove some indigo dye used in denim products. Such a process eliminates indigo dye deposits on the filling yarns. Chlorine derivatives, often sodium or calcium hypochlorite, are commonly used for this process step. These hypochlorites act as strong bleaching agents effective in removing certain dyestuffs. Peroxide based bleaching is a better alternative as discussed earlier in the pre-treatment section.

Brightening

This step, sometimes referred to as ”top brightening”, is conducted after bleaching to further whiten or brighten the decolourized areas in the garment. This enhances the contrast between light (or white) and dark areas in the fabric. It can be achieved using a milder bleaching agent like hydrogen peroxide or by utilizing an optical brightener, also known as fluorescent whitening agents (FWAs). Optical brighteners absorb invisible UV radiation and transmit the light as visible (white) light, contributing to a brighter appearance.

Tinting/over-dyeing

This step involves the application of additional colourants to garments that have already been dyed or printed. If some areas of the garment are undyed or white, then these areas fully absorb the additional colourant, Also, dyed or printed areas can pick up some of colour again, resulting in unique effects. A wide range of colourants, such as dyes, pigments, or metal salts, can be used for tinting, based on the substrate. Over-dyeing with different colours can change the hue of pre-existing colours and create interesting new visual effects.

Softening

The final step in garment washing; softener application significantly impacts the garment's hand, drape, abrasion resistance, and tear strength. Various chemicals act as softeners, including sulphates, sulfonates, amines, quaternary amines, ethylene oxide derivatives, and hydrocarbon waxes. The selection of softeners depends on the desired hand-feel: dry (petrochemical/polyethylene), greasy (organic/fatty derivatives), or slick (silicone). Approximately, one-third of softeners used are silicone-based. Silicone reduces the coefficient of friction of fibres and yarns, enhancing comfort. Proper softening enhances the overall quality and feel of the garment, making it more appealing to consumers.

Potential impacts

Most techniques involved in garment processing, both dry and wet, have significant environmental considerations that encompass resource extraction, chemical discharge, and potential hazards to human health.

> **Dry Processing Impacts:** Dry techniques, while not using chemicals, still have notable environmental effects. The extraction of abrasive media from natural habitats disrupts ecosystems, and the transportation of materials to processing facilities, often over long distances, contributes to carbon emissions. Disposal of spent abrasive media through landfilling further adds to the environmental burden. Occupational safety is a concern, especially in countries with inadequate enforcement of safety precautions. Although banned in Europe, sandblasting remains prevalent in some Asian production countries.

> **Wastewater and chemical release:** The garment washing process is water-intensive, and the nature of the washing method used can make it energy and chemical-intensive as well. The discharge of chemicals (surfactants, chelating agents, acids, alkalis, oxidizing agents, reducing agents, heavy metals, etc.) and colourants into water systems contributes to aquatic toxicity and increases chemical oxygen demand (COD) or biological oxygen demand (BOD). High BOD and COD levels harm aquatic ecosystems and hinder water reuse. The removal of colour from garments during washing adds colourants to wastewater, posing challenges to aquatic plant life photosynthesis.

> **Colourants:** To ensure colour permanence in textiles, colourants and chemicals used in dyeing and printing are developed to resist environmental impact. However, this durability often makes these colourants less biodegradable and difficult to remove from dyeing and printing process wastewater.

> **Softeners:** The choice of softeners in the garment process impacts toxicity and biodegradability. Fatty derivatives tend to be highly biodegradable, unlike petrochemicals, while silicone resists biodegradation by microorganisms but degrades in soil, as seen in landfills. Knowledge of the potential environmental impacts of softeners is crucial for minimizing the overall ecological footprint of garment processing.

Balancing of the desired aesthetic and comfort enhancements with eco-friendly practices requires continuous research and development of more sustainable methods, chemical alternatives, efficient water usage, and proper waste management strategies.

Minimize pollutants and resource consumption

Fabric selection

A key strategy in mitigating the environmental impact of garment washing is to choose fabrics designed with desired hand-feel and aesthetics, thereby reducing the need for intensive treatment. By altering factors like fibre diameter, length, tenacity, yarn twist, and fabric stitch density, garments can exhibit the desired qualities with minimal post-washing modifications. These slight physical adjustments, often visually undetectable, not only enhance efficiency but also minimize the overall environmental footprint.

Water reuse

Beyond minimizing water intake, water conservation post-processing is crucial. The garment washing process entails multiple cycles, each accompanied by rinses, leading to significant water consumption. Implementing water reuse practices, particularly for front-loading rotary washer/extractors, can dramatically cut water usage. Treating process water to remove chlorine, reduce metal content, salts, alkalinity, pH, and residual dyes enables recycling or reusing water, promoting eco-friendly practices in the textile industry.

Frequency of machine cleanings

The frequency of machine cleaning impacts total water consumption in garment washing. An effective approach involves scheduling machines to process progressively darker shades, minimizing the need for frequent cleaning between colour batches. This not only conserves water but also optimizes the efficiency of the garment washing process.

Low-liquor-ratio washing

Liquor ratio, the ratio of the chemical bath (including water) to the weight of the material (garments), significantly influences water and energy consumption. Adjusting load sizes in machines to match their capacity reduces liquor ratios and water volumes, thus optimizing water and energy usage while minimizing waste. Front-loading rotary washer/extractors offer flexibility, accommodating various load sizes, enhancing water and energy efficiency.

Proper chemical selection

Choosing chemicals wisely is a vital element of pollution prevention. Chemicals should be selected based not only on their performance but also on environmental considerations such as toxicity, biological oxygen demand (BOD), and chemical oxygen demand (COD). Biodegradability is a critical factor; alternatives to undesirable chemicals, such as alkyl phenol ethoxylates (APEO), should be prioritized. Enzymes, which are biodegradable, can replace chemicals in processes like desizing, wet abrasion, and bleaching, reducing the environmental impact.

Combination/elimination of garment washing processes

Considering the combination or elimination of specific garment washing processes can lead to waste reduction. Combining processes like de-sizing and wet abrasion, when technically feasible, reduces process time, water, energy, and chemical consumption. Challenges, such as dye presence in de-sizing baths, can be addressed with specific enzyme combinations. This approach, termed a ”combi-process”, streamlines operations while minimizing resource use.

Waste minimization/source reduction

Careful assessment of the necessity of garment washing is essential. While certain fabrics or garments, like denim, require washing, alternatives exist for others. For instance, fibre and yarn modifications, or manufacturing procedures like Sanforizing, can eliminate the need for washing in some cases. Starting with a fabric shade closer to the desired post-wash garment shade significantly reduces the degree of decolourization, leading to energy, dyestuff, and waste reduction.

By integrating these strategies, the textile industry can substantially reduce the environmental impact of garment processing, creating a more sustainable and responsible approach to garment production.

Optimize sustainability benefits

Design pportunity	Considerations
Look for opportunities to avoid garment washing.	Fabric suppliers will need prompting to show physically engineered fabrics, if these wash-saving processes have not been requested before.
	Investment, availability and knowledge of these technologies.
Select fabrics that are closer in shade to the desired garment shade after wash.	Speaking with a technical person, rather than a sales person, may be necessary.
Encourage water conservation with existing suppliers and/or seek new suppliers that use water conservation techniques.	There can be a possibility of local variations and fastness issues of the alternate effects.
Create awareness that water and energy conservation is important and possible, without sacrificing hand-feel or aesthetic.	Water use by garment laundries varies widely.
Promote proper wastewater treatment.	Water treatment by garment laundries varies widely.
Leverage the aesthetic differences that low impact garment washes offer. Turn the differences into positive stories.	

Innovative technologies

Adopting innovative technologies for abrasion and decolouration, like lasers offers alternatives to traditional processes. Lasers, based on wavelength, can either decompose colourants or alter fabric surface chemistry. This approach, commercially available and increasingly utilized, closely mimics traditional abrasion techniques like hand sanding, providing efficient results with reduced environmental impact.

LASERS HAVE GREAT POTENTIAL. LASERS CAN BE ABSORBED BY AND ALTER THE SURFACE CHEMISTRY OF THE FABRIC AND HAVE GREAT POTENTIAL TO REPLACE TRADITIONAL TECHNIQUES SUCH AS HAND SANDING.

Marketing opportunities

- Emphasize water-saving advantages by implementing alternative bleaching methods.
- Highlight the use of non-chlorine based fading methods as eco-conscious alternatives.
- Highlight laser treatments as a modern, tech-driven choice for a consumer base that values innovation.

Suggest sharing information on the company's website regarding environmentally friendly practices in washing, finishing, and bleaching, highlighting the brand's commitment to lower impact processes.

Part 7: Recycling of textile waste

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Evaluation of and challenges in the sorting of textile waste

Introduction

According to statistics, only a small percentage of textile waste material is re-used or recycled worldwide. In the United States of America only 15% of the fibre waste is re-used or recycled. While in Europe, today less than 1% of textile waste is fibre-to-fibre recycled due to several barriers to scale that need to be overcome.[1]

Textile recycling is the new standard, and not anymore an option. To face the fatal consequences of global warming and the crisis of textile waste with their huge impacts on environment, in 2022, the EU came up with new strategy for sustainable and circular textiles. In this strategy, the European Commission has stated their vision that "By 2030 textile products placed on the EU market are long-lived and recyclable, to a great extent made of recycled fibres, free of hazardous substances and produced in respect of social rights and the environment... The circular textiles ecosystem is thriving, driven by sufficient capacities for innovative fibre-to-fibre recycling, while the incineration and landfilling of textiles is reduced to the minimum"[2], Additionally, a plan follows for a smooth transition of this vision (2022–2024), facing the global challenges of sorting and the traceability of supply chain.

Sorting of waste textiles is a crucial step for efficient recycling. It involves separating different types of collected textiles based on their material composition, colour, and other factors. The sorting process can vary widely based on geographical locations and available infrastructure.

Most of the sorting today is conducted manually, mainly based on information from the labels, and sorted based on the fibre material and content of these textiles. However, this process is slow and can be unreliable.[2] The labels may be removed, unclear due to prior use, or contain faulty information about the composition which is common for the blended textiles.

Collection Type	Advantage	Disadvantage
Charity shop drop-off	Large scale is possible	Users have to bring the items
Home pick-up	Convenient for users	Expensive
Collection containers in neighborhoods	Convenient for users Large scale is possible	Logistics needed for storing, transportation and sorting
Municipal waste collection	Large scale is possible	Textiles need to be separated from other types of waste
Retailer drop-off and brand returns	Large scale is possible	Users have to bring or mail the items

As a first step, the waste textiles need to be collected; this is usually conducted using different routes as summarized in the table below.
There are already different methods available for the identification of textile materials, such as quantification methods based on different dissolutions (such as ISO standards), microscopy for morphological differences, and methods based on the thermal behaviour detected by calorimetry, thermos-gravimetric analysis and gas chromatography. These methods are accurate, but slow and require sample preparation. Thus,

1 https://www.mckinsey.com/industries/retail/our-insights/scaling-textile-recycling-in-europe-turning-waste-into-value
2 J.P. Juanga-Labayen, I. V. Labayen, Q. Yuan, A Review on Textile Recycling Practices and Challenges, Textiles. 2 (2022) 174–188. https://doi.org/10.3390/textiles2010010.

other technologies are needed to keep up with the urgent need of large-scale textile identification systems in recycling given the obligation under EU waste legislation to establish separate collection structure for textile waste by 2025. Scaling up sorting of textile waste using new technologies should be a major step forward, since this process is still being conducted manually in most cases, hyperspectral near-infrared imaging is now being tested for this purpose.[3] Near InfraRed Spectrometry (NIRS) where materials, for ex wool, PA and PET, can be detected and separated based on the fact that materials or polymers absorb specific wavelengths in addition to Visual Spectroscopy (VIS), where sample preparation is not required. These spectroscopy methods are now used for textile material identification to facilitate and accelerate the automated sorting of waste textiles.[4]

However, there are factors that affect the efficiency of these technologies including,

The Effect of coatings: coated textiles are generally harder to recycle than the uncoated structures and require mechanical or chemical treatment prior to the detection.

The effect of blended and low content materials: a textile with the presence of a material at low content in a blended material, such as elastane, may cause misrecognition as it might not be detected due to lower spectrum recognition as it is "hidden within the yarn" structure.

The effect of structure: differences in the mono-material textile structure based on production methods used don't impact on the detection of materials via these technologies (ex, whether knitted or woven). However, very loosely knitted thick fabrics with different layers were not recognized because the NIR sensor cannot detect the middle layers due to limitations in penetrating the surface layers.

Other effects: the effect of ageing or mercerization on materials like cotton will make them unrecognizable with NIR. Additionally, the effect of colour can be noticed, especially with dark colours, which can make it more difficult to detect what material the garment is made from. Researchers are working to further develop these technologies to be more efficiently for used in upscaled sorting and material detection of textile waste.

Although at present, automatic sorting suffers from some limitations, but the achievements solving this is important closing the loop of textile circularity. New technologies like artificial intelligence (AI) and the Internet of Things (IoT) technology are being implemented for this purpose. IoT can assist in collecting data along the value chain, through various sensors, including smart materials. It is important mentioning that IoT requires big amount of data, since smart sensor and radio frequency identification (RFID) technologies are required collecting personal information, therefore its use maybe limited due to lack of transparency and regulations in many countries towards this subject matter.

Initiatives regarding sorting of textile waste

The EU strategies for sustainability and textiles are pushing for more circular economy models and forcing producers to take responsibility for textile waste management. New initiatives are growing and starting to develop and invest in scaling up automated sorting systems for textile waste, leading to more efficient recycling within the circular textile sector. Some of those are:

SIPTex[5]

Partially funded by Swedish government and owned by SYSAV, SIPTex is one of the first large scale facilities for automated textile sorting. Textiles are sorted by colour and fibre composition using near-infrared and visual spectroscopy (NIR / VIS). Sensors detect and recognise the type of fibre. Sorting is made by compressed air that blows the fabric to the right container. The plant can be programmed to sort out three different flows simultaneously.

Fibresort™ technology by Valvan[6]

Fibresort is a new technology that enables the recycling industry to identify and separate textiles based on fibre composition and colour. The technology is based on a combination of NIR (Near-Infrared) and RGB camera technology to detect and identify both material and colour. Their system can recognize and separate wool, cotton,

3 M. Kahoush, N. Kadi, Towards sustainable textile sector: Fractionation and separation of cotton/ polyester fibres from blended textile waste, Sustainable Materials and Technologies. 34 (2022). https://doi.org/10.1016/j.susmat.2022.e00513.

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5 Siptex - textile sorting, (2022).

6 Fibresort TM technology, (2023).

polyester, viscose, acrylic and nylon at present. By using advanced machine learning algorithms, it can determine the fibre composition of fibres in textiles. Furthermore, the RGB camera enable accurate sorting by different colours whether the textile is mono or multi-coloured, and what is the detected colour. This system is facing some challenges that hinders the detection, some of which are wet textiles, darker colours, or blended textiles with more than three types of fibres.

WARGÖN Innovation AB[7]

They focus on innovating and develop complete system for sorting and valuing of textiles with a material and colour scanner and they are also developing linked AI decision-tools.

SOEX and I:CO[8]

Their technology relies on artificial intelligence (AI) to recognize individual garments and sort them by materials or colours. 78 different materials and material combinations can already be detected by the AI, with measurement accuracy over 95%. Materials or textiles sorted can therefore consist of a complex number of different mixtures.

Post-sorting processes

Once the textiles are sorted, they are often compacted into bales. These bales are easier to transport and store, and they maintain the separation between different types of textiles.

Before recycling of the sorted textiles can be made, additives and trims need to be removed from the garments, such as zippers, buttons, and chemicals. This can be conducted through mechanical and chemical processes.

In order to minimize the degree of downcycling such procedures have to be implemented. The materials that make up the End-of-Life, EoL textile products needs to be identified, including fibre identity/identities, additives such as dies, finishes or print, sewing thread composition etc. Based on that analysis suitable recycling strategies can be selected for each object.

7 Wargön Innovation, 2023. (n.d.).
8 SOEX - Sorting for recycling, (2023).

General strategies of textile recycling according to material type

If reuse or redesign options are ruled out suitable recycling routes are identified. Based on knowledge about the composition of the textile and guided by the strive to minimize downcycling, also expressed as maximized preservation of added value of the End of Life (EoL) textile objects, different recycling routes may be selected.

Recycling of cellulose based fibres as raw material for regenerated fibres

Regenerated cellulose fibres such as viscose or lyocell are made from dissolving pulp. The dissolving pulp may be directly dissolved or chemically modified in the dissolved state to enable complete dissolution. Dissolving pulp is usually made from wood-based sources but in principle all cellulose containing raw materials can be utilized once their properties has been fine tuned to fit the processing window. Also (end-of-life) EoL textiles made in part or entirely from cellulose fibres such as cotton, viscose or lyocell may be utilized as raw material. This is already exercised commercially. For neat cellulose EoL textile products the route is pretty straight forward whereas mixed fibre products call for separation that complicate the processes and may jeopardize the bottom-line sustainability gain from the additional process steps, added chemicals and energy they request.

Recycling of Thermoplastic fibres

Based on their purity, how they were polymerized, their service history, their vulnerability to degradation during use and chemical robustness to recycling determines what options that are technically feasible to render acceptable and foreseeable quality after recycling. Whether the recycled polymer or fibre can compete with new fibres is in the end an economical decision that may be determined by corporate policies and regulatory frameworks.

This chapter will outline the different technical options that are at hand for the designer who wants to utilize recycled thermoplastic man-made fibres or enable recycling of products that are under development at their end-of-life.

There are a number of synthetic fibres such as elastane, acrylic, UHMWPE and aramides, which are not thermoplastic and therefore will not be covered in this chapter.

Recycling options

When it comes to recycling strategy one should choose the method that preserves as much as possible of the textile's added value. This is in accordance with the waste hierarchy.

Mechanical recycling

The most resource efficient and still the least costly recycling method is to go directly from fibre-to-fibre, i.e. by mechanical recycling. However, thermoplastic fibres are often meltspun to multifilament yarns that upon texturizing achieve comfort properties that are very similar to staple fibre yarns but without the need for several processing steps of yarn spinning. Meltspun filaments that are cut to staple fibres are primarily used in blends with other staple fibres, in particular with cotton. This blend is often referred to as polycotton. When multifilament-based fabrics are recycled by mechanical recycling the fibre length distribution becomes very wide, which makes the recovered fibres very difficult to spin into yarns of good quality.

FOR MORE INFO: SEE MECHANICAL RECYCLING.

Thermomechanical recycling

The second most resource efficient recycling method is to heat the fibres above their melting point and melt spin them over again. This is an attractive option for chemically, environmentally and thermally stable polymers such as polyolefin fibres, i.e. polyethylene and polypropylene. Unlike other thermoplastic fibres these hydrophobic fibres don't need drying before remelting and melt spinning. Polyethylene terephthalate, PET, sometime referred to as PES, albeit hydrophobic in nature calls for very thorough drying to avoid hydrolysis during processing. The high melting temperature of PET also induces thermo-oxidative degradation with discolouration and thermal degradation. All three degradation mechanisms render reduced molecular weight that might jeopardize its meltspinnability. PET is also used for beverage bottles and food containers. The grades that are used for these applications are based on polymers with higher molecular weight, which also make them more viscous. A limited degree of degradation might therefore be advantageous since it makes the recycled bottle PET suitable as fibre grade. PET labelled as recycled polyester has in fact gone through this route.

Polyamide has potential to be thermomechanically recycled provided that it is properly dried before melting. However, the labelling of polyamides lacks stringency. Albeit the similar properties of polyamide 6 and polyamide 66 the latter has about 40°C higher melting temperature. They must not be mixed during processing since polyamide 6 cannot stand the processing temperatures required for the 66 version. The very similar chemical structure of the two makes automated sorting very demanding.

Other emerging fibres are usually less stable during their user phases and also during remelting. One such example is polylactic acid, abbreviated PLA, which is prone to hydrolysis.

Physical recycling

Next step down the waste pyramid is physical recycling, meaning dissolution and precipitation of the dissolved thermoplastic fibres. Solvents that are able to dissolve textile fibres needs to interact very strongly with the polymers. Hence, they are reluctant to let go of the polymers meaning that it is challenging to eliminate all residual solvents. Great dissolving power often implies health and environmental issues. The solvents also need to be recycled and used repeatedly for economical sustainability. That takes energy and cleaning of extraction and recovering media. If the dissolved fibres can be precipitated into fibres directly, i.e. solution spinning then the process that would be more economically sustainable than if the precipitated fibres first needs to be molten again and melt spun.

Physical recycling can be considered when blend fibre products reach their EoL and the fibres need separation before rematerializing.

Chemical recycling

The intended chemical modifications that take place during chemical recycling unavoidably render loss of added value. Such recycling methods usually mean that the polymers are shortened, most often all the way back to an intermediate stage or to their original constituents, monomer. The depolymerization means consumption of chemicals that cannot be reused and new polymers needs to be polymerized again, using the segments, monomers or molecules from depolymerization as raw materials. Polymerization takes energy and refining but the polymers become as good as new so there is no quality loss. For selected fibres it is also possible to accomplish the depolymerization stage by enzymatic catalysis to improve the economical sustainability scores.

Just like the physical recycling, chemical recycling is suitable if fibre blend separation is desired as different fibres can be extracted separately. There are a number of processes at hand that can handle this technically.

Thermal recycling

Converting the chemical energy of thermoplastic fibres by incineration into heat is second to landfilling the least attractive EoL option.

MECHANICAL RECYCLING IS THE MOST ESTABLISHED TECHNOLOGY FOR TEXTILE RECYCLING ON INDUSTRIAL SCALE.

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Mechanical recycling

Mechanical recycling of textile waste is probably the most used method on an industrial scale due to its efficiency and reduced costs compared to other methods. In most cases, mechanical recycling will consume 5–20% of the energy used in primary fibre production.[1,2] Both post- and pre-consumer products can be mechanically shredded. This process is possible to use for different fibres both thermoplastics and natural fibres.

In the case of thermoplastics, these can be shredded, remelted and respun into new fibres. However, the contamination of the original fibres should be minimal to obtain a good-quality recycled fibre.

In the case of natural fibres, the shredded fibres can be combed and spun into new yarns.[3]

For mono-material fibres, these processes can be a good option, however, when the recycled material is blended (such as the common blend of cotton- polyester), the separation of these fibres can be challenging after shredding.

Mechanical shredding of textile waste reduces the length of fibres in most cases. Therefore, the mechanical properties of the primary fibres and their spinnability will be affected and it is usually advisable to blend them with better-quality or primary fibres.[4]

The mechanical forces during this process, added to ageing and wear of fibres due to washing and use, decrease the degree of polymerization (DP) of the fibre, which negatively affect fibre strength and length, thereby causing problems during spinning.

Due to the shortening of fibres, ring spinning is not advised for the obtained fibres. Hence, rotor or friction spinning should be considered in most of these cases.

One of the strategies to deal with blended waste without separating the fibres according to type, is the production of nonwoven structures from the mechanically shredded fibres.

This approach was reported for blended cotton-polyester from "Cut and sew" knitwear waste materials (pre-consumer). Both cotton and polyester were mechanically fractionated then converted into nonwoven webs for insulation applications.[5,6]

To maintain the efficient re-spinnability of the mechanically obtained fibres after mechanical shredding, the understanding of inter-fibre cohesion is crucial. This is influenced by a number of factors, including the flexural rigidity of the fibres, their friction, their shape, in addition to their length and denier.[7] To reduce the friction among fibres during mechanical shredding, the use of lubricants is being investigated, materials like polyethylene glycol (4000) showed to be successful in reducing the loss in fibre length, decreasing inter-fibre cohesion, and facilitating the tearing process. The authors showed that it was possible to rotor-spin 100% of mechanically shredded fibres after this treatment.[8]

One of the pioneer textile recycling initiatives in Sweden aiming to drive the development towards efficient recycling is the Textile Recycling Test Bed, that was run by Swerea IVF in collaboration with the Swedish School of Textiles. By combining Swerea IVF's expertise and equipment in textile and polymer materials with the competence of The Swedish School of Textiles with regards to textile production, design and business models; the test bed was a great initiative with a positive impact lasting until present.[9]

Since cotton is one of the most used fibres world-wide, its mechanical recycling is of a great importance, and it will be discussed in more details.

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Mechanically recycled cotton

Recycling

Using recycled fibres achieves a number of ecological benefits. Most notably, it reduces the burden on arable land and water deprivation caused by cotton cultivation, as well as reducing the load on landfills and pollution caused by incineration.

Mechanically recycled cotton

Benefits

Recycling of fibres through a mechanical process mainly reduces the environmental burden caused by fibre production. This means that for recycled cotton (rCO), the main benefits are reduced load on arable land and water deprivation.[1] Mechanical textile recycling also has the potential to reduce impacts associated with dyeing, since the colour from the previous life of the garment remains in the fibre, and avoids emissions associated with disposal in landfill or incineration.

Mechanically recycled cotton can be processed from post-industrial (pre-consumer) or post-consumer waste. Recycled fibres can also be named secondary fibres. In contrast, primary fibres are made from new material grown or extracted from the earth.[2] Recycled fibres can be used in textiles (fibre-to-fibre recycling) or be used in other industries as insulation or in composites.

Cotton can also be recycled chemically. In this process, the chemical construction of the fibre is altered, and the resulting fibre will be a type of viscose fibre. This process uses more energy and chemicals. However, the fibre will be of same or similar quality as a primary viscose fibre.

Cotton recycling: post-industrial waste recycling

Post-industrial waste (also known as pre-consumer waste) utilizes material generated during product manufacturing. Examples of post-industrial waste include fibre waste during yarn spinning, selvage from weaving, fabric remnants, cutting room waste, excess production, inventory and unsold items. Note that only material that is diverted from a waste stream should be called pre-consumer waste.

Wasted materials are collected throughout the manufacturing process. Manufactured cotton apparel products typically generate 20–40% waste in the production pipeline (from yarn spinning, weaving and knitting, dyeing and finishing, to cutting and sewing). Of this about 5–10% occurs in the yarn spinning stage (mainly in the form of fibre) and 15–30% occurs after fabric construction (in weaving/knitting, dyeing/printing, and cutting and sewing).

Rather than discarding this waste, manufacturers and mills recycle it within the existing textile manufacturing system. Energy may be required to convert the waste into usable forms, and the waste may be used as a raw material in the textile plant. The textile may also be sold and used for some other purpose unrelated to textiles and apparel, such as stuffing or padding in automobiles, furniture or mattresses, as raw material for paper or for coarse yarns (e.g., yarn for mop heads, industrial belting, rope, twine), and as insulation.

Spinning Waste

Fibre waste from spinning is often segregated into “fibrous waste” and “trashy waste”. Fibrous waste contains a high percentage of short fibres, and will ordinarily have reduced strength, which can lead to fibre breakage. When the yarn type and quality demands allow, fibrous waste can be fed back into the production line and blended with incoming primary fibre, a practice which also reduces costs. The key is consistency and thorough blending to maintain a quality yarn.

Trashy waste is generated by cotton openers/cleaners and cotton carding and is generally composed of 50% fibres and 50% trash (also called ”non-lint”). The trash component usually includes plant leaf, stem, seed particles, bale wrap fragments, etc. Unlike fibrous waste, trashy waste must be processed through a special fibre reclamation machine before reuse. Only a small percentage of yarn spinners have the capability to reclaim fibres from trashy waste.

Cutting room waste, fabric remnants and unsold items

Cutting room waste and fabric remnants can be recycled and returned to fibre form if they are 100% cotton. Garneting is the process by which these forms of waste are shredded to a fluffy, fibrous condition simulating the original condition of the fibre.

For sewn garments, all trims (zippers, buttons, rivets, leather patches, etc.) and heavy/taped, folded and double-stitched seams are removed before garneting. The items are then separated by type and colour and chopped into small pieces (usually measuring 2–6 square inches). The fabric is then run through a series of high-speed cylinders covered with wire (e.g., saw wire), or steel spikes, until it forms individual fibres.

Since the waste is usually sorted by colour prior to garneting, each resulting bale of recycled fibre is one colour or one colour family. The yarn spinner can create custom shades and heather effects by blending fibres from several different bales together, not unlike the way dyes are used to create tertiary colours.

1 “Siptex WP5 report: Life cycle assessment of textile recycling products”, IVL, 2022.
2 “Textile Exchange Guide to Recycled Inputs”, Textile Exchange, 2021

THE VISUAL EFFECT CAN BE QUITE STRIKING, SINCE COLOURS CREATED THIS WAY HAVE A DEPTH AND LIVELINESS.

Because of short fibre length, recycled cotton is normally blended with primary cotton or synthetic fibres to facilitate processing and add strength to the yarn. Today, 20–40 % rCO fibres can be added to a cotton yarn for apparel use. As the mechanical recycling process is developing into a more gentle process that retain more of the fibre length, a higher percentage recycled fibres could be added in the future.

The synthetic fibre acrylic, polyacrylonitrile (PAN), and polyester (particularly recycled polyester) can be used to add softness to the yarn and the resulting fabric. By blending recycled cotton with acrylic or recycled polyester, a 100 % recycled product can be produced.

Estimates are that 18–26 % of fibres sold in Europe could be fibre-to-fibre recycled. Of all cotton fibres sold on the market in 2021, approximately 1 % were recycled. Looking at all fibre materials, polyester is the fibre with the largest share (approx. 15 %) sold as recycled.[3] However, it should be noted that approximately 99 % of recycled polyester fibres available today are from a source outside the textile industry, plastic bottles. As the material in bottles are of food-grade quality, there is an ongoing debate if it is better to keep the material within the food industry and use lower grade polyester in the textile industry.

Types of cotton recycling: post-consumer waste recycling

Discarded material from households, commercial, industrial and institutional facilities (e.g., garments, carpet, automotive upholstery) are collected, deconstructed if necessary, and either recycled and used as raw material in the textile facility or sold and used for some other purpose unrelated to textiles and apparel.

Post-consumer cotton waste tends to be "down-cycled" (converting waste used in lower quality products) to non-visible products such as nonwovens and felts for applications in car insulation, roofing felt, loudspeaker cones, fillings, etc. Upcycled garment-to-garment solutions are ideal but are currently complex and costly to develop, since they involve labour-intensive operations and are carried out in rich consumer economies, where labour costs are high.

READ MORE ABOUT UP-CYCLING IN APPENDIX.

Post-consumer recycling demands a collection of post-consumer textile waste. Today, textile collection is mostly performed by non-profit charity organizations. Although some countries within the EU already have a separate collection of left over or unused textiles carried out by the state, this will be obligatory by the year 2025. This means that the availability of post-consumer waste will increase which could lead to an increase in the availability of recycled fibres. Further, the European Parliament is working on legislation to increase the use of recycled fibres in textile and clothing manufacturing.[4]

Fibre properties

During the mechanical recycling process, the fibres undergo a rather harsh treatment which cut off the fibres and results in a significantly shorter fibre. When comparing the fibre length of different fibre batches, the mean length and short fibre content (SFC) is often referred to. Short fibre content is given in percentage and includes all fibres shorter than 12.7 mm. Mechanically recycled fibres have a lower mean length and a higher SFC. Further, the neps content is larger in mechanically recycled fibres, due to the large SFC and more fragile fibres.

Post-consumer textile waste has had a life where it has been used; it has been exposed to laundry, drying and sunlight. Because of this, the fibres have lost some if its initial properties and we can expect that the quality of post-consumer recycled fibres are lower.

Post-consumer waste from a known source with large quantities of similar quality can be recycled more easily. This is because the recycling process can be adapted to a specific textile material (fibre material, yarn, textile construction) and the fibre thereby loose less of its properties.

Rieter has attempted to classify mechanically recycled cotton fibres, see below table for fibre details.[5] Mean length is the average length of fibres and short fibre content is the proportion of fibres shorter than 12.7 mm.

3 "Preferred Fibre and Materials Market Report", Textile Exchange, 2022

4 "EU Strategy for Sustainable and Circular Textiles", The European Parliament 2022

5 "The Increasing Importance of Recycling in the Staple-Fibre Spinning Process", Rieter 2020

Classi-fication	Very good	Good	Medium	Poor	Cotton reference
Mean length	17 mm	14 mm	13 mm	10 mm	21 mm
Short Fibre Content	45 %	55 %	60 %	78 %	24 %

Table Classification of mechanically recycled fibres according to Rieter (2020).[5]

Due to the shorter fibres of recycled cotton, there are limitations to the thinness of yarn that can be produced with these fibres, depending on the percentage of recycled fibres used. Generally open-end spinning methods works better for short fibres, while ring spinning has limitations in terms of short fibre content. This is also reflected in the certification of products made from recycled products. The yarn spinning method used and percentage recycled fibres regulate if the yarn can be passed as recycled.

There are two standards from Textile Exchange for certification of recycled content in textiles; Recycled Claim Standard and Global Recycled Standard.[6,7] Both standards have the same definitions for recycled content and follows the recycled material through chain of custody. Both standards also have restrictions regarding the thickness of the yarns used in certified products depending on the content of recycled fibres. This is a result of the short length of recycled fibres that makes the spinning of thin yarns more difficult. However, these limits may change over time as the recycling methods improves.

Source: TextileExchange

6 "Recycled Claim Standard", Textile Exchange, 2020.

7 "Global Recycled Standard", Textile Exchange, 2020.

Optimize sustainability benefits

- Promote yarn spinners that make optimum use of waste.
- Promote yarn spinners that use trashy waste.
- Promote suppliers who make use of recycled cotton yarns.
- Encourage all manufacturers within the supply chain to reclaim and recycle raw materials. Bring together supply chain partners to make the use of recycled materials more convenient and less expensive.
- Minimize, to the extent possible, transport of the waste.
- Ensure that there is proper evidence that the material being used would have otherwise gone into the waste stream.

Availability

The availability of recycled cotton for textiles is growing today, and is likely to increase as resources and landfills become more restricted and recycling innovations are developed.

Several projects and sources for recycled fabrics exist in the United States, India, Japan, China and Europe. Cotton textiles are recycled both mechanically and chemically today on a growing market.

End use

Post-industrial waste is reused by the textile industry and spun into yarns with new apparel applications.

Post-consumer waste is mostly reused in nonwovens and felts, insulation materials, linings, furniture padding and filling and paper manufacturing. Development is ongoing and we can expect the area of use for mechanically recycled post-consumer textile fibres to be used in high value products in the near future will increase. Post-consumer cotton waste is also chemically recycled for use in textile applications.

Innovation opportunities

1. Create merchandising and marking opportunities to turn any negative associations with recycled yarns into positive stories.
2. Design products that feature promote the unique, heathered or tweed characteristics of recycled cotton.

3. Create stripes with recycled cotton blends and primary cotton for heather/solid effects.
4. Develop “closed-loop” opportunities, such as collecting waste from your company’s customers, textile or apparel producers and re-using that their waste in new products.
5. Develop garments that are designed to be easily deconstructed to enable a retail take-back and recycling program. Experiment with seaming, and a variety of disassembly mechanisms in different fabrics.
6. Develop the mechanical recycling process towards a gentler disentanglement of fibres to retain more of the fibre’s initial properties.
7. Develop the separation of recycled fibres to use different length fibres for different end uses.

Novel Enzymatic recycling of Textiles

Enzymatic recycling of textiles is an innovative and sustainable approach to address the challenges posed by textile waste generated in the fashion and textile industry. This method involves the use of enzymes, which are biological catalysts, to accelerate the rates of some degradation reactions of textile materials into their base components, according to the type of enzyme used and the processed material. This process enables either the degradation and/ or the recovery of the fibres coming from a textile structure, minimizing overall environmental impact due to the milder conditions of the enzymatic treatments compared to conventional chemical recycling.

In most cases, the enzymatic approach is used for the recycling process of blended waste textile materials.

Enzymes are selective catalysts, they catalyse specific reactions according to their class.

Cellulase enzymes can be used to catalyse the breaking down of cellulose fibres found in cotton and other natural fibres containing cellulose and polysaccharides, and thus have no effect on protein-based fibres like wool. In recent years, this approach has been studied for the recycling process of blended waste textiles to separate fibres according to type.

Cellulose: Cellulases are usually a cocktail of multi-enzyme complexes with different functions and targets, this enzymatic mixture works along the cellulose chains and accelerate their breakdown remarkably.[8] The sugars and carbohydrates resulting from this process can be used to generate bio-products by fermentation to produce bioethanol or simple glucose.

Additionally, this cellulase mixture can be used to recycle textiles waste from blends that contain cellulose (such as cotton/polyester blends) by separating the cellulose component, such as cotton, from the blend with polyester, which facilitate the recovery of the polyester as well to be reused.

Furthermore, enzymatic treatments of cellulose can be used in technologies such

8 M. Kahoush, N. Kadi, Towards sustainable textile sector: Fractionation and separation of cotton/ polyester fibres from blended textile waste, Sustainable Materials and Technologies. 34 (2022). https://doi.org/10.1016/j.susmat.2022.e00513.

as BioCelSol.[9] It works as a first step to regenerate cellulose fibres. An advantage of this technology compared to the conventional viscose process is the carbon disulphide is not used, which makes it better for the environment and also the health of the working force.

It is worth mentioning that some polymers are not possible to re-polymerize after their break down into smaller fragments. Cellulose for example, decomposition via enzymes to glucose monomers which cannot be used to reform cellulosic chains again.

Poly(ethylene terephthalate) (PET): The recycling process of PET utilizing enzymes is a biotechnological route with a big potential for monomer recovery and resynthesis.

All enzymes that have been characterized as PET hydrolases for recycling so far, belong to the class of esterases enzymes, such as carboxylesterases, cutinases and lipases.[10]

Cutinases are biocatalysts for the hydrolysis process of ester bonds of the cutin,1 which is a substance found in plants that has similar chemical structure as PET. While lipases catalyse hydrolysis of lipids like wax and fatty materials.

However, the enzymatic PET depolymerization still faces challenges to become a competitive alternative at an industrial level. The large size of the enzymes molecules hinders their penetration into the polyester material, thus making it hard to access the layers beneath the surface, which results in a time-consuming hydrolysis process with low yields. In addition to the problem of separation of used enzymes after their use for treatment, increasing the overall cost of the process.

Wool: Enzymatic recycling and or decomposition of wool, especially from its blends have been reported in research. Complete degradation of wool fibres was achieved by application of a keratinase enzyme in a two-step process where wool was separated from PET fibres.[11] The polyester fibres were used to produce recycled PET and the nutrient rich keratin hydrolysate is suitable for bio-fertilizers or animal feed, to increase the circularity of the process.

Pre- and post-treatments

The collected textile waste is cleaned, removing any contaminants, and buttons, zippers, or other non-textile components. The textiles are then shredded or mechanically processed to increase their surface area, which makes them more accessible to enzymes and improves the yield.

After the treatment, an isolation and purification processes are conducted so the resulting mixture of decomposed products is isolated, and purification process is applied to separate impurities and residual additives from the desired fibres or monomers.

In the case of synthetic fibres like polyester, the isolated monomers can be polymerized again to create new fibres with properties similar to primary fibres. This can involve chemical processes or bio-based approaches, depending on the desired end-product. Finally, the recycled fibres or polymers are then spun into new yarns and used to produce textiles, which can be used for producing clothing, accessories, and other products.

Sustainability aspects of enzymatic approach to recycling

Advantages of enzymatic recycling of textiles	Challenges facing the enzymatic recycling of textiles
Reduced environmental impact	Research on finding different enzymes that can be used on different materials
Maintaining fibre quality	Higher costs compared to traditional methods
Good option when recycling blended textile waste	Scale-up challenges from lab to industrial scale requires careful consideration of factors
Improve circularity since the resulted materials after treatment are beneficial for many applications	Some materials obtained cannot be used to produce a recycled fibre and must go to different applications

9 M. Vehviläinen, M. Maattanen, S. Grönqvist, A. Harlin, Sustainable continuous process for cellulosic regenerated fibres, n.d. https://www.researchgate.net/publication/349213305.

10 A. Carniel, V. de A. Waldow, A.M. de Castro, A comprehensive and critical review on key elements to implement enzymatic PET depolymerization for recycling purposes, Biotechnol Adv. 52 (2021). https://doi.org/10.1016/j.biotechadv.2021.107811.

11 L. Navone, K. Moffitt, K.A. Hansen, J. Blinco, A. Payne, R. Speight, Closing the textile loop: Enzymatic fibre separation and recycling of wool/polyester fabric blends, Waste Management. 102 (2020) 149–160. https://doi.org/10.1016/j.wasman.2019.10.026.

The TEX2MAT project[12] is an Austrian-based research project conducted by a consortium of thirteen research institutions and private businesses that offers a solution for material recycling. It is one of the bigger examples of efforts towards the biological approach for textile recycling. Multiple case studies, pre- and post-consumer cotton/polyester textiles from the Austrian SME sector were investigated involving the enzymatic hydrolysis of cellulose. As previously mentioned, cotton can be converted into glucose and polyester can be recovered. The project team achieved complete removal of cotton from the textile and the weaving of new towels with the recovered and recycled polyester.

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12 B. Piribauer, U. Jenull-Halver, F. Quartinello, W. Ipsmiller, T. Laminger, D. Koch, A. Bartl, Tex2mat – next level textile recycling with biocatalysts, Detritus. 13 (2020) 78–86. https://doi.org/10.31025/2611-4135/2020.14030.

Part 8: Textiles for sustainability and circularity

The technical and digital advances in Artificial Intelligence, Robotics and Internet of Things

Artificial Intelligence

Artificial intelligence (AI) is the intelligence of software and machines combined as opposed to the intelligence in humans, animals, and plants. We use it every day in search engines such as Google, and in recommendation systems at Spotify, Netflix, or YouTube. Artificial intelligence is nothing new, it was first described in 1935 by Alan Turing[1] but it is not until recently that computation power became affordable potent enough to cater to the masses and more advanced applications such as ChatGPT became available for everybody to use.

AI is being used in the apparel and textile industry in different settings and is currently limited to applications that only involves transmission of information and decision making, it still has limited abilities to guide robots and other manufacturing equipment and to create flexible automation for apparel- and textile manufacturing. Current application include:

Marketing

Recommendation systems for up-sales and cross sales. Depending on what you have browsed in an online store or what you have previously bought, AI can predict what other things that you would like to purchase and suggest something more expensive (up-sales) or something that would complete the outfit you just bought (cross-sales).

AI can do market scans and predict demand through advanced image- and data analysis. It can scan vast amounts of relevant web shops and inform product- and marketing teams about current fashion trends, what are exposed in other companies' web shops, and assist to predict sales.

1 https://www.britannica.com/technology/artificial-intelligence/Alan-Turing-and-the-beginning-of-AI

Supply chain management

AI can be used to allocate inventory to locations where demand of a certain product is higher and increase service level, sell-thorough and decrease lost-sales.

AI is widely used to assess the performance of suppliers and production processes and can be used to predict machinery maintenance, to warn if machine operators are unwell, and to plan production runs. It can also be used to predict supplier and facility performance and estimate need for audits and other interventions for increased sustainability performance.

Sustainability opportunities

Artificial Intelligence has several opportunities to enable increased sustainability in textile value chains due to modern computers ability to processes and make sense of large amount of data. In a not too far future AI will enable flexible automation for textile manufacturing in several stages of the textile value chain, from raw material to end-of-use processes. Flexible automation is often seen as a crucial component for manufacturing close to market in high-cost regions.

Application: Remake machine

At Science Park Borås, Do-tank centre an AI-enabled re-make machine is being built. It is built to up-cycle garments that for various reasons come back from the market, such as customer returns, warranty claims, dead-stock, second hand etc. Figure 1 illustrates the system.

The system consists of:

- A conveyor system that moves the garments to the assessment station, to the different production stations and that holds the garment in inventory
- Workstations with sewing, printing, embroidery and other up-scaling processes
- Vision system for assessing garment

Each garment that comes into the system is assessed by a vision system that identifies the issue with the garment (greasy spot, ripped hole, abrasion, pilling etc.) and where it is located. Depending on the type of issue the machine suggests various up-cycling options. The system is demand driven so when a garment has been assessed it is

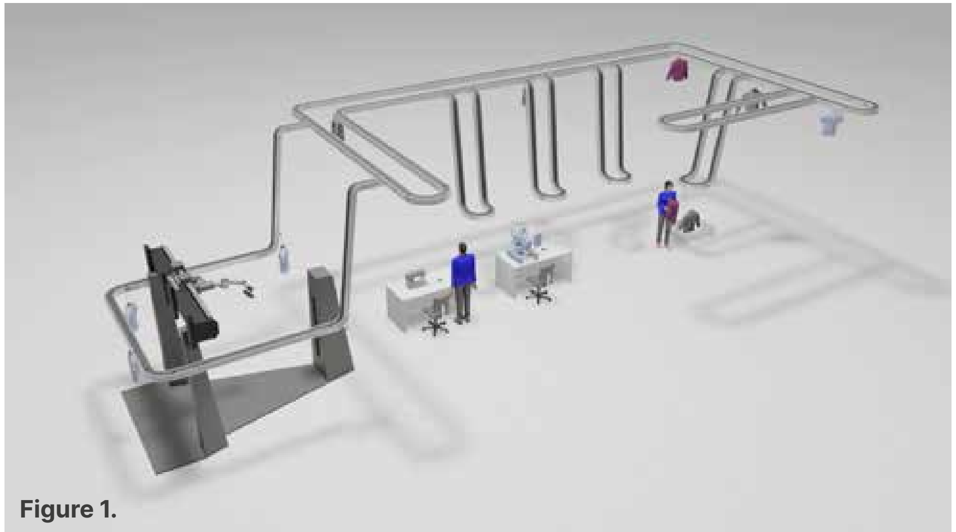


Figure 1.


Figure 2.

placed in an on-line shop and waits in a storage area for a customer place an order before any other processes are made.

Robotics

Currently AI has many applications where only information needs to be transmitted and managed. The applications where AI is used to suggest, control and perform advanced production operations such as sewing is still in its infancy. Development is picking up pace and within a few years robots will become intelligent and dexterous enough to manipulate flexible material and manage changing environments. The largest challenge for increased robotization in textile manufacturing is to control the textile material that moves continuously and that the robots are still not intelligent enough to predict and react to such movement and does not have the dexterity to manipulate flexible materials.

Example of Application: Robotic seamstress

Science Park Borås together with TEKO explored the opportunities around robotics in sewing operations. The project's long-term purpose is to enable production in high-cost regions such as Sweden with the help of automation and robotization of the assembly process for clothing, furniture upholstery, technical textiles etc. The goal of the project is to create a picture of what is possible in the current situation and gather relevant partners for further research and development.

The project included two tracks, one digital track where a virtual environme-nt was built in a simulation software, where a digital robot was trained how do find and manipulate a virtual fabric. When the digital robot has had enough training the set up will be tested in a real live setting, issues are mapped and then it goes back into virtual training to fix those issues. Figure 2 illustrates the digital environment where the robot practice on virtual fabric.

The physical track included desig-ning and testing new gripping devices for increased dexterity of the robot arm.

Figure 3.

Figure 3 illustrates the gripping device that was developed in the project by Charles August at Mälardalen Univeristy in collaboration with the project Mikrofabriker at Science Park Borås. The gripping device works well for a wide range of fabrics, even thin fabrics and can be 3D-printed in household machines.

Autonomous delivery

The last mile of any delivery process is usually the most expensive and resource intensive part of any textile value chain. In general it accounts for 11-13% of the carbon emissions from the value chain but it is not uncommon that it accounts for up to 25%, if a car truck is used and the transportation is a few kilometres in distance. In a circular system we will also have a first mile delivery problem where things need to be taken back from the customers at a very low cost and with low environmental impact to be profitable and sustainable. One way to address this issue is by using autonomous delivery robots such as Hugo Delivery robot[2] (Figure 4).

Figure 4.

It has approximately 98% lower climate impact compared to a conventional delivery truck and each delivery costs about 2 SEK. Hugo can also operate outside convenient work hours and is less intrusive visually and audibly in for example city environments. In addition to being less expensive and less resource intensive technology, Hugo also has the potential to create better customer experiences and make return processes much faster. Hugo's low cost enables it to wait outside the house when someone is trying on what was just delivered and to bring returns back to the distribution centre.

Internet of things

The Internet of Things is described as devices with sensors and the ability to process and exchange data through Internet-like networks. It is expected that the world will have close to 30 billion connected by the year 2030[3]. For sustainability purposes in the apparel- and textile industry this have a few applications.

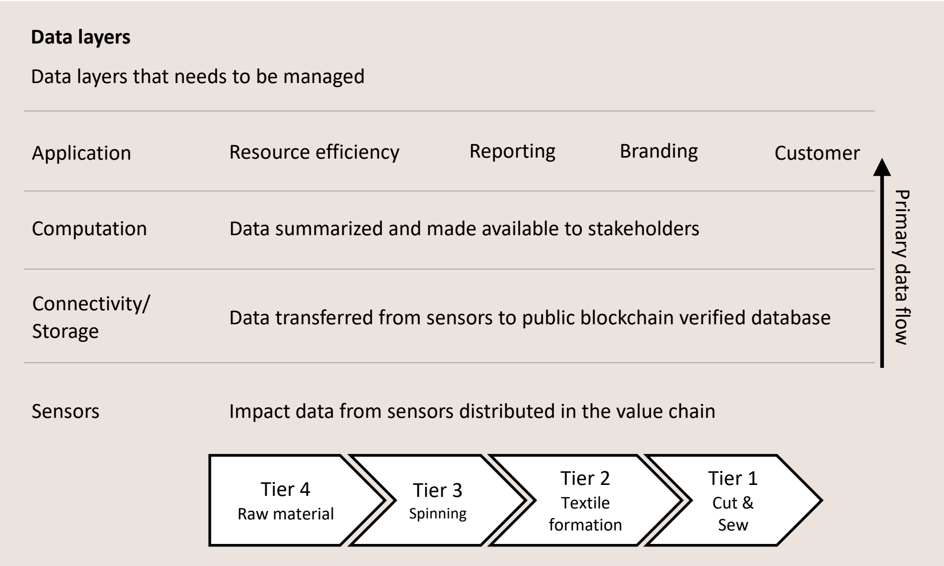
Transparency, traceability and the digital product passport

In 2022 it became painfully evident for several apparel- and fashion companies that the use of global averages of climate impact data rather than primary impact data to communicate their environmental impact was not accepted by the consumer authorities in several European countries. The data that was used was too old, irrelevant for their specific supply chain and had too low external validity for customers to be able to evaluate the actual sustainability impact of an apparel or textile product. Additionally, the European Union released the EU Textile Strategy[4] and set starting dates for the digital product passport and several other directives and policies that require companies to report on primary data sets. One way to get primary data and then be able to communicate truthfully with stakeholders is to use Internet of Things sensors to collect data from production facilities. This includes energy consumption, water use, wastewater treatment and quality, emissions to air, soil quality, indoor air quality etc. Figure 5 illustrates an energy meter that collects energy consumption data, transfers it via Internet to a cloud-based vision system and makes it available to stakeholders.


Figure 5.

2 https://hugo.tech/
3 https://www.statista.com/statistics/1183457/iot-connected-devices-worldwide/
4 https://environment.ec.europa.eu/strategy/textiles-strategy_en

Figure 6 illustrates the different data layers that are typically associated with transmitting data.



Example of Application: Black box for transparency

Science Park Borås has in the project Mikrofabriker[5] together with the industry partner Wideco AB[6] developed a sensor package with data transfer capabilities. The aim of the project was to develop an innovative and integrated scheme deploying sensor packages that can be easily distributed in textile value chains. The sensors have the capability to collect primary impact data, verify the data on a public blockchain and make it available on an open application program interface (API). The innovation offers a twofold benefit. First it provides insights to suppliers and producers in global value chains with information that affects their textiles and clothing sector business model. Second it provides valuable data to scientists and engineers seeking to develop solutions to pollution problems. Relevant data can also be conveyed to customers through a related consumer facing app (Figure 7).

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5 https://scienceparkboras.se/2022/11/mikrofabriker/
6 https://wideco.se/

Batteryless technology

With the help of batteryless broadcast techniques and smartphone, products can communicate with users and machines throughout the textile value chain in completely new conditions. A sweater that is forgotten in a wardrobe could for example remind the owner of its existence and either put itself up for sale at second hand web-shops, find another potential user nearby, or simply be worn again as a part of a new outfit and by doing so create a new life for it. Batteryless sensors can activate locked up products and contribute to new circular consumption patterns for fashion products where the products start to generate revenue several times during its life cycle and becomes beneficial for more users. There are a few technology providers such as Wiliot[7] and Nexit[8] Figure 8 illustrates a conversation between a garment and user/owner and includes the delivery robot Hugo as well.

Figure 7.

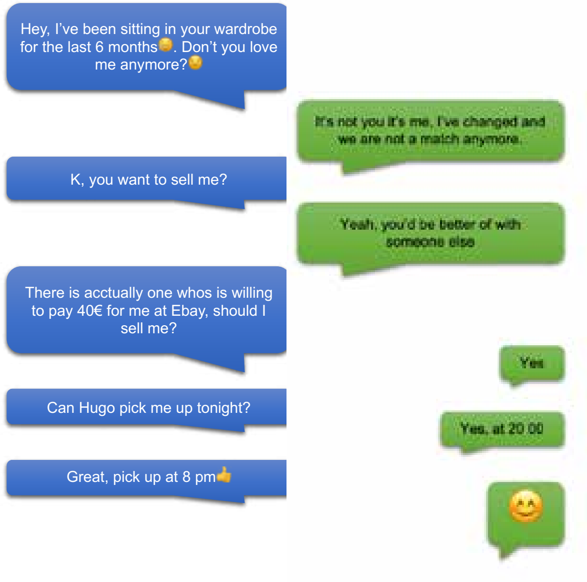

Figure 8.

Sustainability opportunities

	Before use	During use	After use	Considerations
Artificial intelligence	Demand prediction to increase sell through, service level and decreased lost sales Supply chain sustainability assessment	Enabler for services that activates products in use-phase.	Assessing quality of second-hand garments. Finding new users and use-cases for garments at the end of their useful life.	Making sure AI is a helpful tool for humanity to take us out of the mess we made and refrain it from realizing humanity is the problem and wiping us of the earth.
Robotics	Ease seamstresses from strenuous and monotonous work Enable production in high-cost regions.	Delivery robots can enable efficient garment sharing services.	Delivery robots can enable more sustainable take-back systems and ensure that products are taken back in ways that keeps garments fresh.	Look out for unwanted rebound effects. Such as when something can be made more efficient it does not necessarily result in lower use of resources but increased consumption.
Internet of things	Collection of primary data from production.	Digital product passport Enabler for services that activates product in usephase	Data that is collected through sensors in garments in usephase can inform sorting facilities	•Integrity and data privacy risks for people. •Trade secret risks for companies.

7 https://www.wiliot.com/
8 https://nexite.io/

Circular Design

Designing for a circular economy can be described as adopting a holistic approach to material use, product design and the business model, in order to create a system that is as resource-efficient and as sustainable as possible. Circular design can be defined according to the four system principles, as proposed by the expert group for Circular Design, working on behalf of the Swedish Government's advisory board, the Delegation for Circular Economy:

> Reduce the need for material resources
> Keep products and materials in use
> Design out waste, loss and pollution
> Regenerate natural systems

In practice, designing for circularity implies developing a coherent design strategy, working toward the circular principles in all phases of the product lifecycle; before, during and after use. However, designing for circularity might also lead to conflicts of interest, for example between product recyclability and longevity, and it can be difficult to know what to prioritise. When designing for circularity it is therefore important to start with the purpose of the product, taking to account the customer needs, desired functions and the aesthetic vision. It is also crucial to develop services and infrastructure linked to the products to unlock the value potential in the circular flows, both for the company as well as for the customer. Such services can be take-back schemes and re-sell operations or repair and upgrading of products.

Science Park Borås has developed a three-step process for companies to start implementing circular design.

1. Develop a circular strategy.

The strategy should be integrated in the company's mission and core values and driven by the company's passion. There needs to be a clear link between strategy, business model, product development and material use.

Company Strategy

Make design choices and trade-offs with the company´s strategy and the product´s purpose in focus

Circular objective	Material	Functionalization	Construction	User behaviour
Circular materials Raw materials that contributes to circular cycles (technical/biological).	Use raw materials that contribute to the restoration of biological systems. Use raw materials of recycled origin.	Use the best available technolofy for reduced chemcial,energy and water usage	Design the product so that material consumption is minimized. Enable waste material to be used as raw material in other processes (industrial symbiosis.	
Longevity Enables reuse, remanufacturing, remake and service based on business models.	Use materials that last over time in terms of quality. Use materials that age beautifully. Use materials that do not pollute the enviroment during the use phase.	Choose functional chemicals and dyes that do not harm the user and the enviroment during the user phase. Choose colors and chemicals that do not lose effect during use or care.	Allow for worn-out garments and components to be easily repaired or replaced. Make products that allows multiple application.	Encourage the wearer to use the product over time, for example through timeless or iconic design. Enable the product design to be updated or renewed during phase. Enable the size of the product to be adjusted or changed during use phase. Enable the product function to be upgraded during use phase. Enable versatility and encourage wearing the product many different ways.
Material recycling	Aviod mixing different fibers in a textile material. Avoid stretch materials.	Use Chemicals that are compatible with the intended material recyling process.	Strive for garments parts and components to be of the same type material. Allow for easy separation of different materials and components in the recycling process	Enable redesign and repair that does not add new components of additional material types.

Purpose and function of the product

Develop circular guidelines for product categories

The next step is to plan the desired product life cycle and develop circular design guidelines for each product category. This is not a "one size fits all"-approach, and it is important to consider the purpose of the product to understand, for example, how longevity is best achieved, or the most suitable end of use-solution. Similar to regular design processes, it is important to start with the needs of the user, but designing for circularity also includes the needs of all stakeholders in planned life cycle, for example the second customer, sorting facility, remanufacturer or recycling company.

A model that combines design criteria with circular objectives throughout the life cycle has been developed.

2. Start designing for circularity

On this level, circular design can be divided into four objectives:

1. sustainable resource use – this includes the use of renewable energy and a regenerative approach to resource extraction and production processes, as well as avoiding overproduction and other unnecessary use of resources.
2. long and safe life – products should be well designed according to the right functions and aesthetic vision. They should be free from chemicals and materials that can harm the user or be released into the surrounding.
3. Extended life and reuse – products should be made to ensure multiple use-phases in circular business models, for example resell or rental schemes. They should also be designed to facilitate repair and upgrading to extend the life.
4. remanufacturing and recycling – products should be designed to fit into existing recycling processes according to the planned life cycle.

Science Park Borås has developed Designers Toolkit to help designers implement circular design criteria in products. The toolkit covers 17 circular aspects and is free to use.

READ MORE: DESIGNERS TOOLKIT - DESIGNERS TOOLKIT (CIRCULARHUB.SE)

Challenges and opportunities

When comparing textile fibres in terms of sustainability, it's important to reflect on various factors such as environmental impact, social aspects, resource consumption and economy.

It's essential to consider fibre's entire life cycle and value chain, including cultivation or extraction, processing, and disposal. It's preferable to try to use renewable fibres where possible, and extend the life span of already existing fibres, both oil-based and natural fibres, through reuse, recycling and keeping them in the production loop.

No fibre is perfect, but some often exhibit more sustainable characteristics. Making informed choices about the fibres used and supporting eco-friendly production practices contribute to a more sustainable fashion industry.

There is no single solution to the selection of a sustainable fibre. Each fibre has different impacts at different points in its lifecycle. Lack of transparency about current manufacturing practices, traceability, a fragmented industry, lack of agreement on the means to measure and assess lifecycle data, cost and more—all influence our decisions for sustainability we have to make on a daily basis.

The implication of higher costs of sustainable fibres is one of the main challenges facing the industry. This can be a barrier for widespread adoption, especially in price-sensitive markets.

While some sustainable fibres are still facing certain performance challenges, comfort and durability limitations compared to traditional synthetic fibres ensuring that the future sustainable options meet quality and durability standards is important.

On the other hand, the extraction and processing of certain sustainable fibres might require specialized equipment and technologies that are not readily available, posing challenges for scalability on industrial level that will delay implementation.

Trade-offs are inevitable, since It's not always straightforward to determine which fibre is the most sustainable for a certain application. Thus, it might be wise to make trade-offs between factors such as water usage, energy consumption, land use, and more.

THESE CHALLENGES CAN ALSO BE EXCITING, FOR THEY INEVITABLY LEAD TO INNOVATION.

In order to innovate for sustainability, understanding the impacts of each fibre that your company currently uses is essential. And be aware of the options and processes currently available can lead to rapid adoption of alternatives, with multiple benefits.

The textile industry has an opportunity to invest in research and development of new sustainable fibres that offer both functionality and environmental benefits. Innovations in processing methods of existing fibres to increase their sustainability is required more than ever to implement the new strategy of the European Commission regarding the textile sector.

Designing textiles with end-of-life considerations in mind is important, it can generate new circular business models, where fibres can be recycled or upcycled and hence, reducing waste.

Collaborations among stakeholders across the supply chain to develop and promote sustainable fibre solutions can play an important role towards a sustainable textile industry.

Finally, raising the consumer awareness and demand for sustainable products, along with introducing new regulations can put pressure on manufacturers and brands to prioritize eco-friendly fibres.

We'd like to invite you to play an active role in the continued development of this Toolkit. Feel free to contact us with additional thoughts and recommendations as you ask questions of suppliers and manufacturers and test your own ideas in the field.

Appendix

Biodegradability

Although natural fibre in its pure form is biodegradable, the amount of time it could take for a natural fibre to decompose naturally and in a short period of time is dependent upon a number of conditions—including how much air, temperature, sunlight and microorganisms the fibre is exposed to. If the waste is buried in a landfill, it can take even longer for it to decompose.

According to the European Commission, biodegradable waste does not include natural textiles.[1] The United States Federal Trade Commission (FTC) defines biodegradable in their Green Guide as a product or package that "completely breaks down and returns to nature, decomposing into elements found in nature within a reasonably short period of time after customary disposal."[2]

Natural fibre garments or products that are:

1. ...dyed with synthetic dyes
2. ...blended with synthetic fibres
3. ...sewn with synthetic thread or have synthetic trims
4. ...blended with natural fibres treated with chemicals

... will take even longer to decompose, and will leave residues behind in the soil, which can be toxic.

Furthermore, the type of textile finishing and treatment used can hinder the biodegradability in some cases of natural fibres. Antimicrobial treatments for example can affect the ability of microorganisms to degrade the fabric.

It should be mentioned that bio-based textiles are not necessarily biodegradable, and vice versa.

1 ec.europa.eu/environment/waste/compost/

2 www.ftc.gov/news-events/media-resources/truth-advertising/green-guides

Reuse and Waste to energy

Waste-to-energy is a recovery method that creates energy from incineration of waste, providing Europe with a significant part of the energy needs, but should not be used if the waste can be recycled in any other way. The waste hierarchy must always be considered in first place by giving priority for waste prevention, reuse, material recycling and biological treatment, other recycling such as energy recovery and at the end disposal.

The Government in Sweden proposes that municipalities should inform households and operators to ensure that textiles are reused whenever possible.

According to the Swedish waste management report of 2022, on average, 40 percent of the bulky waste went to material recycling, including biological treatment of garden waste, such as scrap metal, hard plastic, corrugated cardboard, textile waste, flat glass and gypsum. Of the remaining 60% of the bulky waste, 56 percent went to energy recovery and 4 percent to landfill.[3,4] With the implementation of the producer's responsibility for textiles, starting in 2025 the incineration of textiles is expected to gradually decrease.

The reuse of materials should be considered a priority before relying on waste-to-energy incineration. This allows for the maximization of the embodied energy and resources used to create the product, and the ability to capitalize repeatedly off the same materials.

Outside of the european union

Any garments or products sold outside of the European Union could increase the load on landfills or end up in oceans and large bodies of water, where they can harm aquatic species and potentially end up back in our food and water. Lack of regulations and transparency in supply chain in these regions are contributing to this problem.

3 http://www.avfallsverige.se/fileadmin/uploads/Arbete/Avfallshantering_2017_eng_low.pdf

4 https://www.avfallsverige.se/in-english/

Upcycling

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Upcycling is an approach to deal with waste-textile materials, in attempt to manage the increasing amounts of this waste due to fast fashion and changing trends.

It is described as "*a process in which used or waste products and materials are repaired, re-used, repurposed, refurbished, upgraded and remanufactured in a creative way to add value to the compositional elements*".[5]

This approach is gaining more and more attention due to environmental impacts and limited resources from repairable products wasted. Although it has been conducted for centuries on small levels. Upcycling can contribute to reducing waste and extend the lifespan of materials and, therefore, their sustainability.[6,7,8,9] However, it is still considered as a "niche practice" and is still facing many challenges in scaling up, since it is mostly conducted by small businesses and individuals. Additionally, there is no "agreed on" specific definition of upcycling; some consider it as a form of improved recycling, while others adopt the concept of creating a higher-value product, following "cradle to cradle" approach.[10]

5 J. Singh, K. Sung, T. Cooper, K. West, O. Mont, Challenges and opportunities for scaling up upcycling businesses – the case of textile and wood upcycling businesses in the UK, Resour. Conserv. Recycl. 150 (2019), 104439, https://doi. org/10.1016/j.resconrec.2019.104439.

6 S. Kliuciute, Up-Cycling Textiles, 2020.

7 Y. Ma, L. Rosson, X. Wang, N. Byrne, Upcycling of waste textiles into regenerated cellulose fibres: impact of pre-treatments, J. Text. Inst. 111 (2020) 630–638, https://doi.org/10.1080/00405000.2019.1656355.

8 org/10.1016/j. wasman.2019.07.040.

9 P. Pandit, G.T. Nadathur, S. Jose, Upcycled and low-cost sustainable business for value-added textiles and fashion, Elsevier Ltd, 2018, https://doi.org/10.1016/ B978-0-08-102630-4.00005-4.

10 Kahoush, M., Kadi, N. (2022). Towards sustainable textile sector: Fractionation and separation of cotton/polyester fibres from blended textile waste. In "Sustainable Materials and Technologies" (Vol. 34). Elsevier. https://doi.org/10.1016/j.susmat.2022.e00513</div>

Consumer Care and Washing

Proper instructions about care have several benefits, such as fewer quality claims, prolonging the consumer user-phase of the textile product, and decreasing the textile product's impact on the environment.

To further enhance the durability of a textile product, it is essential to consider the care and washing procedures of a product in the design phase and continue to address them before the product reaches the customer. The care instructions can be seen as an instruction manual for the textile product, which also may give new opportunities to satisfy customers.

Small changes for new opportunities

> Design garments that are easy to wash and care for.
> Utilize the wide range of symbols in the standards to match the care instruction to the textile product.
> Explain to the customer how to wash textile products in the best way.
> Encourage the use of eco-labelled laundry detergents.
> Encourage customers to avoid using fabric softeners.
> Advise light-soiled products to be washed at a lower temperature than the care instructions.
> Advise heavy-soiled products to be washed according to care instructions.
> Encourage spot cleaning and, when needed, recommend eco-labelled spot cleaning products.
> Avoid dry cleaning. Suggest alternatives such as professional wet cleaning.
> Complement the care symbols on the label with additional information.
> Create a garment that allows the consumer to detach and wash pieces of the garment that quickly get soiled.
> Design garments that are easy to repair and adjust.
> Use tools such as Clevercare and Cleanright to share information with the customer.

Heading	Link
Clevercare	https://clevercare.info/
Cleanright Laundry room	https://cleanright.eu/en/rooms/laundry-room.html

Care symbols

Selecting the right care symbol is essential. Care symbols may be required in legislation and described in standards such as ASTM and ISO. Standards and legislation are constantly updated, so ensure using valid standards and legislation.

The labelling standard ISO 3758 is commonly used, and the care symbols used in this standard are very similar to the GINETEX care labelling system: GINETEX is the International Association for Textile Care Labelling and owns the

commonly used care symbols labelled on textile products worldwide. To use the GINETEX symbol, in some countries, companies must have a licensee agreement with GINETEX. In Sweden, TEKO, the Swedish Textile and Clothing Industries Association, has an agreement that allow all TEKO members to use the symbols as a service included in the membership.

Heading	Link
ASTM D5489-18 Standard Guide for Care Symbols for Care Instructions on Textile Products	https://www.astm.org/d5489-18.html
Textil - Symboler för skötselmärkning (ISO 3758:2012)	https://www.sis.se/produkter/terminologi-och-dokumentation/grafiska-symboler/speciell-utrustning/sseniso37582012/
GINETEX care symbols	https://www.ginetex.net/GB/labelling/care-symbols.asp
Tvättrådssymboler	https://www.teko.se/markning/ginetex/tvattradssymboler/

Microplastics

All textiles have the potential to emit microplastics, or fibre fragment, during their lifecycle, which ultimately can find their way into oceans and freshwater sources as illustrated in the figure.[11] According to the Swedish Environmental Protection Agency (Naturvårsdverket) microplastics are small plastic pieces less than five millimetre long. Fibres with a length between 3 nm to 15 mm and a length to thickness ratio > 3 are also included in this concept.[12] These fibre fragments can originate from synthetic materials like polyester, nylon or acrylic which do not easily biodegrade, or from natural fibres that have been treated or dyed in a way that makes them non-biodegradable.

Fibre fragments can be formed and released unintentionally when textiles or plastics objects are exposed to friction. The friction can be caused during production and use and especially each time a fabric is washed.[13] Depending on the type of fabric and yarn used, between 15–45.400 microfibres/ gram have been reported.[14]
In other words, from a washing machine with a load capacity of 6 kg, between 135,000–272,4 million microfibres can be released with each wash. Although many of these fibres will be caught in the wastewater treatment centres filter but some very short fibres can end up as sewage sludge or straight into the oceans.

Potential impacts

Environmental pollution: Microfibres made from non-biodegradable materials polymers can persist in the environment for a long time. When the microfibres are spread in the environment, they can end up in water bodies, soil, and air, contributing to pollution and can thus posing risks to various ecosystems.

Marine life impact: The presence of fibre fragments in aquatic environments can pose a threat to marine life. Fish, shellfish, and plankton can ingest these microfibres which

11 Microplastics from textiles: towards a circular economy for textiles in Europe — European Environment Agency (europa.eu)

12 Mikroplaster (naturvårdsverket.se) https://www.naturvardsverket.se/amnesomraden/plast/om-plast/mikroplast/

13 Palacios-Marín, A. V., & Tausif, M. (2021). Fragmented fibre (including microplastic) pollution from textiles. Textile Progress, 53(3), 123-182.

14 Cai, Y., Mitrano, D. M., Heuberger, M., Hufenus, R., & Nowack, B. (2020). The origin of microplastic fibre in polyester textiles: The textile production process matters. Journal of Cleaner Production, 267, 121970.

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can lead to bioaccumulation in the food chain.[15] Certain chemicals utilized in the dyeing and finishing of textiles are known to be hazardous and when ingested potentially harmful levels of bioaccumulation can be reached in larger predators.

Air pollution: Microfibres can become airborne and be inhaled, potentially affecting air quality and pose respiratory health risks for humans and animals.[16]

Human health concerns: There is a growing concern about the potential health risks associated with ingestion and inhalation of microplastics. While research is ongoing, it is possible that microplastics could enter into the human food chain through consumption of contaminated seafood, drinking water or via polluted air.[17]

Innovation opportunites

Reducing the release/spread of fibre fragments and thereby mitigating the impact microplastics' requires a combination of consumer awareness, sustainable product design, improvements in waste management, and better regulatory measures. As a consumer you can wash your clothes less often and dispose potential lint in the garbage bin rather than down the drain.

> Use textile fibres that degrades both in terrestrial and aquatic environments to reduce the plastic pollution in the environment in the long term. Natural materials derived from cellulose such as lyocell are known to degrade in seawater.[18]

> Avoid using toxic chemicals such as dyes and finishes on textiles as they can be released in the environment via the shedding of microfibres. The chemicals used can also impair the biodegradation of fibres.

> Some studies have shown that certain type of yarns and fabric constructions are more prone to microfibre shedding, especially if the construction used is loose. Optimisations in both yarn construction and fabric construction can reduce the generation of microfibres.[19]

> Microfibres are predominantly released during laundering of textiles. Installing filter to collect microfibres in the wastewater can reduce the pollution of water bodies. Filters can be installed locally in the washing machine or collectively by the municipality in wastewater treatment plants. There are also special washing bags design to collect fibre fragments during washing that can be used.[20]

> With increasing production of textiles made from mechanically recycled material/fibres, it is speculated that fibre fragments will increase and accumulate in the environment in the future. This because the shredding of fabrics can result in a significant large number of small fibres. It is recommended to pay attention to this in the industry if countermeasures need to be implemented.

15 Cverenkárová, K., Valachovičová, M., Mackuľak, T., Žemlička, L., & Bírošová, L. (2021). Microplastics in the food chain. Life, 11(12), 1349.

16 Cai, Y., Mitrano, D. M., Hufenus, R., & Nowack, B. (2021). Formation of fibre fragments during abrasion of polyester textiles. Environmental Science & Technology, 55(12), 8001-8009.

17 van Raamsdonk, L. W., van der Zande, M., Koelmans, A. A., Hoogenboom, R. L., Peters, R. J., Groot, M. J., ... & Weesepoel, Y. J. (2020). Current insights into monitoring, bioaccumulation, and potential health effects of microplastics present in the food chain. Foods, 9(1), 72.

18 Royer, S. J., Wiggin, K., Kogler, M., & Deheyn, D. D. (2021). Degradation of synthetic and wood-based cellulose fabrics in the marine environment: comparative assessment of field, aquarium, and bioreactor experiments. Science of The Total Environment, 791, 148060.

19 Cai, Y., Mitrano, D. M., Heuberger, M., Hufenus, R., & Nowack, B. (2020). The origin of microplastic fibre in polyester textiles: The textile production process matters. Journal of Cleaner Production, 267, 121970.

20 GUPPYFRIEND Online Shop | Stop Microplastics

Corporate Social Responsibility

Corporate Social Responsibility (CSR) is defined by the EU Commission as the responsibility of enterprises for their impact on society. For a company, CSR means voluntary efforts taken for integrating social, environmental, ethical, consumer, and human rights concerns, beyond following the law. Social compliance has specific focus on the social issues such as the health and safety of employees and the accountability for safe practices.

The work with CSR must be integrated in all activities for the whole organization and be a natural part of daily work, but not only in the company's own policies and practices, but also those throughout the supply chains and other related businesses. It is of greatest importance to involve and collaborate with stakeholders in the process of CSR to be able/enable to think innovatively and to develop new business models, products and services based on both social and environmental responsibility.[21,22]

In the CSR process, internationally recognized principles and guidelines can be of help:

> The ISO 26000 Guidance Standard on Social Responsibility[23]
> United Nations Guiding Principles on Business and Human Rights[24]
> The ten principles of the United Nations Global Compact[25]
> The ILO Tri-partite Declaration of Principles Concerning Multinational Enterprises and Social Policy[26]
> The GRI Sustainability Reporting Standards[27]
> Pay attention to and stay up to date with upcoming directives and regulations from the EU. You will find the proposal for the upcoming Directive on Corporate Sustainability Due Diligence in related documents.[28,29]

21 http://ec.europa.eu/growth/industry/corporate-social-responsibility_en
22 https://www.iso.org/iso-26000-social-responsibility.html
23 http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014L0095&from=EN
24 http://www.ohchr.org/Documents/Publications/GuidingPrinciplesBusinessHR_EN.pdf
25 https://www.unglobalcompact.org/what-is-gc/mission/principles
26 http://www.ilo.org/empent/Publications/WCMS_094386/lang--en/index.htm
27 Ghttps://www.globalreporting.org/standards
28 https://commission.europa.eu/publications/proposal-directive-corporate-sustainability-due-diligence-and-annex_en
29 TEKO:s Hållbarhetsguide- https://www.teko.se/hallbarhet/hallbarhetsguide/tekos-hallbarhetsguide/

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Standards and Certifications

Moving towards to more sustainable textile products, it can be helpful to consult/refer to standards, and certifications within the field. This is challenging as it is an area in constant change with more than 100 standards on the subject and can be difficult to make rational or correct decisions. Pay attention to and stay up to date with directives and regulations from the EU. Each standard and certification has its own scope and has to be selected to match the material, product type and market.

Raw material, Process or Product

There are several stakeholders within the area of sustainability. These stakeholders are active in different parts of the supply chain, market or segments of the market. Below you will find an introduction to identified challenges and how each certification support improvement.

Raw material

Standards for Better Cotton and Textile Exchange are known certifications within the textile industry on the raw material level, but they cover/represent different areas. Better Cotton uses the mass balance concept to improve the cotton industry. Textile exchange focuses on the raw materials in the products and how these resources are farmed, sourced, and extracted from the earth, plants, and animals.

BCI	OCS	RCS & GRS
Better Cotton Initiative (BCI) is based on production principles and criteria to support growing cotton more sustainably: socially, environmentally and economically.	The Organic Content Standard (OCS) is a standard from Textile Exchange. OCS is tracking and verifying organic fibres in the product.	Recycled Claim Standard (RCS) and Global Recycled Standard (GRS) are standards by Textile Exchange, tracking and verifying recycled fibres. The GRS has higher and broader criteria.
https://bettercotton.org/	https://textileexchange.org/organic-content-standard/	https://textileexchange.org/recycled-claim-global-recycled-standard/

Process and Product

Standard 100 by Oeko-tex, sets human ecology requirements for a product; in addition, Oekotex offers several other certifications covering various scopes, such as STeP by Oeko-tex certifying manufacturing processes.

Bluesign and **GOTS** are standards with the process in focus, aiming to ensure that textile products have less impact on the environment and humans using different approaches. Whereas Bluesign takes a holistic view of safety and environmental issues in the supply chain, GOTS promote natural organic fibres in all aspects, from fibre to customer. There are also other certifications related to processes in the supply chain, such as the **EU flower**, **the Swan**, **Bra Miljöval** and **Fairtrade.**

To compare and find further information and updated details, the United Nations has developed the "**Standards Map**", a tool to support sustainable production, consumption and trade and with in-depth information to compare the sustainability standards and certifications. https://standardsmap.org/en/home

Oeko-tex 100	Fairtrade	GOTS	Bluesign
Standard 100 by Oeko-Tex certifies products to limit the use of known harmful substances to protect human health.	Fairtrade promote social requirements in the supply chain to create better working conditions.	From fibre to product manufacturing, GOTS sets the requirements for organic textiles.	Through the supply chain, Blusesign aims for safer workplaces and textile products with less environmental impact.
https://www.oeko-tex.com/en/our-standards/oeko-tex-standard-100	https://fairtrade.se/om-fairtrade/det-har-ar-fairtrade/ra-varor-och-produkter/bomull/	https://global-standard.org/news	https://www.bluesign.com/en/home

Heading	Link
Green Claims Directive	Proposal for a Directive on green claims (europa.eu)
Eco label index	https://www.ecolabelindex.com/ecolabels/?st=category,textiles
The world's largest database for sustainability standards	https://standardsmap.org/en/home
Textile Exchange	https://textileexchange.org/
Oeko-tex	https://www.oeko-tex.com/en/
Bluesign	https://www.bluesign.com/en
GOTS	https://global-standard.org/
EU-Flower	https://environment.ec.europa.eu/topics/circular-economy/eu-ecolabel-home/product-groups-and-criteria_en
Swan	https://www.svanen.se/
Bra Miljöval	https://www.bramiljoval.se/
Fairtrade	https://info.fairtrade.net/product/textiles
Textile Standards and Legislation	https://www.textilestandards.com/

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