Textile Raw Materials in Circular Economy

Study Material

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Natural fibers

Cotton: Definition

Cotton is a soft, natural fiber obtained from the protective boll of the cotton plant, primarily composed of cellulose. It is spun into yarn to create breathable, versatile textiles widely used in clothing, home furnishings, and industrial applications. Known for its strength, absorbency, and comfort, cotton is also valued for blending with other fibers like polyester. It is resistant to alkalis, biodegradable, and plays a vital role in both traditional and modern industries.

PICTURE: Figured by Hashan Disanayakage using Ai.

Parameter	Value
Fineness	1–4 dtex / 2.3–6.9 micronaire
Fiber length	10–60 mm
Density	1.5–1.54 g / cm^3
Moisture regain	8.5 %
Breaking strength	25–50 cN / tex
Elongation	5–10 %
Color	Creamy yellow

PICTURE: Properties of cotton fiber.

Cotton spinning

Source: Ahmed, S. Ali, Z. Ashraf, M. Hussain, T. Nawab, Y. 2016. Textile Engineering. Textile Raw Materials. Cotton. 1st Edition. Berlin, Germany ; Boston, Massachusetts : De Gruyter Oldenburg . P8-10.

Cotton: Possibilities in Circular Economy

- Cotton fiber is considered as sustainable as it is renewable, biodegradable, and environment friendly throughout its entire lifecycle. Important sustainability parameters involved in cotton fiber production are soil, water, land, energy, and air quality. (Senthilkannan 2014)
- The use of land for the cultivation of cotton has decreased considerably through the use of modern agricultural technologies (Senthilkannan 2014)
- Inventory calculations proved that cotton fiber production consumes about 40 % less energy than polyester fiber production (Senthilkannan 2014)
- Cotton waste, particularly untreated and organic cotton, can be composted to enrich soil, closing the loop on agricultural and textile waste.
- Cotton can be blended with other fibers like recycled polyester for hybrid materials that combine performance and sustainability.
- Can be used as raw material (cotton linter, cotton-rich cutting scrap or end-of-life textiles) for man-made cellulose fibers

Source: Senthilkannan, M.2014. Roadmap to Sustainable Textiles and Clothing. Sustainability Studies on Natural Plant Fibers. Lifecycle Assessment of Cotton Fiber: Springer Singapore. P 16-20.

Cotton: Limitations in Circular Economy

- Use of fertilizers and pesticides, CO_2 and SO_2 emissions, and water use are the main concern for cotton fiber affecting its sustainability.
- Cotton is very sensitive to intensive growing conditions in monocultures and warm climate favors pests attack.
- Chemical treatments used between the time of sowing and harvesting of cotton leads to environmental pollution by evaporation into the atmosphere, persistence in soil, leaking in watercourses and contamination of cotton.
- Cotton stalks which are still burned in the field causing severe air pollution.
- Processing cotton fibers requires extra time and energy, as it involves cleaning, bleaching, and separating the fibers to achieve the desired quality and usability.

Source: Kozlowaski, R. Muzyczek, M. 2017. Natural Fibers. Properties, mechanical behaviour, Functionalization, and application. Cotton Dominant Natural Fibers. Nova Science Publishers: New York. P 1-17. Chapter 1

Flax: Definition

Flax, derived from the *Linum usitatissimum* plant, is one of the oldest textile fibers. Cultivated for fiber and seed, flax thrives in moderate climates. Fiber extraction involves pulling, retting, drying, scutching, and hackling. Composed mainly of cellulose, flax fibers are durable, breathable, and moisture absorbing, making them ideal for clothing, upholstery, paper, and technical uses. Linen is valued for its softness, durability, and deformation resistance, becoming softer with washing and widely used in apparel, towels, and composite materials.

PICTURE: Harvested flax.

TABLE: Properties of flax fiber.

Parameter	Value
Fineness	10–40 dtex
Diameter	10–80 μm
Fiber length	200–800 mm
Density	1.43–1.52 g / cm³
Moisture regain	12 %
Breaking strength	30–55 cN / tex
Elongation	2–3 %

Picture: Hundredfold Farm. N.d. Flax. Harvesting, Rippling and Retting Flax — Pembina Fibreshed
Source: Ahmed, S. Ali, Z. Ashraf, M. Hussain, T. Nawab, Y. 2016. Textile Engineering. Textile Raw Materials. Flax. 1st Edition. Berlin, Germany ; Boston, Massachusetts : De Gruyter Oldenburg . P 10-12.

Life cycle of flax

Flax: Possibilities in Circular Economy

- As a natural fiber, flax decomposes safely, contributing to environmental sustainability.
- They allow for excellent air permeability and can absorb and release moisture, ensuring breathability and comfort.
- Flax by products, such as seeds, serve as valuable raw materials for the production of pharmaceuticals, dietary supplements, and cosmetics. Seed flax has only moderate fiber properties (e.g. fiber length and strength)
- Flax is gentle on sensitive skin and does not trigger allergic reactions.
- Cellulose content ca. 70%
- Flax contains lignin (ca. 2%), which offers natural UV protection.

Source: Kozlowaski, R. Muzyczek, M. 2017. Natural Fibers. Properties, mechanical behaviour, Functionalization, and application. A New Challenge for Flax and Hemp Bast Fibers. Nova Science Publishers: New York. P 19- 41.

Flax: Limitations in Circular Economy

- The flax retting process can lead to higher water consumption (20-30m^3 of warm water temp. 30-34°C per 1 ton of straw) and potential water pollution.
- Natural fibers, such as flax are prone to biodeterioration caused by microorganisms such as fungi and bacteria, which decompose lignocellulosic substances and weaken their strength properties.
- The retting process for flax often requires additional time and chemicals, complicating the processing and increasing environmental concerns.
- The cultivation of flax often involves the use of fertilizers and pesticides, which can contribute to soil degradation and environmental pollution.
- A limitation of flax processing is the high energy consumption of the technologies currently used for producing pulp and composite materials, largely due to the technical solutions applied.
- Very limited production capacity (ca. 0.4-0.7 mill. Tons / year)

Source: Kozlowaski, R. Muzyczek, M. 2017. Natural Fibers. Properties, mechanical behaviour, Functionalization, and application. A New Challenge for Flax and Hemp Bast Fibers. Nova Science Publishers: New York. P 19- 41.

Hemp: Definition

Hemp fiber, derived from the fast-growing *Cannabis sativa* plant, is a durable, lightweight, and versatile bast fiber used in textiles, construction, paper, composites, and animal bedding. Grown in countries like China, Canada, the U.S., and France, hemp fibers are cylindrical with a coarse texture and can reach up to 2 meters in length. (Habib et al. 2020, 3).

PICTURE: Hemp plant and rope. Figure created by Hashan Disanayakage using AI.

TABLE: Hemp properties.(Ahmed et al. 2016, 13).

Parameter	Value
Fineness	2- 6 dtex
Diameter	15-50 µm
Fiber length	600- 750 mm
Density	1,48-1,5 g/cm^3
Moisture regain	12,00 %
Breaking strength	35-70 cN/ tex
Young's modulus	1- 6 %

Source: Habib, A. Yasir, N. Adnan, A. Anjanga. Hazizan, M. Shukur, A. 2020. Environmental benign natural fibre reinforced thermoplastic composites: A review. P 3. Environmental benign natural fibre reinforced thermoplastic composites: A review - ScienceDirect
Source: Ahmed, S. Ali, Z. Ashraf, M. Hussain, T. Nawab, Y. 2016. Textile Engineering. Textile Raw Materials. Other Vegetable Fibers. 1st Edition. Berlin, Germany ; Boston, Massachusetts : De Gruyter Oldenburg . P 13.

Hemp: Possibilities in Circular Economy

- Hemp fibers are strong, moisture-absorbing, and versatile, with properties influenced by cultivation factors. They are used in clothing, technical products, household textiles, nonwovens, and canvas, as hemp yarn swells in wet conditions for added durability.
- One of the most beneficial properties of hemp is its exceptional ability to absorb carbon dioxide.
- Another useful property of hemp is its ability to extract heavy metals (copper, cadmium, lead) from soil.
- Moderate climate zone hemp plants do not need any plant protection chemicals.
- High ability to protect against the UV radiation (due to the presence of lignin).

Source: Kozlowaski, R. Muzyczek, M. 2017. Natural Fibers. Properties, mechanical behaviour, Functionalization, and application. A New Challenge for Flax and Hemp Bast Fibers. Nova Science Publishers: New York. P 19- 41

Hemp: Limitations in Circular Economy

- The hemp retting process can lead to higher water consumption (20-30m^3 of warm water temp. 30-34°C per 1 ton of straw) and potential water pollution.
- A limitation of hemp processing is the high energy consumption of the technologies currently used for producing pulp and composite materials, largely due to the technical solutions applied.
- A limitation of hemp is its considerable thickness, low uniformity, stiffness (due to higher lignin content compared to linen), and low elongation.
- Need additional time and chemicals for retting.
- The fiber produced by the decorticator requires additional cleaning to remove the shive.
- Very low production capacity (ca. 0.2 mill. Tons / year)

Source: Kozlowaski, R. Muzyczek, M. 2017. Natural Fibers. Properties, mechanical behaviour, Functionalization, and application. A New Challenge for Flax and Hemp Bast Fibers. Nova Science Publishers: New York. P 19- 41.

Jute: Definition

Jute, known as the "golden fiber" for its golden-brown colour and significance, is a bast fiber spun into coarse threads. Unlike most vegetable fibers, which are mainly cellulose, jute contains both cellulose and lignin. It is valued for its strength, affordability, durability, and versatility, being used in items like sacks, twine, ropes, and carpets. The jute plant matures in 120 days and is harvested either by hand or with sharp tools. Stems are bundled and immersed in water for retting, a bacterial process that loosens fibers from the stalk, taking 12–25 days. Stripping, usually done manually by beating the bark, separates the fibers, which are then dried.

PICTURE: Jute textile fibers.

TABLE: Properties of hemp fiber.

Parameter	Value
Fineness	2–3 dtex
Diameter	15–25 μm
Fiber length	650–750 mm
Density	1.44 g / cm³
Moisture regain	13.75 %
Breaking strength	30–34 cN / tex
Elongation	2–8.2 %

Jute spinning

Picture: Else Marie. 2020. Jute – the most sustainable material in the world. Jute – the most sustainable material in the world – F2F™
Source: Ahmed, S. Ali, Z. Ashraf, M. Hussain, T. Nawab, Y. 2016. Textile Engineering. Textile Raw Materials. Jute. 1st Edition. Berlin, Germany ; Boston, Massachusetts : De Gruyter Oldenburg . P 12.

Jute: Possibilities in Circular Economy

- In agriculture, jute is valued for soil erosion control, seed protection, weed management, and geotextiles, offering biodegradable and sustainable advantages over synthetic alternatives. (Ahmed et al. 2020, 12)
- Jute, a renewable and biodegradable rain fed crop with high biomass yield, embodies circular economy principles by providing sustainable, eco-friendly products that naturally decompose at the end of their lifecycle (Marie 2020).
- Jute benefits the environment by absorbing large amounts of CO_2, releasing oxygen, and contributing to air purification (Marie 2020).
- Jute, maturing in 120 days during the monsoon, complements rice in crop rotation, preserving land for food production while providing both fiber and currently underutilized sticks (Marie 2020).

Source: Else Marie. 2020. Jute – the most sustainable material in the world. [Jute – the most sustainable material in the world – F2F™]
Source: Ahmed, S. Ali, Z. Ashraf, M. Hussain, T. Nawab, Y. 2016. Textile Engineering. Textile Raw Materials. Jute. 1st Edition. Berlin, Germany ; Boston, Massachusetts : De Gruyter Oldenburg . P 12.

Jute: Limitations in Circular Economy

- The overall greenhouse gas emission and waste water in the retting phase cause negative environmental impact.
- The disposal of jute products in an unmanaged landfill leads to the greenhouse gas effect due to methane emission.
- The manufacturing phase contributes to the greenhouse gas effect due to CO_2 emissions resulting from the use of fossil-fuel–based energy generation, purchased electricity, and freight.
- Jute fiber production have significant environmental effects, including eutrophication, climate change, and acidification, due to emissions from natural and chemical fertilizers.

Source: Senthilkannan, M.2014. Roadmap to Sustainable Textiles and Clothing. Sustainability Studies on Natural Plant Fiber. LCA of Jute Fibers: Springer Singapore. P 24-27.

Wool: Definition

Wool is a natural animal fiber obtained from sheep through shearing or chemical treatment, with quality influenced by sheep breed and environmental conditions. Classified into fine, medium, long, and carpet types, wool is spun into woolen or worsted yarns. Its unique crimp structure gives it elasticity, durability, warmth, and moisture absorption, while its flame-resistant properties make it self-extinguishing. Fibres can be of different length and different curliness as well as the diameter.

PICTURE: Sheep. Figure created by Hashan Disanayakage using AI.

PICTURE: Microscopic longitudinal appearance of wool.

Wool spinning

Source: Ahmed, S. Ali, Z. Ashraf, M. Hussain, T. Nawab, Y. 2016. Textile Engineering. Textile Raw Materials. Wool. 1st Edition. Berlin, Germany ; Boston, Massachusetts : De Gruyter Oldenburg . P 14-15.

Wool: Possibilities in Circular Economy

- Wool is renewable since sheep continuously produce fleece.
- Wool decomposes well at the end of its life cycle, unlike synthetic fibers, as it is made of keratin.
- Sheep farming has comparatively low water and land requirements.
- Wool has a negligible environmental impact at the end of life and can potentially be used as a fertilizer.
- Ensuring the well being of sheep contributes to sustainability through higher productivity and animal rights.
- Wool has high moisture regain, it resists flame without chemical treatment.
- It is possible to reprocess wool fiber, so it is recyclable. Wool considered as more economical valuble fibre for recycling
- Wool recycling business is important, e.g. in Northern Italy. Recycled wool can be used in yarn spinning and further for fabrics, or in technical nonwovens, for example in the oil spill prevention products

Source: Jose,S. Thomas, S. Basu, G. 2024.The Wool Handbook.Sustainability, biodegradability and life cycle analysis of wool: Woodhead Publishing. P 401- 440.

Wool: Limitations in Circular Economy

- The scouring (cleaning) of wool fibers is identified as another significant stage in the wool lifecycle, contributing to environmental concerns due to water and chemical usage.
- Over-grazing may lead to erosion and loss of biodiversity
- The stage of wool harvesting (sheep raising) is responsible for a significant environmental impact due to the high methane emissions from sheep. Methane is a potent greenhouse gas that contributes significantly to global warming.
- The global survey on washing machine characteristics showed that the water requirement appears to be slightly higher than that of cotton and synthetic apparel.
- Wool is susceptible to pests like moths, which can lead to additional expenses and challenges in garment storage.

Source: Jose,S. Thomas, S. Basu, G. 2024.The Wool Handbook.Sustainability, biodegradability and life cycle analysis of wool: Woodhead Publishing. P 401- 440.

Silk: Definition

Silk is a protein fiber produced by silk larvae (*Bombyx Mori*) as a fine filament from their body fluid, primarily after feeding on mulberry leaves. Silk is durable, heat-insulating, and resistant to alkalis but sensitive to sunlight, high temperatures, and moisture. Silk larvae create their cocoons using continuous silk fibroin strands coated with sericin, which can be unwound for use, though silk is vulnerable to moths and mildew.

PICTURE: Silk fibers and silk cocoons.

TABLE: Properties of silk.

Parameter	Value
Fineness	1–3.5 dtex
Diameter	10–13 µm
Fiber length	700–1500 m
Density	1.37 g / cm³
Moisture regain	9–11 %
Breaking strength	25–50 cN / tex
Elongation	10–25 %
Color	Lustrous white

Silk Spinning

Source: Ahmed, S. Ali, Z. Ashraf, M. Hussain, T. Nawab, Y. 2016. Textile Engineering. Textile Raw Materials. Silk. 1st Edition. Berlin, Germany ; Boston, Massachusetts : De Gruyter Oldenburg . P 15-16.
Picture: Textile Engineering. 2023. Types, Properties and Uses of Silk Fibre. Types, Properties and Uses of Silk Fibre - Textile Engineering

Silk: Possibilities in Circular Economy

- Silk is considered a sustainable fiber. It is a renewable resource, can biodegrade.
- Adding natural colors and biomaterials during sericulture avoids the need for fabric dyeing at a later stage, reducing chemical usage.
- Cocoon drying can be done using solar energy, which is a renewable and environmentally friendly energy source.
- Reduces water consumption by up to 66% compared to furrow irrigation during mulberry cultivation.
- Woody biomass and unsuitable leaves from sericulture are valuable by-products, serving as sources of firewood, raw material for paper making, and livestock fodder.

Source: Nayak, R. 2022. Sustainable Fibres for Fashion and Textile Manufacturing. Wool and silk fibres from sustainable standpoint. Silk: Elsevier Science & Technology. P 168-173.

Silk: Limitations in Circular Economy

- Most silk larvae are killed in their cocoons before maturing into a moth.
- Mulberry cultivation faces limitations such as pesticide use, eutrophication from fertilizers, limited annual yields, and high water and energy demands for irrigation.
- Silk production is energy intensive, particularly in transporting materials, controlling temperature in rearing facilities, and cooking cocoons.
- Extensive amounts of water are used in reeling and materials processing to clean the silk and remove sericin.
- Toxic chemicals may be used during reeling and materials processing to both clean the silk and remove sericin.
- Many silks fabrics require dry cleaning. Dry cleaning solvents can harm the environment, and their use and disposal should be restricted.

Source: Council of Fashion Designers of America. N.d. Silk. Silk | Materials Index | CFDA

Man-made cellulose fibres

Viscose: Definition

Viscose fiber is made by treating cellulose with chemicals to form a solution, which is spun into yarn in a controlled spinning bath. The fibers are drawn to align molecular chains and undergo treatments like washing, bleaching, and finishing to enhance properties such as brightness and strength. Process adjustments enable specialized fibers, including high-tenacity, crimped, hollow, and modal types. Adding specific chemicals allows the creation of spin-dyed, flame retardant, and other unique viscose fibers for diverse applications.

PICTURE: Viscose fibers.

TABLE: Properties of viscose.

Parameter	Viscose
Fiber length	38–200 mm
Tenacity	15–30 cN / tex
Elongation	15–30 %
Density	1.52 g / cm³
Modulus	8–12 cN / tex
Melting point	175–205 °C

Source: Ahmed, S. Ali, Z. Ashraf, M. Hussain, T. Nawab, Y. 2016. Textile Engineering. Textile Raw Materials. Viscose. 1st Edition. Berlin, Germany ; Boston, Massachusetts : De Gruyter Oldenburg . P 17-18.
Picture: Hossain, N. 2021. Textile learner. Viscose Rayon: A Regenerated Cellulosic Fiber. Viscose Rayon: A Regenerated Cellulosic Fiber - Textile Learner

Viscose: Possibilities in Circular Economy

- Viscose is the most widely used regenerated cellulosic fiber and very popular due to its aesthetic properties like silk fiber, and good feel and drape characteristics (Senthilkannan 2014).
- The trees (e.g., pine, beech) used for viscose fiber are replenishable, grow with rainwater, and require no additional water. Their cultivation is on designated land with no environmental impact (Senthilkannan 2014).
- Bamboo viscose is made from bamboo pulp. Bamboo grows quickly without pesticides, fertilizers, or irrigation. It produces more oxygen than trees and helps prevent soil erosion (Senthilkannan 2014).
- Pure viscose is biodegradable under the controlled industrial compost conditions, making it a better alternative to synthetic fibers like polyester, provided it’s disposed of correctly.

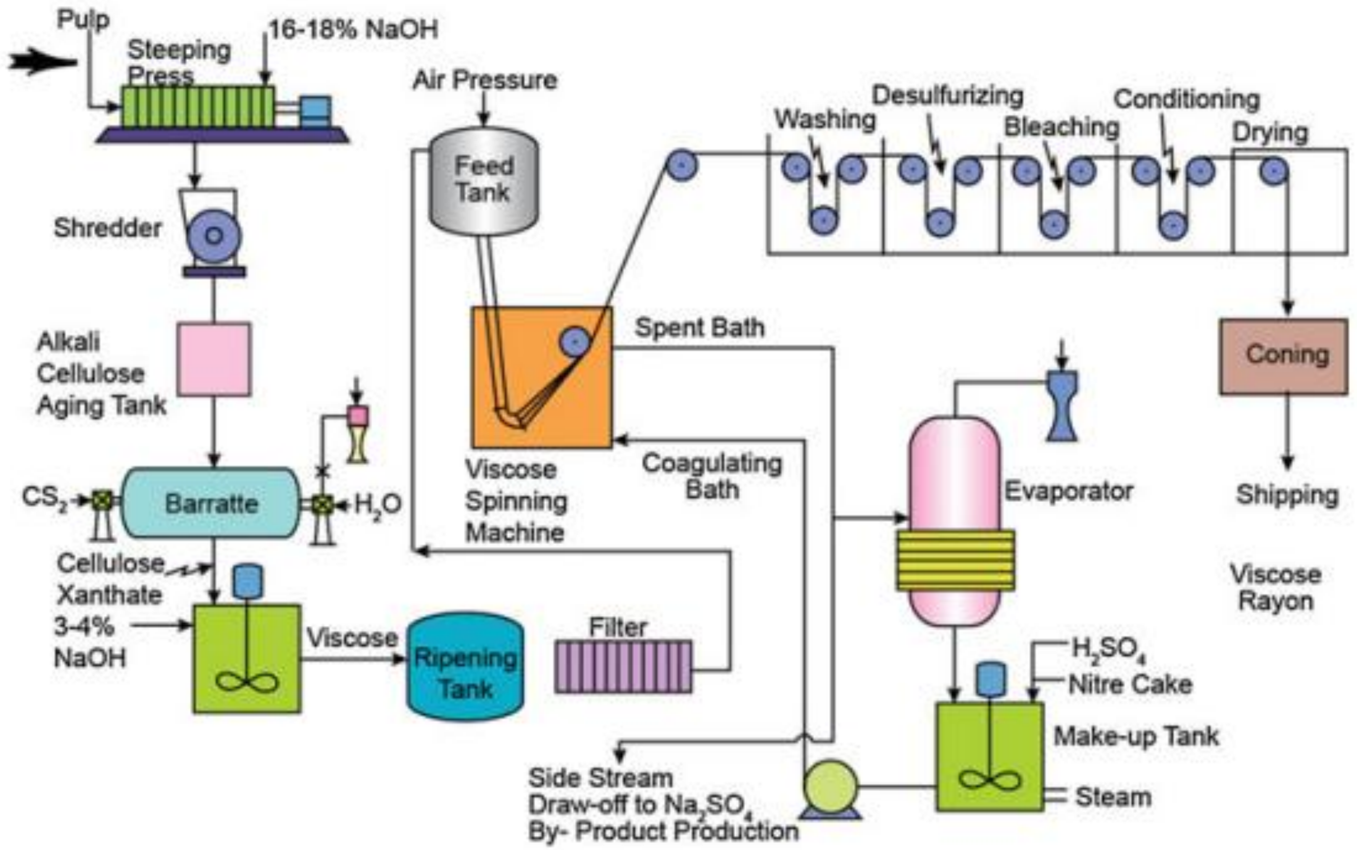
Source: Senthilkannan, M.2014. Roadmap to Sustainable Textiles and Clothing. Regenerated Cellulosic Fibers and Their Implications on Sustainability's: Springer Singapore. P 239-273.

Viscose: Limitations in Circular Economy

- The main sustainability concern in the fiber production stage is the consumption of energy and the use of fossil fuel in fiber production.
- Among the regenerated cellulosic fibers, the highest impact on abiotic depletion is shown by viscose (Asia).
- Viscose (Asia) has the highest impact on ozone layer depletion of all fibers studied.
- Cellulose II crystalline structure does contribute to the difficulty of chemical recycling.
- Viscose (Asia) requires more energy than cotton and other regenerated cellulose fibers due to inefficient coal based power.
- Viscose production uses chemicals like carbon disulfide, caustic soda, sulfuric acid, and sodium hypochlorite, posing health risks and causing environmental pollution.

Source: Senthilkannan, M.2014. Roadmap to Sustainable Textiles and Clothing. Regenerated Cellulosic Fibers and Their Implications on Sustainability's: Springer Singapore. P 239- 273.

Viscose: Production Process



Source: Senthilkannan, M.2014. Roadmap to Sustainable Textiles and Clothing. Regenerated Cellulosic Fibers and Their Implications on Sustainability's: Springer Singapore. P 239- 273.

Modal: Definition

Modal is a wood pulp-based cellulosic fiber made from beech tree chips, making it a type of viscose rayon with high tenacity and wet modulus. First developed by Lenzing AG in Austria, modal is now widely produced and used as a cotton alternative. Modal fibers have enhanced strength, stretch, and molecular orientation. Common in clothing, modal is often blended with cotton, wool, or synthetic fibers like elastane.

PICTURE: Modal fibers (VNPOLYFIBER).

TABLE: Properties of Modal fibers (Senthilkannan 2014).

Properties	Modal fiber
Fiber density (g/cm^3)	1.53
Tenacity (g/d)	
Dry	2.2–4.0
Wet	3.8–5.0
Breaking elongation (%)	
Dry	7.0
Wet	8.5
Moisture regain (%)	11.8

Source: Verma, P. 2010. Fiber2Fashion. Modal: Fiber to fabric. Modal Fiber,What is Modal Fibre,Modal Fabric,What is Modal Fabric,Modal Fabric - Fibre2Fashion

Modal: Possibilities in Circular Economy

- Modal is produced through regeneration of cellulose obtained from the wood pulp.
- The Global Warming Potential (GWP) of modal is nearly zero, making it an environmentally sustainable choice.
- Modal fiber has high modulus in both dry and wet conditions and possesses silk-like texture (luster, shine, and gloss) and a smoother surface than mercerized cotton.
- Modal fiber is widely used in clothing, home furnishings, undergarments, socks, and stockings, among other applications, helping to reduce the reliance on synthetic fiber materials.

Source: Senthilkannan, M.2014. Roadmap to Sustainable Textiles and Clothing. Regenerated Cellulosic Fibers and Their Implications on Sustainability's: Springer Singapore. P 239- 273.

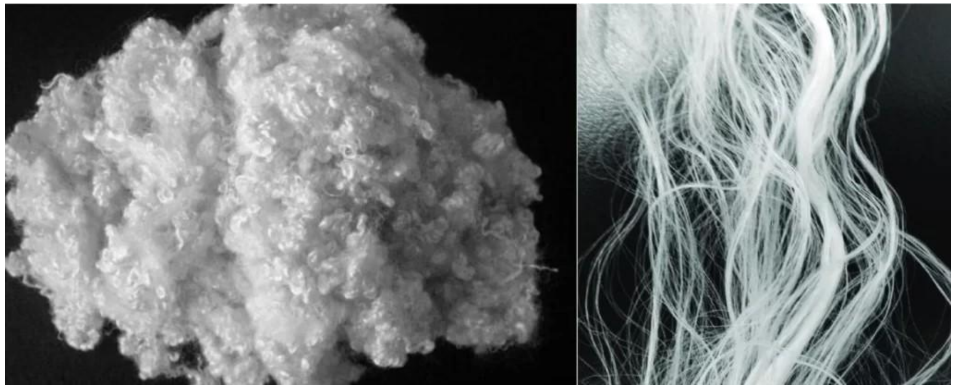
Modal: Limitations in Circular Economy

- 100% Modal requires ironing, and has tendency to pile due to long fibers (Verma 2010).
- Modal is more expensive than viscose and cotton (Verma 2010).
- Processing the wood pulp into a cellulosic fiber is a man made process which uses more energy than processing natural fibers (Verma 2010).
- Production of regenerated fibers such as modal and viscose, involves many chemical reaction steps and the use of many chemicals, and harms to humans and environment (Senthilkannan 2014).
- Modal fibers lose some strength when wet, which can make them prone to damage during washing or while in use. This can reduce their durability over time. The strenthg loss of modal is smaller compared to the strength loss of viscose.

Source: Verma, P. 2010. Fiber2Fashion. Modal: Fiber to fabric. Modal Fiber,What is Modal Fibre,Modal Fabric,What is Modal Fabric,Modal Fabric - Fibre2Fashion
Source: Senthilkannan, M.2014. Roadmap to Sustainable Textiles and Clothing. Regenerated Cellulosic Fibers and Their Implications on Sustainability's: Springer Singapore. P 239-273.

Acetate: Definition

Acetate is a type of fiber made from cellulose that has been chemically modified into cellulose ester. The production process involves mixing cellulose with acetic anhydride and glacial acetic acid. It is spun using the dry spinning technique, where the spinning solution is extruded through a spinneret. The filaments are solidified by passing through warm air, which evaporates solvents like acetone and alcohol. The filaments are then drawn, combined, spin finished, and wound onto bobbins.



PICTURE: Acetate fibers (Chemcess 2024).

TABLE: Properties of acetate.

Parameter	Acetate
Fiber length	40–120 mm
Tenacity	20–40 cN / tex
Elongation	20–40 %
Density	1.29–1.33 g/cm³
Modulus	8 cN/tex
Melting point	250 °C

Source: Ahmed, S. Ali, Z. Ashraf, M. Hussain, T. Nawab, Y. 2016. Textile Engineering. Textile Raw Materials. Acetate fiber. 1st Edition. Berlin, Germany ; Boston, Massachusetts : De Gruyter Oldenburg . P 18.

Acetate: Possibilities in Circular Economy

- Cellulose acetate fiber presents very good handle properties (soft, smooth, dry, crisp, and resilient) and comfort properties such as breathability, wicking, quick drying, and no static cling (Senthilkannan 2014).
- Fabrics made from cellulose acetate are easily dyeable to brilliant, soft, and attractive shades (Senthilkannan 2014).
- This fiber possesses good luster and is softer than viscose and other textile fibers (Senthilkannan 2014).
- When disposed of responsibly, acetate can decompose under industrial composting conditions.
- Acetate's aesthetic appeal and durability make it suitable for upcycling into high value goods.

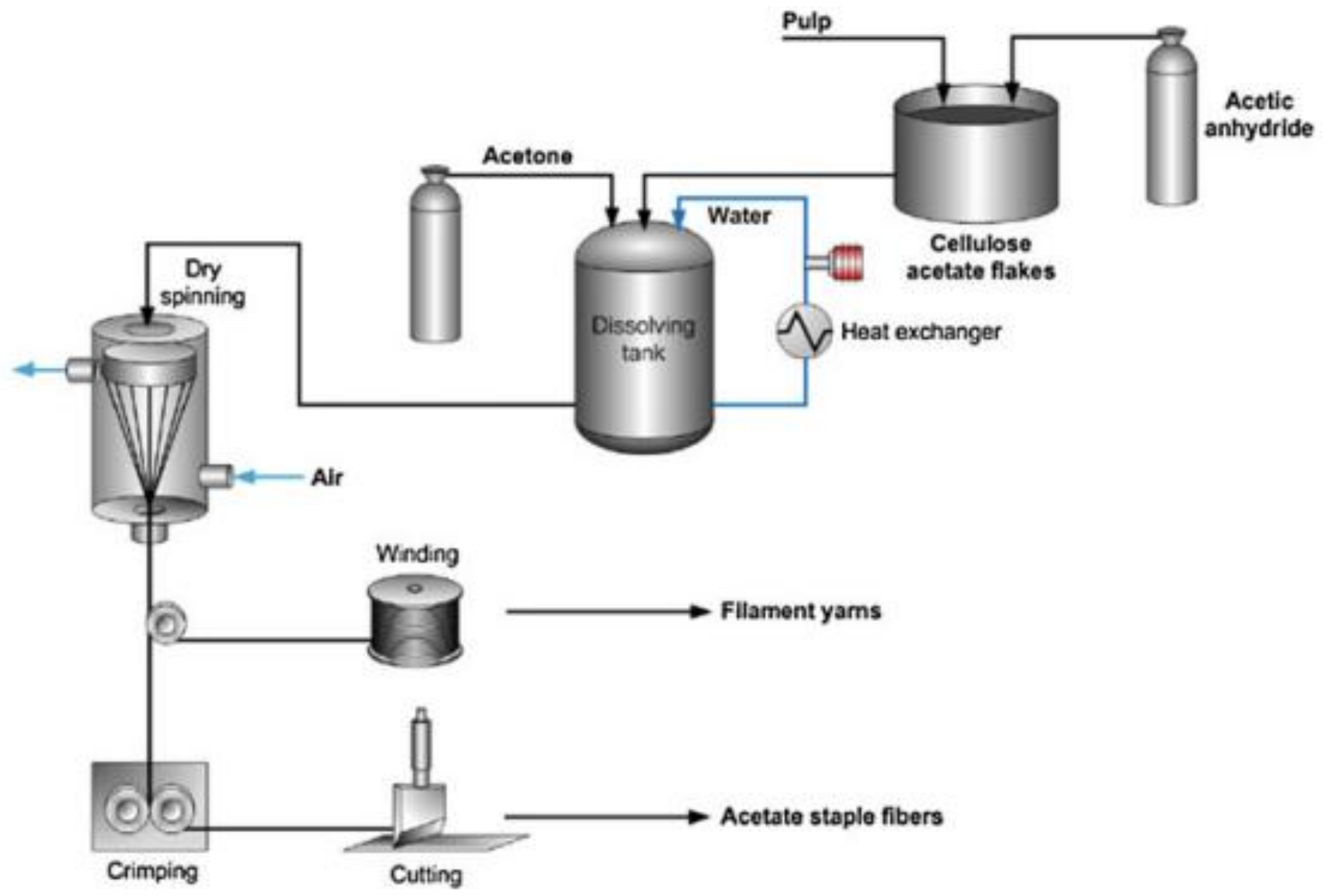
Source: Senthilkannan, M.2014. Roadmap to Sustainable Textiles and Clothing. Regenerated Cellulosic Fibers and Their Implications on Sustainability's: Springer Singapore. P 239- 273.

Acetate: Limitations in Circular Economy

- Acetate fibers have low mechanical strength and heat resistance due to amorphous polymer structure.
- Acetate has a cellulose backbone that acids can hydrolyze, leading to polymer degradation and material weakening or destruction.
- Acetate fabrics wrinkle easily, and shape retain is low

Source: Wimalaweera, W. N.d. Textile Fibers lecture notes.

Acetate: Production Process



Source: Senthilkannan, M.2014. Roadmap to Sustainable Textiles and Clothing. Regenerated Cellulosic Fibers and Their Implications on Sustainability's: Springer Singapore. P 239-273.

Lyocell: Definition

Lyocell fiber, also known by its trade name Tencel®, is a next generation cellulosic fiber made using solvent spinning technology. Developed in response to the demand for eco-friendly processes using renewable materials, it was first produced in 1984 and commercialized in 1988. Lyocell is biodegradable and has excellent moisture absorbency, high strength in both wet and dry states, and can blend easily with fibers like cotton, wool, and linen. It features unique fibrillation, creating surface fibrils that enhance its aesthetic appeal. Fabrics made from Lyocell offer benefits such as wrinkle resistance, washing stability, dyeability, and good drapeability.

PICTURE: Lyocell fibers (Tencel^{TM}).

TABLE: Properties of Lyocell.

Property	Tencel
Fiber fineness (dtex)	1.7
Dry tenacity (cN/tex)	38–42
Dry elongation (%)	14–16
Wet tenacity (cN/tex)	34–38
Wet elongation (%)	16–18

Source: Senthilkannan, M.2014. Roadmap to Sustainable Textiles and Clothing. Regenerated Cellulosic Fibers and Their Implications on Sustainability's: Springer Singapore. P 239- 273.

Lyocell: Possibilities in Circular Economy

- Lyocell fiber is produced using raw material which is renewable. The trees from which the cellulose pulp is extracted are always replenished. Cotton textile waste can also be used as raw material.
- High recycling rate (ca. 99.7%) of solvents used in the production process of Lyocell fiber.
- Lyocell fiber is biodegradable.
- Lyocell fibers find widespread textile and industrial applications with significant environmental benefits during product manufacturing and use.
- The Lyocell process, however, involves a much lower use of chemicals as compared to viscose.

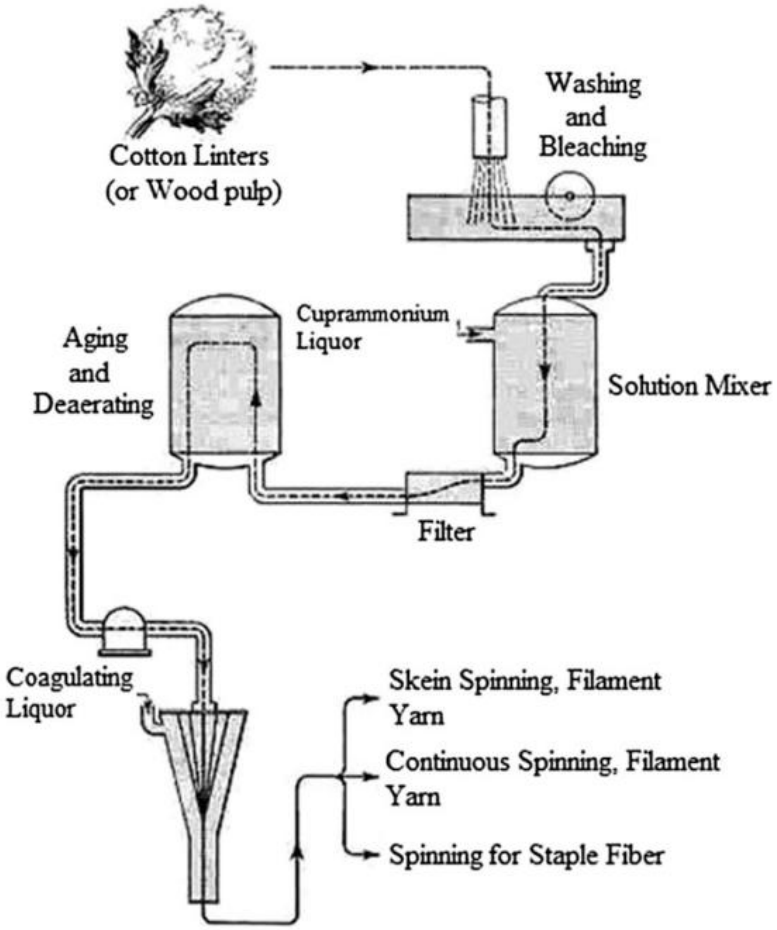
Source: Senthilkannan, M.2014. Roadmap to Sustainable Textiles and Clothing. Regenerated Cellulosic Fibers and Their Implications on Sustainability's: Springer Singapore. P 239-273.

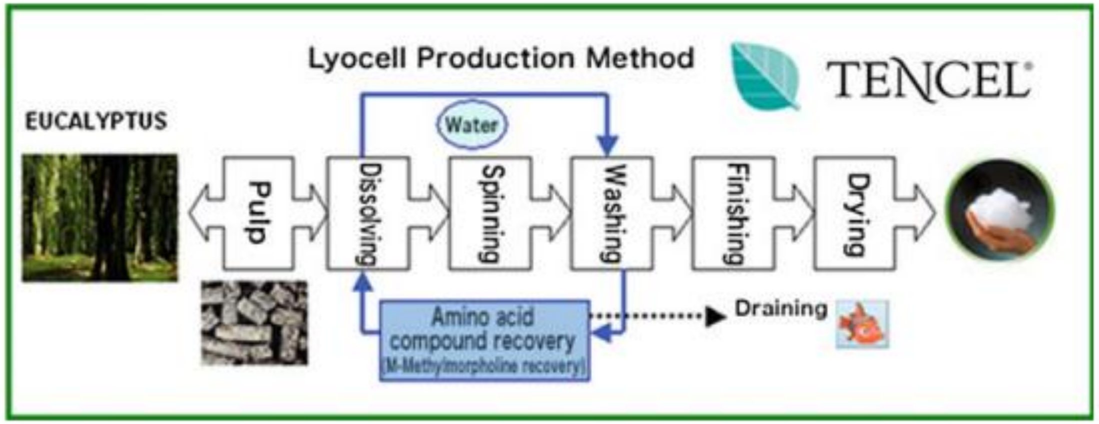
Lyocell: Limitations in Circular Economy

- The cost to produce Lyocell is higher because of the technology required to process and create the fibers. This includes the chemicals, machinery, solvents, etc.
- Cellulose II crystalline structure does contribute to the difficulty of chemical recycling.

Source: Lyocell - The Sustainable Fiber. N.d. [Lyocell - The Sustainable Fiber | True North Gear & DragonWear | True North Gear, Shop today!]

Lyocell: Production Process





Source: Senthilkannan, M.2014. Roadmap to Sustainable Textiles and Clothing. Regenerated Cellulosic Fibers and Their Implications on Sustainability's: Springer Singapore. P 239- 273.

Cupro: Definition

Cupro fiber is a type of regenerated cellulosic fiber produced using the cupro-ammonia process (cuoxam). In this process, cotton linters or wood pulp are dissolved in a copper ammonia solution (cuoxam), forming a shiny, deep blue spinning solution. The solution is filtered, aerated, and spun into filaments, which are then treated with sulfuric acid to remove copper, washed, spin finished, and dried. Cupro fibers are fine, silky, and smooth. Cupro fibers with a hollow structure are used in blood dialysis membranes.

PICTURE: Cupro fibers (Sustainable Review).

TABLE: Properties of Cupro fibers.

Parameter	Cupro
Fiber length	–
Tenacity	16–25 cN / tex
Elongation	16–25 %
Density	1.52 g/ cm^3
Modulus	40–60 cN/tex
Melting point	175–205 °C

Source: Wulfhorst, B. Gries, T Veit, D. 2006. Textile Technology. Raw Materials. Cupro Fibers (CUP): Hanser Publishers. P 43-45.

Cupro: Possibilities in Circular Economy

- It is considered an eco-textile because by definition it uses what would have been a waste product and transforms it into something usable and fabulous through little energy and emissions. (Göktepe et al 2022).
- As a byproduct of cotton production, cupro helps maximize the plant's value and reduce waste. (Chomsky 2024).
- Cupro is more sustainable alternative to silk and rayon fabrics and it reduced the use of virgin materials. (Chomsky 2024).
- As other regenerated cellulose fibers, described above, cupro fibers can be recycled in mechanical or chemical way. (Göktepe et al 2022).
- It is biodegradable. The fibers easily decompose in soil and return to their natural state. So it is gentle on the environment.(Göktepe et al 2022).

Source: Chomsky, R. 2024. Sustainable Review. Cupro Fabric and the Issues Surrounding Its Sustainability. Cupro Fabric and the Issues Surrounding Its Sustainability — Sustainable Review
Source: Göktepe, F. Atav, R, Ünal, P. Yali, V. 2022. International Congress of Innovative Textiles. Fibre Science And Technology. Cupro fibres. ICONTEX 2022. P 26-31.

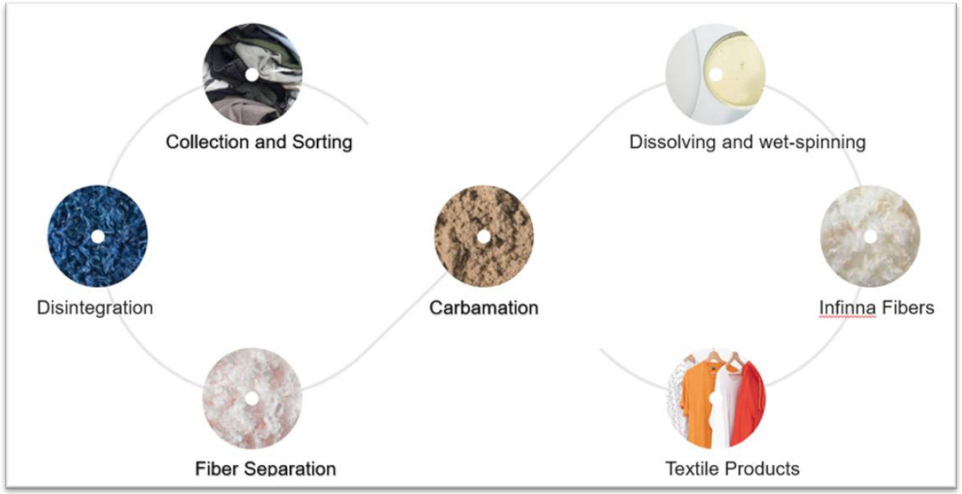
Cupro: Limitations in Circular Economy

- Global cotton production is so extremely water intensive that it has virtually emptied the Aral Sea, which used to be the world’s 4th largest lake.
- Dissolving cellulose pulp from cotton linter and transforming it into a semi-synthetic fiber uses a lot of chemicals that can be harmful to workers who handle the production of cupro.
- Harmful chemicals can also harm the environment when not disposed of properly.
- Cupro makes for a good alternative to silk, but it doesn’t possess the same level of durability as some of its rayon cousins.
- Cupro is not a great material choice for garments that frequently wear and wash.

Source: Chomsky, R. 2024. Sustainable Review. Cupro Fabric and the Issues Surrounding Its Sustainability. Cupro Fabric and the Issues Surrounding Its Sustainability — Sustainable Review

Infinna: Definition

Infinna™ is a high-quality circular fiber made entirely from cotton-rich textile waste, like worn-out clothes, that would otherwise end up in landfills or incinerators. It looks and feels like natural cotton and can be used alone for fully recycled garments or blended with other fibers like organic cotton or viscose. Infinna™ helps brands achieve sustainability goals by replacing virgin materials while producing stylish, eco-friendly clothing.



PICTURE: Infinna process.

Source: Infinna. N.d. From textile waste to fashion. Fashion - Infinited Fiber

Infinna: Possibilities in Circular Economy

- Infinna™ is a virgin quality textile fiber regenerated 100% from textile waste. When finally worn out, clothes and textiles made with Infinna™ can be recycled with other textile waste, enabling textile circularity.
- Infinna whole process has been carefully designed to be safe, eliminate waste, and preserve resources.
- Replace resource heavy virgin raw materials that tax biodiversity with cellulose rich feedstock that's already in use, like old clothes. Keep biomass in circulation and leave the land for food crops and wilderness.
- Infinna™ is completely biodegradable and contains no microplastics.
- Producing the fibers to make one t-shirt with Infinna™ takes almost 90% less water compared to producing a similar amount of conventional cotton.

Source: Infinna. N.d. From textile waste to fashion. Fashion - Infinited Fiber

Infinna: Limitations in Circular Economy

- The chemical recycling process can be costly and often energy-intensive.
- The technology is still in the early stages of development and is not yet widely available.
- The process involves the use of chemicals, which may not be sustainable or environmentally friendly.
- There are extra costs included in pre-processing which comprises of washing, opening, separation process, removal of contaminations, decolour, etc.

Source: Hussain, T. 2023. Sustainable and Circular Textiles. Chemical Recycling of Cotton Waste: Different Technologies. Chemical Recycling of Cotton Waste: Different Technologies

Synthetic man-made fibres

Polyester: Definition

Polyester is a synthetic fiber made from polyethylene terephthalate (PET), widely used due to its low cost, ease of production from petrochemicals, and desirable physical properties. It is strong, lightweight, wrinkle-resistant, and has good wash and wear characteristics. Polyester is produced through condensation polymerization of a dicarboxylic acid with a diol, forming ester linkages in its polymer chain. The fiber is created by melt spinning, where the polymer is melted, extruded through fine holes in a spinneret, and solidified with controlled air cooling.

PICTURE: Polyester fiber (Textile Engineering).

TABLE: Properties of polyester fibers.

Parameter	Polyester
Melting point	480 °C
Softening point	460 °C
Modulus	800–1000 cN / tex
Breaking strength	40–60 cN / tex
Elongation	10–20 %
Density	1.22–1.38 g / cm³
Moisture regain	0.4–0.8 %

Picture: Textile Engineering. 2023. Properties, Manufacturing and Uses of Polyester Fibre.
Source: Ahmed, S. Ali, Z. Ashraf, M. Hussain, T. Nawab, Y. 2016. Textile Engineering. Textile Raw Materials. Polyester. 1st Edition. Berlin, Germany ; Boston, Massachusetts : De Gruyter Oldenburg . P 20.

Polyester: Possibilities in Circular Economy

- The clothing made from polyester fibre is durable, light weight, wrinkle resistant and dries easily. (Nayak 2022).
- Due to these properties, polyester fabrics are easier to maintain compared to their cotton counterpart. (Nayak 2022).
- The manufacturing of polyester fibre results in less environmental impact when the water usage and the use of toxic chemicals ’ impact is considered in the land, water and air. (Nayak 2022).
- R-PET fibre is usually made from PET bottles (lower GHG compared to virgin PET).
- Sportstex, RadiciGroup, and Pure Loop collaborated to recycle polyester textile waste (e.g., sports uniforms) into new fibers, creating a true fiber-to-fiber circular process.

Sources: Nayak, R. 2022. Sustainable Fibres for Fashion and Textile Manufacturing. Sustainable synthetic fibre. Edition 1: Elsevier Science & Technology. P 247- 265.
Source: Radici group. 2023. Polyester, "fibre to fibre" recycling: it can be done! Polyester, "fibre to fibre" recycling: it can be done!

Polyester: Limitations in Circular Economy

- The thermal comfort properties are not as good as cotton due to poor moisture absorbency and breathability.
- Energy usage is more compared to the natural fibres (approximately double compared to cotton), which may be the cause of global warming.
- The resources used for polyester fibre are nonrenewable.
- Clothing made from polyester fibres is non-biodegradable, which may take up to 200 years to biodegrade, hence, lead to plastic pollution.
- Polyester clothing sheds microfibers into water, contaminating the food chain and potentially harming human digestion.
- Can generate greenhouse gases in the land fill.

Sources: Nayak, R. 2022. Sustainable Fibres for Fashion and Textile Manufacturing. Sustainable synthetic fibre. Edition 1: Elsevier Science & Technology. P 247- 265.

Polyamide: Definition

Polyamide (or nylon) is a synthetic fiber first made in the USA (1935) and Germany (1939). It consists of amide-linked macromolecules, produced by condensing diamines with diacids. PA 6 has uniform linkages, while PA 6.6 has alternating ones. Made by melting polymer chips and extruding at 280–300°C, nylon is strong, water-absorbent (3.5–4.5%), alkali- and solvent-resistant, but degrades under UV light, heat, and acids.

PICTURE: Nylon fiber (Textile Flowchart).

PICTURE: Properties of polyamide fibers.

Parameter	Nylon 6.6	Nylon 6
Melting point	255–260 °C	215–220 °C
Softening point	235 °C	170 °C
Modulus	20–35 cN / tex	15–35 cN / tex
Breaking strength	40–60 cN / tex	40–60 cN / tex
Elongation	20–30 %	20–40 %

Picture: Textile Flowchart. 2015. Flow Chart of Nylon 66 Fiber Manufacturing Process.
Source: Ahmed, S. Ali, Z. Ashraf, M. Hussain, T. Nawab, Y. 2016. Textile Engineering. Textile Raw Materials. Nylon. 1st Edition. Berlin, Germany ; Boston, Massachusetts : De Gruyter Oldenburg . P 19.

Polyamide: Possibilities in Circular Economy

- Fabrics made from nylon fibre are strong, durable, lightweight and smooth. Further, the clothing of nylon fabrics dries quickly, and resistant to wrinkle.
- Already existing fibre-to-fibre recycling (examples: Ecover, Econyl)
- In technical textiles, nylon is chosen amongst the best carpet fibres due to its best abrasion resistance and resilience.
- It has high insulating properties that lead to static charges on the fibre. It burns slowly at a high temperature.
- Very strong in nature and used for technical textile.

Sources: Nayak, R. 2022. Sustainable Fibres for Fashion and Textile Manufacturing. Sustainable synthetic fibre. Edition 1: Elsevier Science & Technology. P 247- 265.

Polyamide: Limitations in Circular Economy

- The manufacturing of polyamide fibre is energy-intensive that can lead to global warming (three times energy consumed compared to cotton).
- The manufacturing process releases nitrous oxide, which is a greenhouse gas and more harmful than carbon dioxide in depleting the ozone layer.
- The washing of nylon clothing also generates microfibres, which can lead to marine pollution.
- Nylon fibres are nonbiodegradable and may take up to several years to biodegrade.
- Different chemical composition of polyamides (PA 6.6, PA 6,…) must be recycled separately in chemical recycling

Sources: Nayak, R. 2022. Sustainable Fibres for Fashion and Textile Manufacturing. Sustainable synthetic fibre. Edition 1: Elsevier Science & Technology. P 247- 265.

Acrylic: Definition

Acrylic fiber consists of at least 85% of PAN by weight, and the other 15% either copolymerized or grafted onto the first one. Modacrylic contains 50-85% of additional monomers by weight. Added monomers improve the polymer's solubility for spinning, make the fiber structure more open and improve the polymer's dyeability.

In wet spinning process (usual), sodium thiocyanate or dimethylacetamide is used as solvent; the regeneration bath consists of a mixture of water and solvent; this method if mainly used for coarse fibers' production.

Dry spinning utilizes dimethylformamide as the solvent. In both methods, the filaments are stretched, washed to remove solvent residues, lubricated, crimped, and treated with hot air/steam to reduce shrinkage. Mostly, PAN is produced as staple fibers. (Räisänen et al, 2017.)

PICTURE: Acrylic yarns (Fibre2Fashion News Desk (JL), 2020).

Picture source: Fibre2Fashion News Desk (JL). (2020). *Global trade of acrylic synthetic staple fibres to rise*. Retrieved on 07.02.2025. Global trade of acrylic synthetic staple fibres to rise - Fibre2Fashion
Source: Räisänen et al. Tekstiilien materiaalit. Finn Lectura 2017

Acrylic: Possibilities in Circular Economy

- Dry-spun fibers are stronger than wet-spun.
- Low cost of production.
- Strong (stronger than wool) and durable, resilient. Good acid, oxidation and light resistance, leading to increased life cycle.
- Stain-resistant fibers are possible to produce, not only keeping the material more integral, but also eliminating the need for finishing.
- Research has been conducted on using renewable raw materials, but commercial options are not yet available (Räisänen et al, 2017).
- Despite difficulty and consequent high cost, 97% of the solvents can be recycled (Räisänen et al, 2017).
- Mechanically recycled acrylic can be friction-spun.

Source: Räisänen, R., Rissanen, M., Parviainen, E., Suonsilta, H. (2017). *Tekstiilien materiaalit.* Finn Lectura, p. 85.

Acrylic: Possibilities in Circular Economy

- Can be recycled mechanically and chemically. Also, can be recycled in a way that prevents the material from degrading, so no new (1st life cycle) materials are needed to be added. (Davies, 2022.)
- There were acrylic-digesting organisms found, which is although under research at the moment, can potentially allow for circular economy of an extended loop (Davies, 2022).
- No chemical release at normal temperatures (and other conditions) (Davies, 2022).

Source: Davies, J. Beeco. (2022). *Is acrylic recyclable?* Retrieved on 11.02.2025. Is Acrylic Recyclable? And How Eco-Friendly Is It? – beeco

Acrylic: Limitations in Circular Economy

- Cannot be melt-spun as decomposes near its melting point.
- Wet processing has slow production speed. Both wet and dry methods involve use of toxic organic solvents.
- Chemical-intensive production. Chemicals need to be recovered, but it is expensive.
- Due to its strength and elongation, resembling wool, often used as a wool substitute or blend, both of which hinder woolen supremacy on the market,.
- Acrylic is one of the major contributors to microplastic pollution (1,5 times more than PET) of marine environments (Geographical, n.d.).
- 210 litres of water is required to produce 1 kg of acrylic, emitting 5 kg of CO_2 (357 km of a car ride) and other toxic fumes (Geographical, n.d.). Acrylonitrile and the copolymerization monomers are harmful and potentially carcinogenic.
- Often produced in low quality (particularly clothes) (Geographical, n.d.).

Source: Geographical. (N.d.). *The dirty truth about acrylic and microplastics.* Retrieved on 12.02.2025. The dirty truth about acrylic and microplastics

Acrylic: Limitations in Circular Economy

- Prone to pilling, allowing for material loss and faster wearing out (especially dry-spun).
- Excellent microorganism resistance extends its decomposition period, and acrylic is unrenewable and doesn't biodegrade, remaining in the environment.
- Polyester offers nearly the same properties for outdoor textiles, but at a lower cost. Also, polyester production generates less CO_2 and consumes less energy.
- Cannot be thermally recycled. Modacrylic, when burnt, releases chlorine gas (toxic when inhaled) and hydrochloric acid (causes corrosion in incineration boilers), making thermal conversion also impossible.
- Only a few recycling contractors accept acrylic waste and most of it is landfilled currently (Davies, 2022).
- A non-renewable, non-biodegradable fossil fuel-based resource.

Source: Davies, J. Beeco. (2022). *Is acrylic recyclable?* Retrieved on 11.02.2025. Is Acrylic Recyclable? And How Eco-Friendly Is It? – beeco

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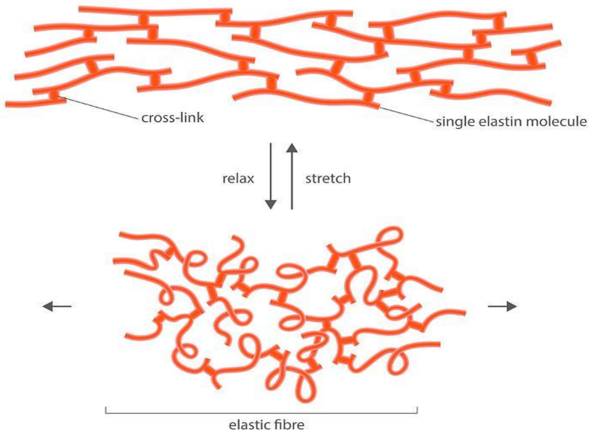
Elastane: Definition

Elastane consists of at least 85% polyurethane by weight, alternating between hard and soft segments (soft make up 65-90% of the fibre's weight). It returns to its original size nearly fully after stretching 5 times in length.

Dry spinning is the primary production method, in which dimethylformamide or dimethylacetamide is used as the solvent. Production speed ranges from 200 to 1000 m/min. Fibers are lubricated and can be crimped.

Thermoplastic polyurethane fibers are produced through melt spinning.

PICTURE: Elastane fabric (House of Uniforms, 2020).



PICTURE: Elastic fiber polymeric behavior (Science Photo Library, n.d.).

Picture sources: 1 – Alex. (2020). *Elastane/Spandex/Lycra.* Retrieved on 08.02.2025. Elastane/Spandex/Lycra - what are they? | House of Uniforms | Melbourne | Australia;
2 – Science Photo Library. (N.d.). *Structure Of Elastin*. Retrieved on 08.02.2025. Structure Of Elastin Photograph by Science Photo Library - Pixels

Elastane: Possibilities in Circular Economy

- Twice as strong as natural rubber, although it is still not a big advantage.
- Withstands stretching well and has good abrasion resistance as covered with other fibers from direct abrasion, which is good in use. The same thing happens in washing.
- Can be partially produced from bio-based resources, as some of its raw materials can be derived from dextrose obtained from corn (Räisänen et al, 2017).
- Can be used in core-spun yarns, improving various properties of recycled sheath fibers.
- Production waste can be reused (Lebby, 2022).
- Some recycling methods are being developed, such as using solvents and reuse of components after separation.

Räisänen, R., Rissanen, M., Parviainen, E., Suonsilta, H. (2017). Tekstiilien materiaalit. Finn Lectura, p. 85.
Lebby, S. Treehugger. (2022). *What Is Elastane, and Is It Sustainable?* Retrieved on 11.02.2025. What Is Elastane, and Is It Sustainable?

Elastane: Limitations in Circular Economy

- Makes conventional mechanical recycling impossible even at small concentrations, if in blends. It is often used in blends or compound (core-spun) yarns. Complicates chemical recycling.
- Has low breaking strength.
- Some elastane types degrade in prolonged water exposure, especially in washing. It doesn't just reduce the lifespan, but also emits microplastics (to water, primarily).
- Melting point is 230-290°C (Räisänen et al, 2017), which makes melt-spinning an energy intensive process. This temperature, however, is considered relatively low – enough to make some contamination possible (with non-recyclable materials or bacteria), hindering the recycling process.
- Poor light resistance: UV stabilizers degrade over time; sweat weakens it further.

Räisänen, R., Rissanen, M., Parviainen, E., Suonsilta, H. (2017). Tekstiilien materiaalit. Finn Lectura, p. 85.

Elastane: Limitations in Circular Economy

- Chlorine-based bleaches weaken strength and elasticity.
- A non-renewable fossil fuel-based resource. Not biodegradable.
- Even if elastane can be mechanically recycled with specialized machines, staple elastane fibers have a narrower scope of applications than filament and requires blending with other fibers for proper performance of the textiles.

Textile processes in the circular economy

Study material

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Content

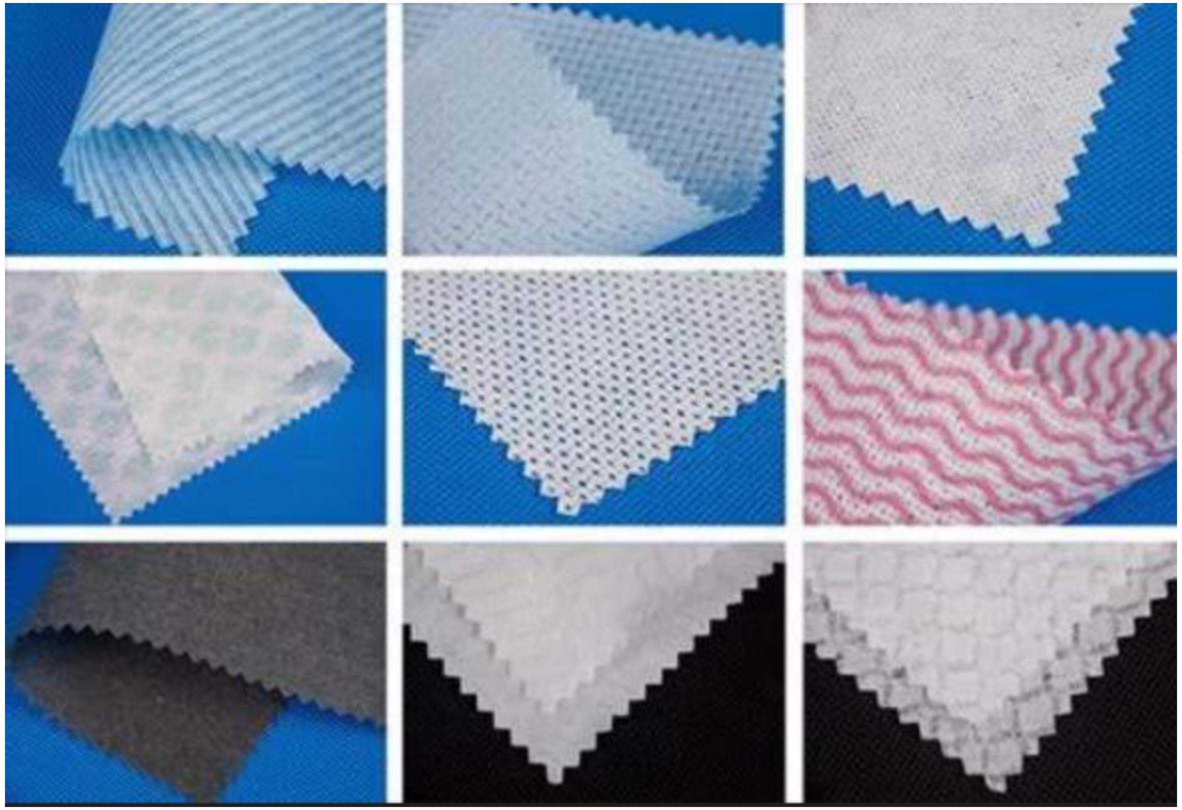
Nonwovens

Possibilities and Limitations in Circular Economy

Content: Nonwovens

- Nonwovens
  - Laying methods
    - Carding
    - Air-laying
    - Wet-laying
  - Bonding methods
    - Thermal bonding
    - Chemical bonding
    - Hydroentangling
    - Needle-punching
- Advanced methods
  - Spunbonding
  - Meltblowing

Nonwovens:



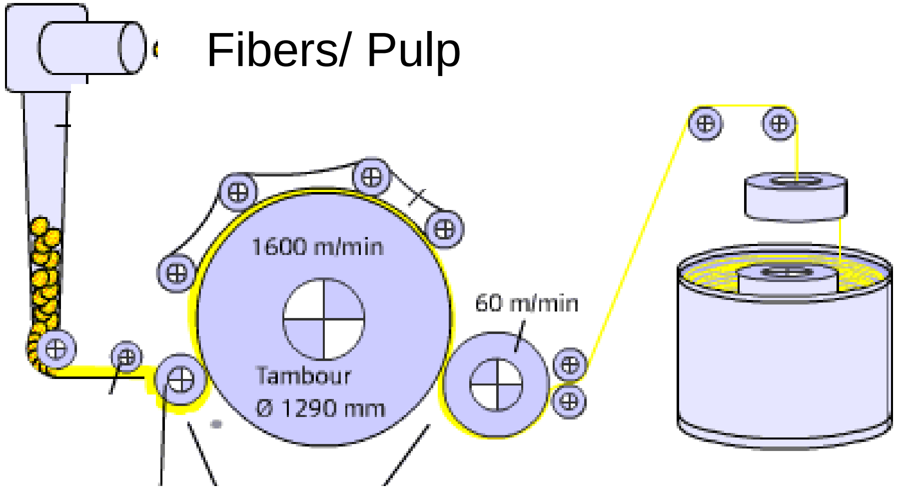
PICTURE. Nonwovens (Ken 2023).

Nonwoven fabrics are created from staple fibers, pulp, or polymers that are bonded through chemical, mechanical, thermal, or solvent processes. These materials can be produced using below techniques,

- Drylaid
- Wetlaid
- Meltblown
- Spunlaid
- Submicron Spinning

Carding: Definition

Fibers/ Pulp



Impurities

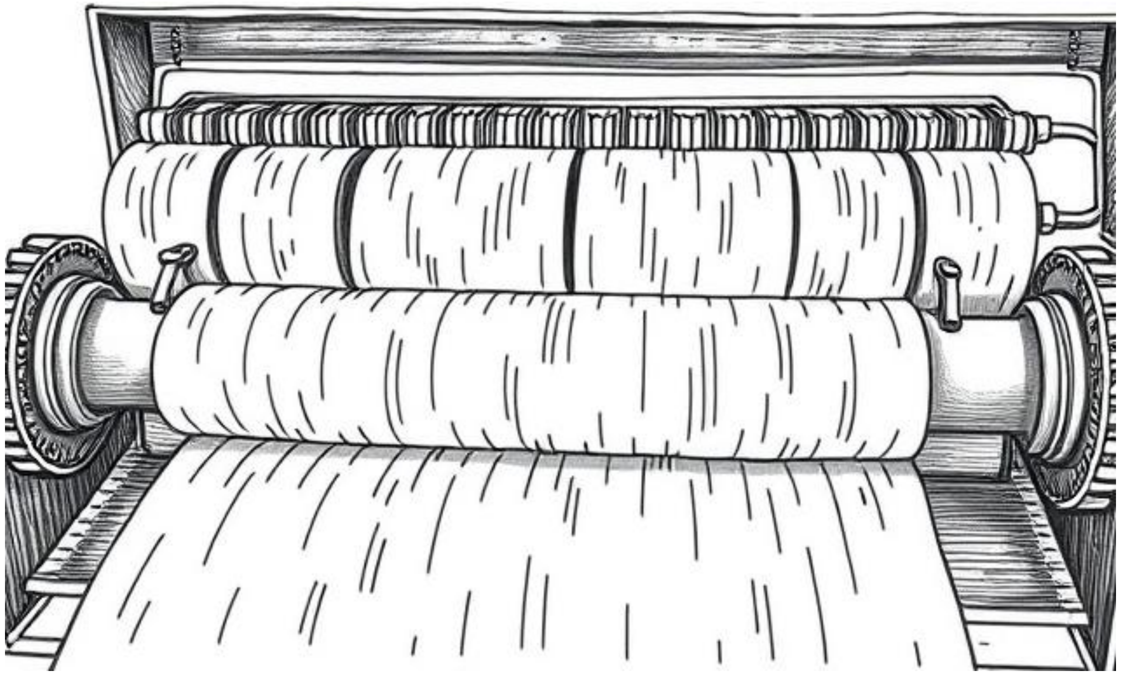
PICTURE. Carding Process.

Carding is a process used to separate, clean, and mix fibers. It helps remove tangles, impurities like dirt and dust, and spreads the fibers evenly.

The goal is to create a smooth, even layer of fibers with the same thickness throughout. This is done by using rollers with small teeth that work together to pull apart, clean, and layer the fibers inside the carding machine.

Carding: Possibilities in Circular Economy

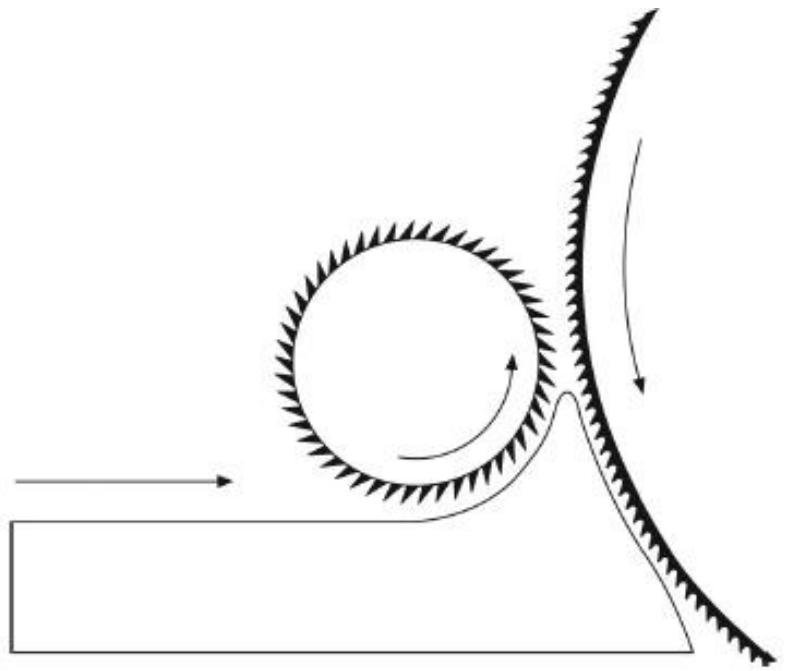
- Carding allows for the reprocessing of textile waste, transforming discarded fabrics into usable fibers for new products.
- The process is energy efficient and does not require water or harmful chemicals, minimizing environmental impact.
- By integrating waste materials into production, carding helps decrease the volume of textiles waste sent to landfills.



PICTURE. Carding Process figured by Hashan Disanayakage using AI.

Carding: Limitations in Circular Economy

- The quality of fibers obtained from carding may be inconsistent and lesser length (<15mm), which can affect the final product's quality.
- Effective separation of different fiber types (cotton, polyester) can be difficult, limiting the use of mixed materials.
- Impurities and contaminants in textile waste can pose challenges, requiring additional processing to ensure clean, usable fibers.



PICTURE. Roll mechanism of carding process.

Carding: Effect on Recyclability of Material

- The carding process can help clean and align fibers, potentially increasing the quality of the recycled material and making it more suitable for new textile products.
- By removing impurities and tangles, carding enhances the purity of the recycled fibers, which is crucial for their acceptance in new applications.
- Carded fibers are often easier to reprocess into new yarns and fabrics, facilitating a circular lifecycle for materials.

PICTURE. Carded web formation figured by Hashan Disanayakage using AI.

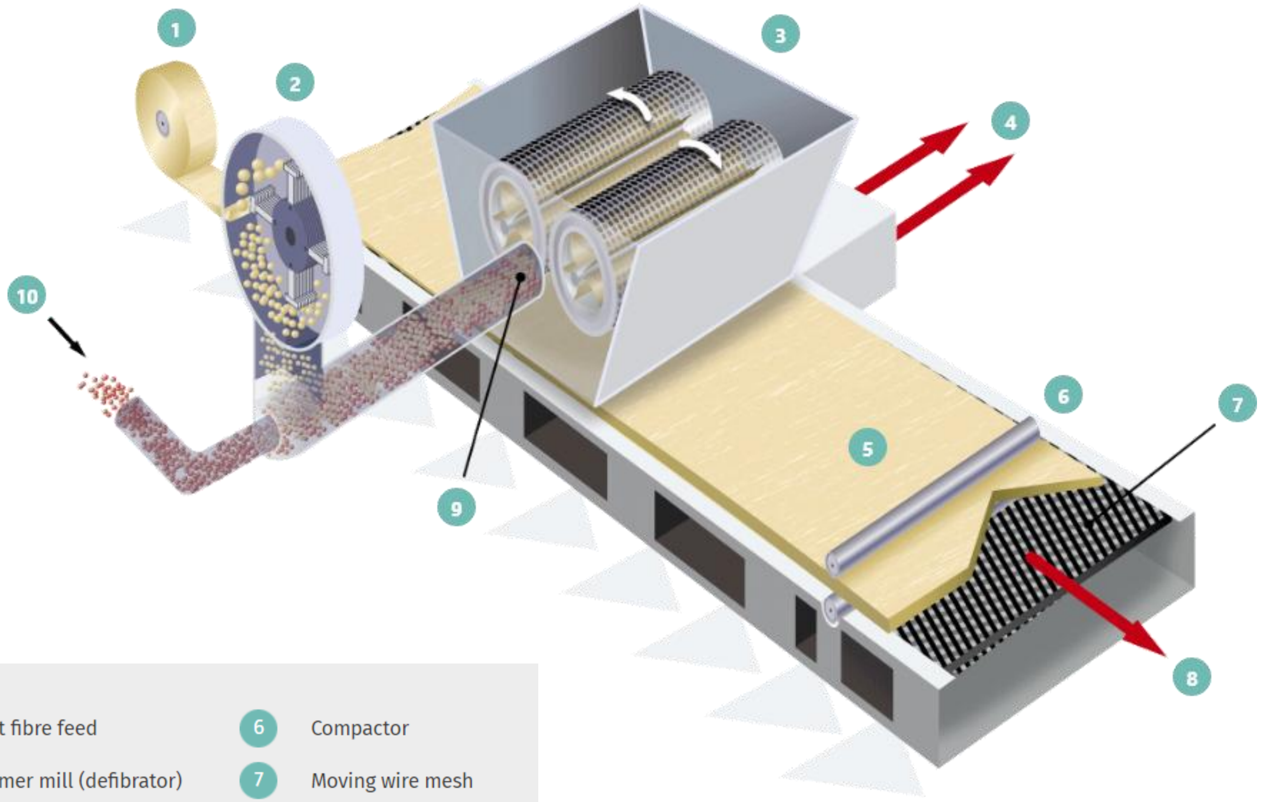
Carding: Utilization of Recycled Materials

- Modern Carding machine brands such as Truetzschler and Margasa Avant Card have developed to use recycled fiber for carding.
- Recycled fibers from pre- and post-consumer textile waste as blend constituents can be used for carding process.
- The waste carbon fibre is converted into a “nonwoven” form using a carding process. This is carried out in a carding machine, with the aim of producing a homogeneous web of aligned fibres.

Air-laying: Definition

In short fiber airlaid processes, fibers are mixed and deposited by air onto a moving belt, forming a randomly oriented web.

Compared to carded webs, airlaid webs are softer, less dense, and more versatile in the types of fibers and blends used.



1	Short fibre feed	6	Compactor
2	Hammer mill (defibrator)	7	Moving wire mesh
3	Forming head	8	To further bonding
4	Air out	9	Fibres + air in
5	Web	10	Thermofusible fibres

PICTURE. Air-laid machine.

[Air-Laying Process]

Air-laying: Possibilities in Circular Economy

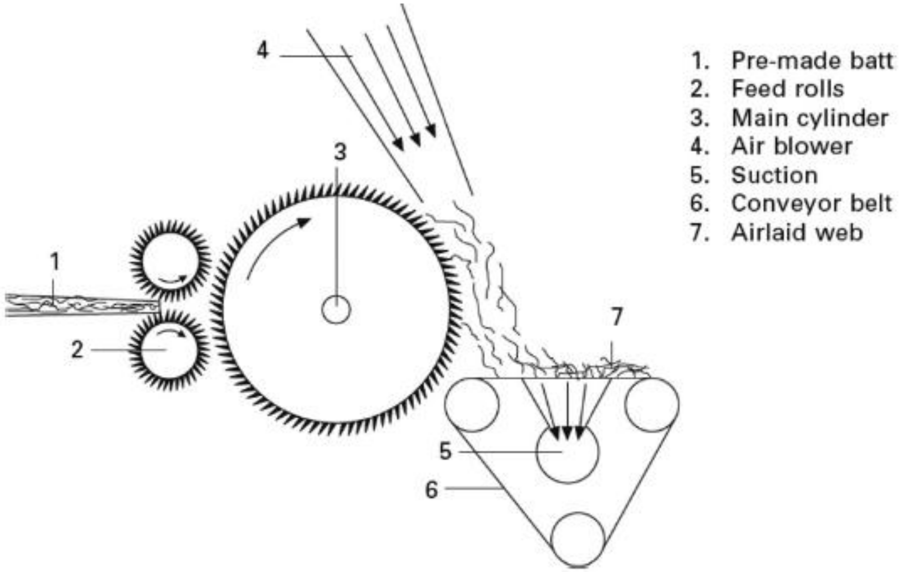
- Airlaid fabrics exhibit good tensile strength and durability, ensuring their structural integrity during use
- Compared to traditional textile manufacturing methods, air-laying generally requires less water and energy.
- The open and porous structure of airlaid fabrics allows for exceptional liquid absorption and retention, making them ideal for applications like hygiene products and wipes.
- Many airlaid nonwovens are made from natural and biodegradable fibers like wood pulp, contributing to their sustainability and eco-friendliness.
- Airlaid nonwoven fabrics can be engineered with a wide range of fibers, bonding methods, and finishing treatments, allowing for customization to meet specific application requirements

Air-laying: Limitations in Circular Economy

- Variable structures of web in width of layer due to irregular air flow close to walls of duct. This problem requires high quality design of duct (Kiron 2023).
- Possible entangling of fibers in air stream. This problem can be reduced by increasing the ratio air/fibers which nevertheless means decrease in performance and increase of energy consumption due to high volume of flowing air (Kiron 2023).
- While air laying is capable of handle also shorter fibres, it has limited production speed and it do not enable production of thin materials. Typical fibre lengths in air laying 5-30 mm (Heikkilä et al 2020, 12).

Air-laying: Effect on Recyclability of Material

- The recyclability largely depends on the types of fibers used. Natural fibers like cotton or wool are generally more biodegradable and recyclable compared to synthetic fibers like polyester or nylon, which can complicate recycling processes.
- Products made from air-laid fabrics can be designed for easy disassembly and recycling, which can enhance their end life recyclability.



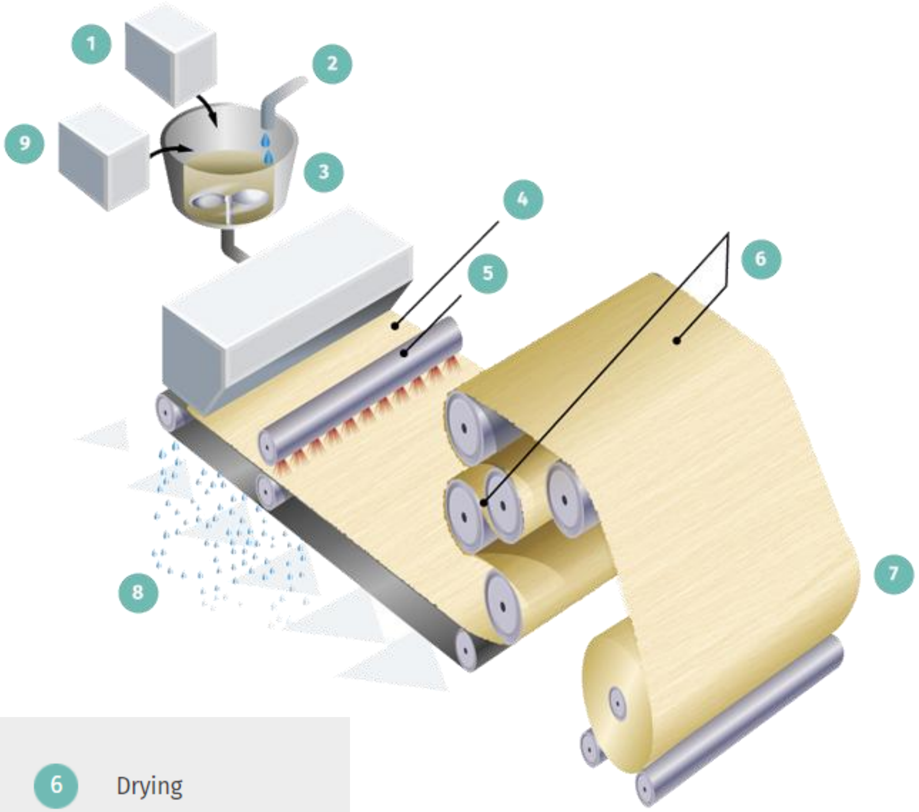
PICTURE. Principle of web formation in a simple airlaying process..

Air-laying: Utilization of Recycled Materials

- Recycled materials can be used in the air-laid process.
- Air laying was suitable method to form nonwovens from recycled cotton. Further optimization of the pre-treatment of fibers is needed to overcome the knots in nonwoven, caused by the fiber entanglements. (Heikkilä et al 2020, 33).
- Before the airlaid web formation process, recycled fibers must be thoroughly opened to ensure proper fiber separation and dispersion, as well as to facilitate even distribution in the airlaid process.
- Nonwoven machine manufacturing companies have incorporated use of recycling materials with their modern Air-laying nonwoven machines.

Wet-laying: Definition

Wetlaid is a process where a dilute slurry of water and fibers is deposited onto a moving wire screen. As the water drains through the screen, the fibers form a continuous web. The web is then further dewatered by pressing it between rollers and subsequently dried.The principle of wetlaying is similar to paper manufacturing.



1. Long fibre
2. Water
3. Fibre and water (slurry)
4. Webforming
5. Binder impregnation
6. Drying
7. Windup
8. Excess water removal
9. Wood pulp

PICTURE. Wet-laid machine.

[Nonwovens manufacturing process (edana.org)]

Wet-laying: Possibilities in Circular Economy

- Wet-laid processes can incorporate recycled materials, reducing dependence on virgin raw materials and promoting resource efficiency.
- Can be used short fibers when compared to other nonwoven web formation processes.
- In wet laying, it is possible to use very short fibers, shorter than in air-laying or carding (Heikkilä et al 2019).

Wet-laying: Limitations in Circular Economy

- The process is often energy intensive due to high water usage and the drying requirements needed after formation, which can limit overall sustainability.
- Some wet-laid products may require chemical bonding or additives that can complicate recycling processes and negatively impact environmental sustainability.
- Managing wastewater and recycling it effectively is still difficult, even with efforts to use less water.

Wet-laying: Effect on Recyclability of Material

- The recyclability of materials made through wet-laying can vary based on several factors, including the type of fibers used, bonding methods, and additives involved.
- Wet-laid natural fibers are more recyclable and biodegradable, while synthetic fibers can be recycled but degrade over time.
- Fiber blends are challenging to recycle due to difficulty in separating the materials.
- Web forming fibers can chemically react with water, leading to changes in their properties and potentially limiting their reusability.

Wet-laying: Utilization of Recycled Materials

- Wet-laying can utilize recycled fibers.
- In wet processing short fiber lengths are actually beneficial for formation, since processing limitations to fiber lengths are related to the maximum length, not the minimum.(Heikkilä et al 2020).

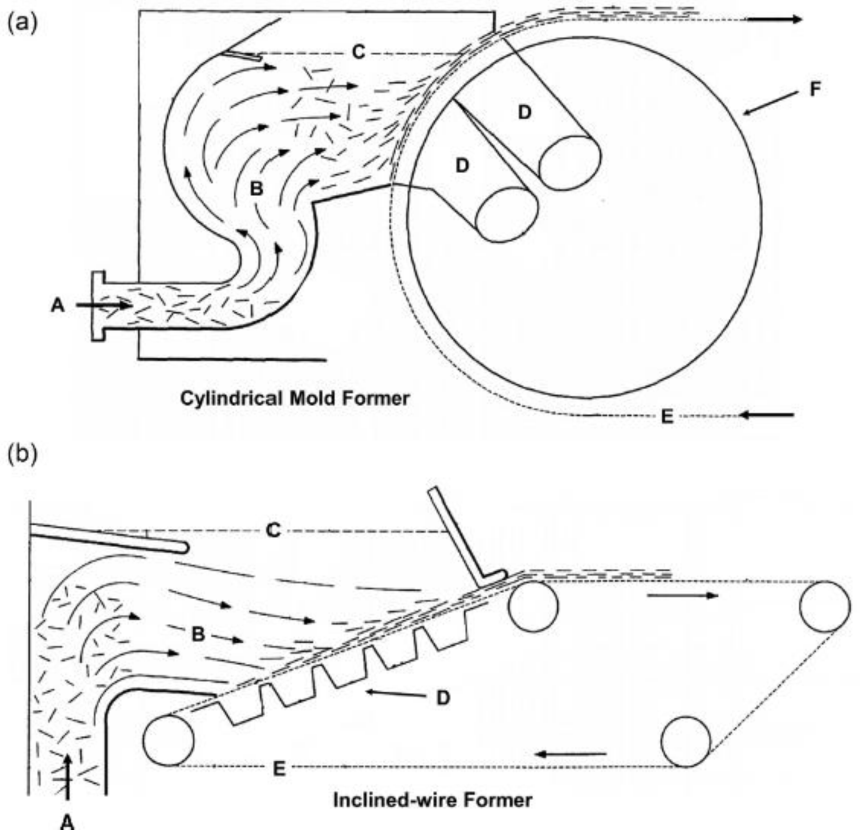
A - stock flow

B - pond height

C - vacuum boxes

D - forming wire

E - rotating forming roll

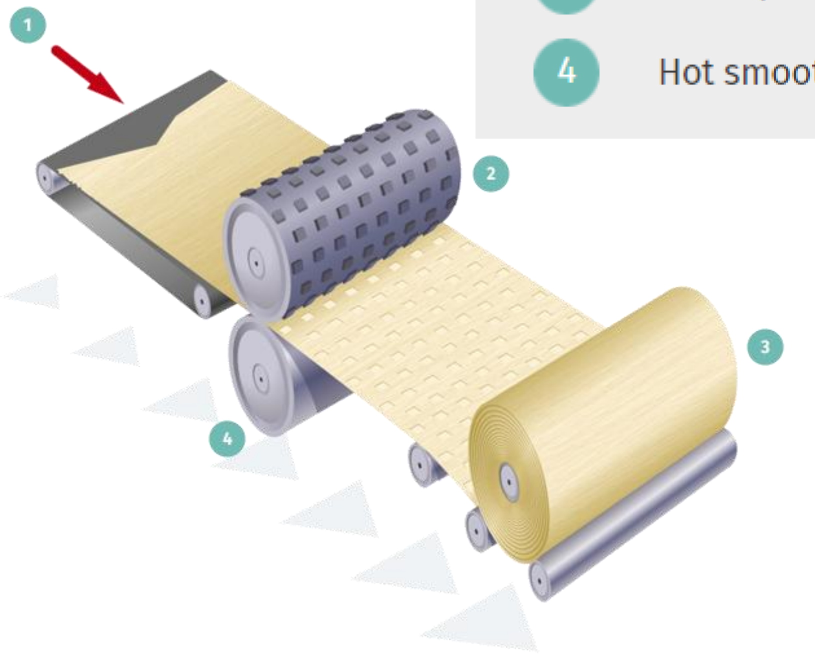


PICTURE. Depiction of stock flows and fiber deposition in two common formers used in Wetlaid manufacturing (Handbook of Nonwovens).

Thermal Bonding: Definition

Thermal bonding is a process that bonds fibers in nonwoven fabrics by applying heat to thermoplastic polymers, causing them to melt and bond at fiber crossover points.

It involves a mechanical process where fibers are fused through heat and pressure, creating adhesive or mechanical bonds.



PICTURE. Depiction of Thermal Bonding.

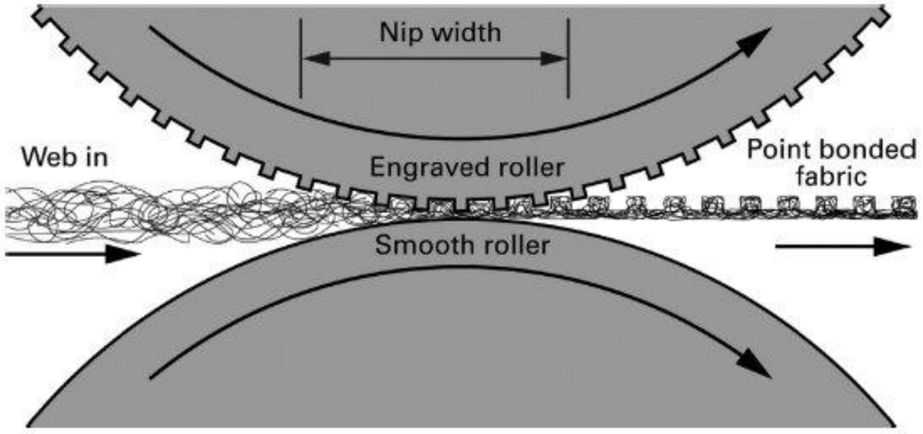
[Nonwovens manufacturing process (edana.org)]

Thermal Bonding: Possibilities in Circular Economy

- No binder agents are required and no curing process is needed. Hence, there is no exhaust air or wastewater problem.
- High economic efficiency as compared to chemical bonding with binder agents because no water evaporation is required, i.e., considerable energy saving results.
- Less expensive machinery. The capital expenditure, maintenance and operating costs are often lower because no binder preparation station and no binder application units are required.
- As pure polymer fibers or blends can be used for thermal bonding processes, recyclability is 100% in practice.
- It is possible to bond even thicker webs uniformly and thoroughly to the core that cannot be achieved by spraying.

Thermal Bonding: Limitations in Circular Economy

- In the thermal bonding process for nonwovens, raw materials may be damaged due to exposure to heat and the calendaring process.
- Thermal bonding process consumes significant energy, leading to higher operational costs and a larger carbon footprint.
- Mostly thermal bonding works best with thermoplastic fibers.



PICTURE. Typical thermal point-bonding roller arrangement.

Thermal Bonding: Effect on Recyclability of Material

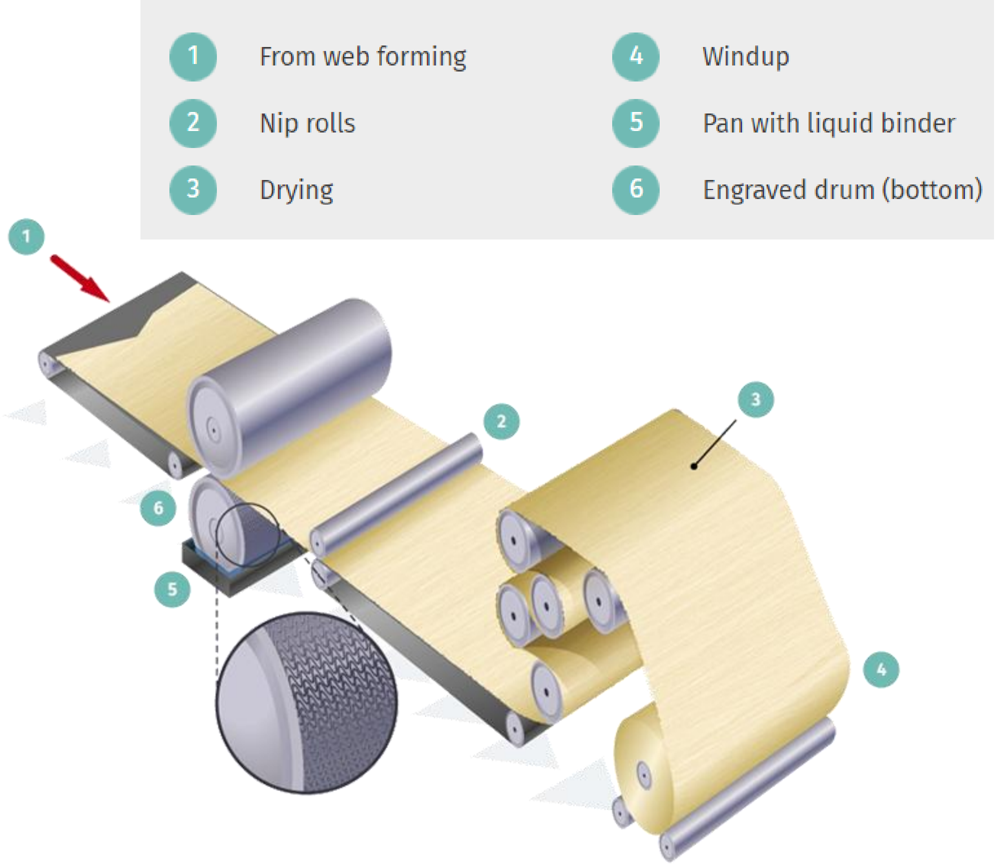
- Thermal bonding often involves combining different materials, such as synthetic fibers or plastics, which become tightly fused. This makes it challenging to separate the materials for recycling.
- The thermal bonding process can alter the structure of materials, potentially affecting their properties and reducing their overall recyclability.
- Fibers is the narrow temperature range that is necessary when thermal bonding. If the temperature is too low, there is inadequate bond strength. If the temperature is too high, the web will melt excessively and lose its identity as a web.

Thermal Bonding: Utilization of Recycled Materials

- The heterogeneous nature and nonuniform fiber length of recycled fibers make them suitable for production of nonwoven fabrics that involve integration of random fibrous web by thermal, chemical and mechanical bonding (Yamini 2021, 42).
- It is possible to utilize recycled materials in thermal bonding. Recycled fibers can be mechanically opened and reprocessed for use in the bonding process.
- However, certain challenges such as maintaining the strength and quality of the recycled materials may arise due to degradation during the previous use or recycling process.

Chemical Bonding: Definition

Chemical bonding uses liquid binders like acrylate, styrene-butadiene, or vinyl acetate copolymers to bond nonwoven materials. These binders are mainly water based and can be applied uniformly or intermittently through methods like spraying, coating, or print bonding.



PICTURE. Depiction of Thermal Bonding (Edana).

Nonwovens manufacturing process (edana.org)

Chemical Bonding: Possibilities in Circular Economy

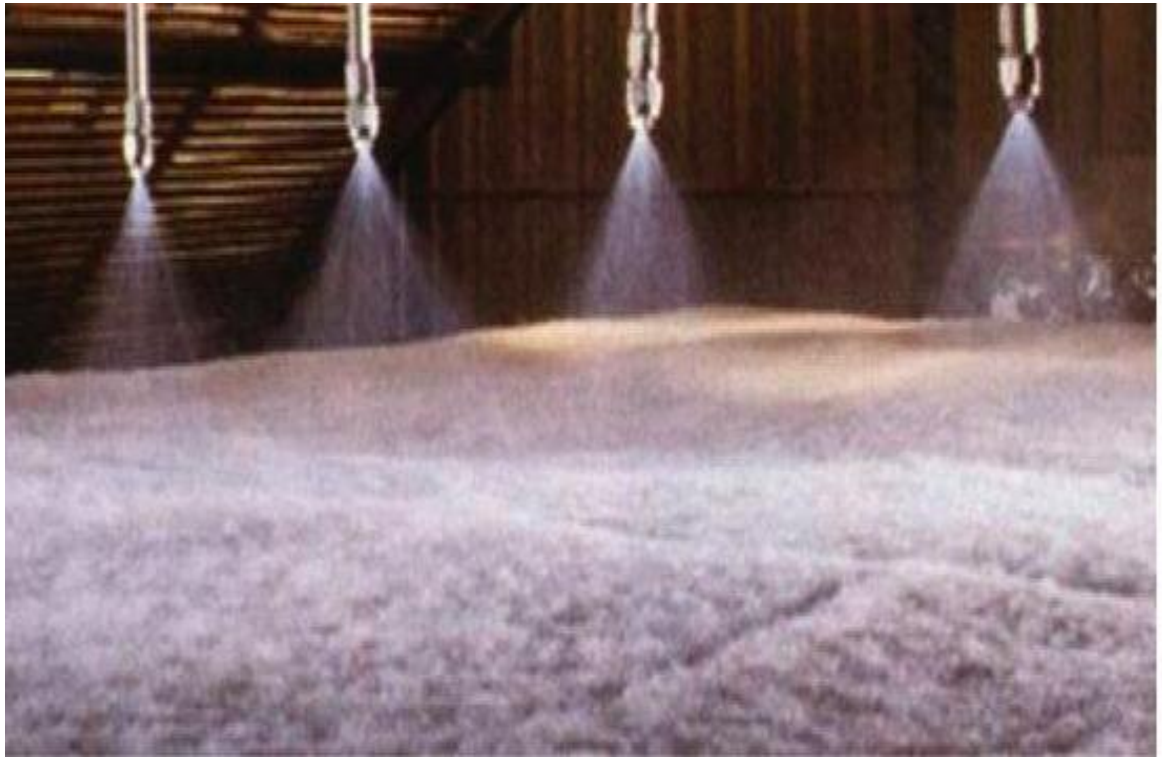
- Contamination of underground water reservoirs and drinking water is the most commonly encountered problem associated with discharge of chemicals that remain unconsumed in textile processing (Yamini 2021, 42).
- Bio-based adhesives, such as those derived from natural polymers, can offer effective bonding while being biodegradable.
- Chemical bonded non-woven fabric offers good strength and durability. The bonding agents create strong connections between the fibers, making the fabric resistant to tearing and stretching. (Jhanji textiles n.d.).

Chemical Bonding: Limitations in Circular Economy

- The use of chemical binders can raise environmental and health concerns if not managed properly.
- Depending on the binder used, the fabric may have limited breathability, making it less suitable for certain applications.
- Binders may migrate within the fabric, affecting its performance and appearance.
- The method of applying the binder (spraying, padding, foam) impacts the uniformity and penetration of the binder within the fabric.

Chemical Bonding: Effect on Recyclability of Material

- The chemicals used may affect the recyclability of the final product if they remain in the product.
- The application of chemicals can alter specific fiber properties, enhancing features like strength, water resistance, or flame retardancy. As well as, these chemical treatments can also impact the recyclability and reusability of the fiber.



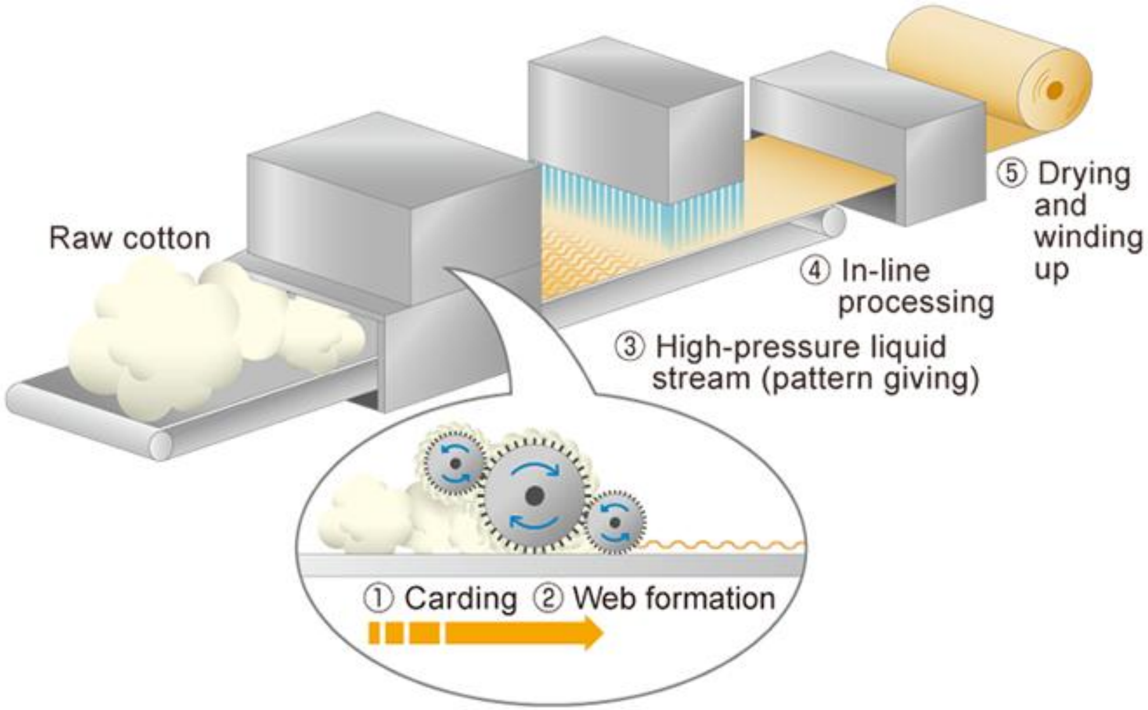
PICTURE. Chemical spray process in chemical bonding.

Chemical Bonding: Utilization of Recycled Materials

- The heterogeneous nature and nonuniform fiber length of recycled fibers make them suitable for production of nonwoven fabrics that involve integration of random fibrous web by thermal, chemical and mechanical bonding (Yamini 2021, 42).
- According to Bogale's and Shakthivel's research results confirm that the chemically bonded nonwovens made from recycled selvedge waste meet functional requirements.
- The analysis demonstrates that recycled selvedge waste can be successfully processed and bonded chemically, thus showcasing its potential for industrial applications

Hydroentangling: Definition

Hydroentanglement is a process where staple fibers, such as cotton, are first formed into a drylaid web through carding. Then, high-pressure liquid streams are applied to the web, causing the fibers to entangle and bond together, resulting in the formation of a nonwoven fabric.



PICTURE. Hydroentangling process.

Hydroentangling: Possibilities in Circular Economy

- Hydroentanglement would be the best binding method for hospital textiles, since no additional chemicals are needed (Heikkilä et al 2020.)
- Hydroentangling can integrate renewable and biodegradable fibers like cotton, hemp, and bamboo, supporting a shift toward sustainable product design.
- The use of water streams eliminates the need for synthetic adhesives or chemical binders, making the process environmentally friendly.

Hydroentangling: Limitations in Circular Economy

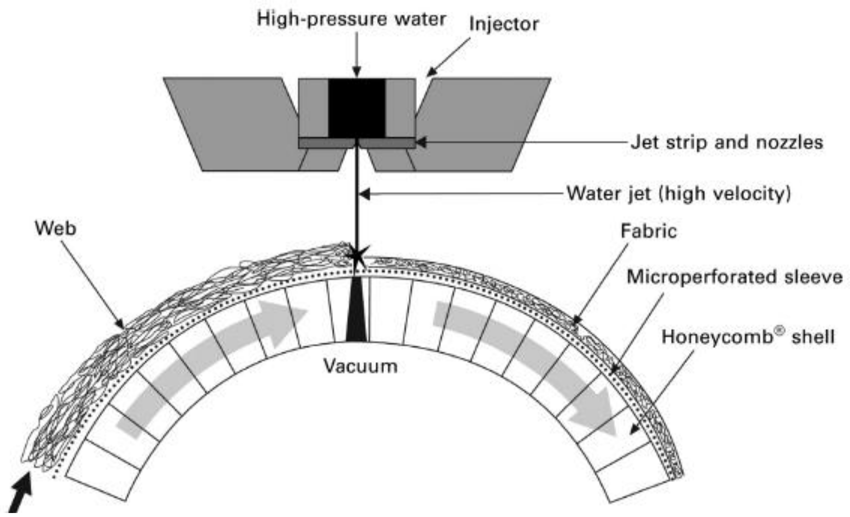
- It is important to consider potential limitations in material selection when the manufacturing process involves contact with water.
- Hydroentangling requires a significant amount of water and high energy, this could lead to sustainability concerns regarding water resource management and energy. The process uses a lot of water, usually around 800 l/kg of nonwoven fabric.
- Nonwoven fabrics produced by hydroentangling may have limitations in durability compared to woven or knitted fabrics.

Hydroentangling: Effect on Recyclability of Material

- The water pressure used directly affects the strength of the nonwoven fabric. Extremely high pressure can break fibers down into micro or nanofibers.
- Hydroentangling process may complicate mechanical recycling due to the strong fiber entanglements that make separating the fibers more challenging.
- While the hydroentangling process fibers can chemically react with water, leading to changes in their properties and potentially limiting their reusability.

Hydroentangling: Utilization of Recycled Materials

- Hydroentangled nonwoven fabric can be made from recycled fibres
- Fiber length can vary between 5 and 60 mm and a fineness of between 0.1 and 20 dtex



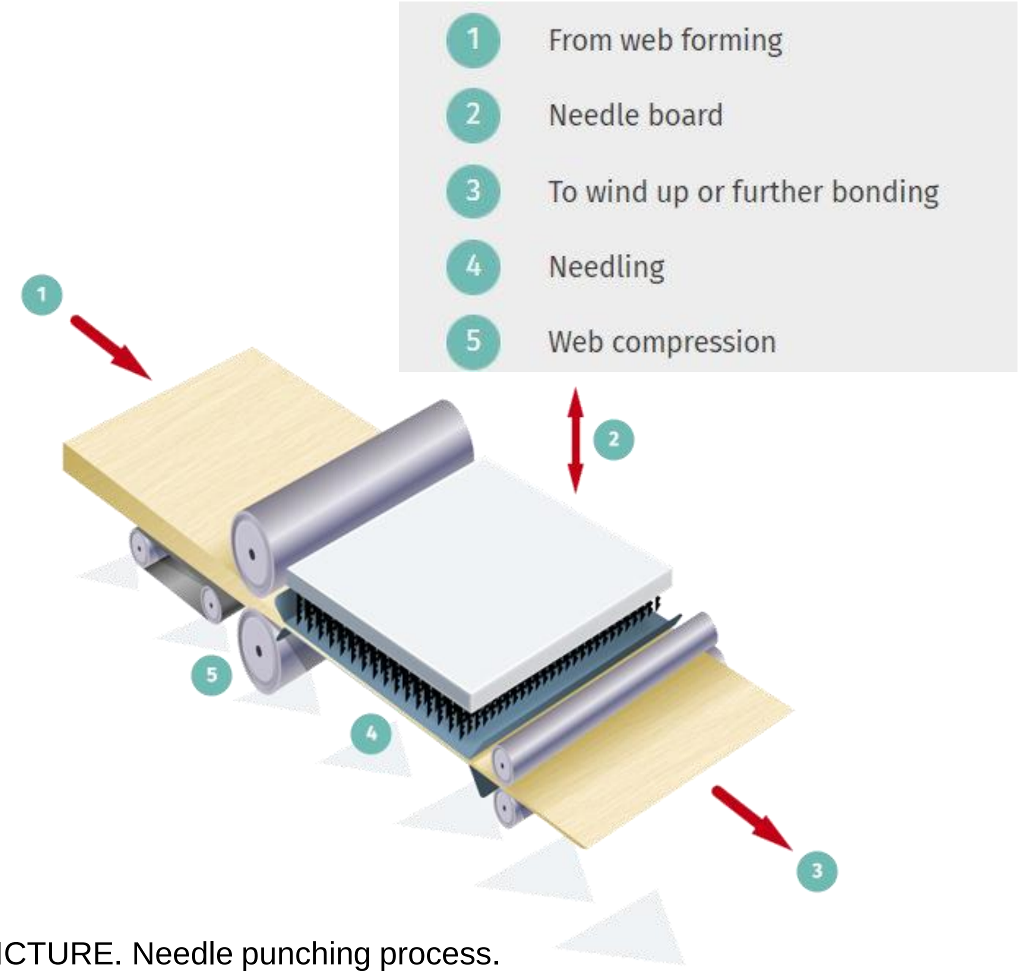
PICTURE. Basic Elements of Hydroentangling process.

Needle-punching: Definition

Needlepunching, specially designed needles are pushed and pulled through the web to entangle the fibres.

Webs of different characteristics can be needled together to produce a gradation of properties difficult to achieve by other means.

Needlepunching can be used with most fibre types but, because of the nature of the process, not with very fine fibers.



PICTURE. Needle punching process.

[Nonwovens manufacturing process (edana.org)](edana.org)

Needle-punching: Possibilities in Circular Economy

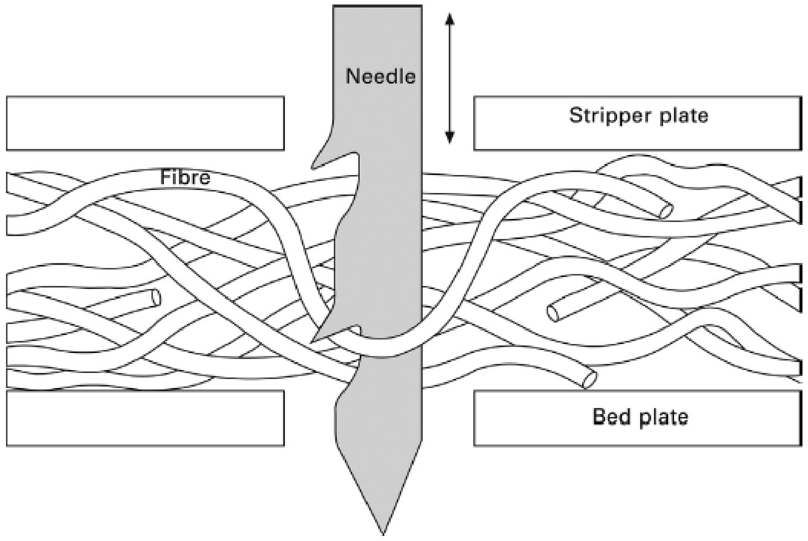
- Needle punching significantly reduces greenhouse gas emissions by eliminating the reliance on gas and other high energy resources, making it a more sustainable choice for environmentally conscious manufacturers and consumers.
- By eliminating the need for costly fuel and chemical additives, needle punching reduces production costs.
- Needle punching reduce the waste of natural resources such as water.
- Needle punching enhances the durability of nonwoven products by mechanically interlocking fibers through repeated penetration of barbed needles, creating a stronger and more cohesive structure.

Needle-punching: Limitations in Circular Economy

- Repeated needle punching can degrade the quality of fibers over time, making it difficult to recycle materials back into quality products. This affects the potential for recycling.
- There is a possibility of fiber damage during the process, which can adversely impact the durability and overall quality of the final product.
- Repeated mechanical action can also reduce the flexibility or elasticity of fibers, making them more brittle over time.
- The disposal of expired needles poses a challenge to the circular economy, as it creates waste that is difficult to reintegrate into sustainable recycling or reuse processes.

Needle-punching: Effect on Recyclability of Material

- Needle punched fabric can be recycled mechanically.
- Sometimes sharp needles used in the needle punching process can potentially damage the fibers, making them difficult to reprocess.
- The entanglement of fibers makes it harder to separate individual fibers during recycling, especially if the material comprises mixed fibers.



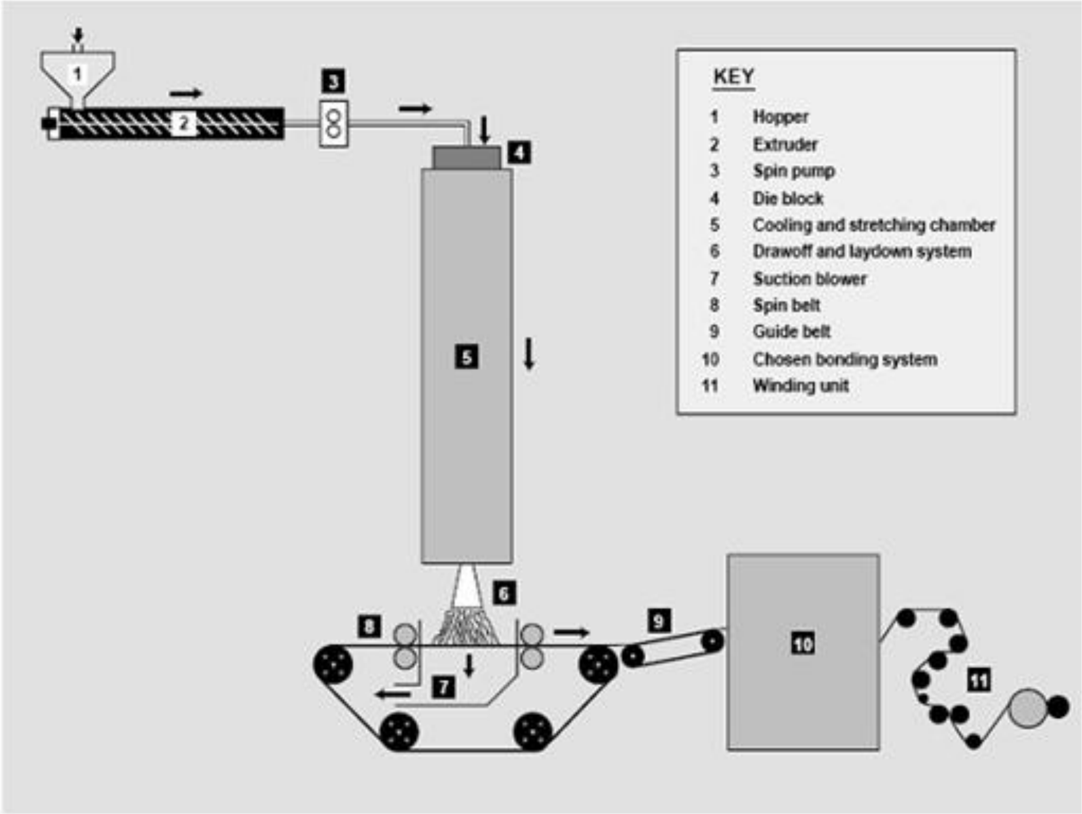
PICTURE. Action of barbed needle.

Needle-punching: Utilization of Recycled Materials

- A study on needle-punched nonwovens repurposed short milkweed fiber waste by blending it with hollow PET fibers to produce nonwoven fabrics of different thicknesses (Gürarslan et al 2024).
- Textile waste materials such as comber noil, silk cocoon waste, and polyester/cotton flat strip waste were successfully repurposed to create needle-punched nonwoven fabrics (Kumar et al 2021).

PICTURE. Needle types.

Spunbonding



A process of creating nonwovens which combines the production of filaments and fabrics together in one machine.

A spun bond fabric consists of continous filaments that are formed into a web structure and then bonded together into a fabric.

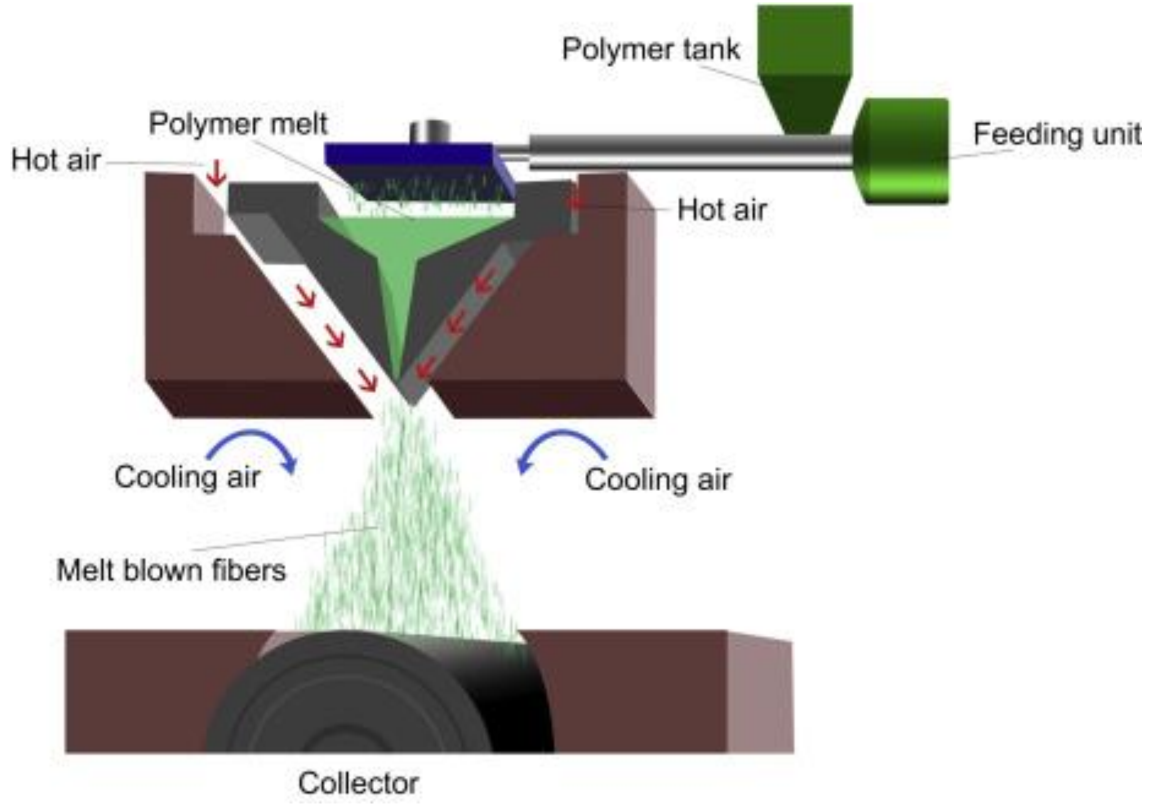
Spunbonding: Possibilities in Circular Economy

- Excellent fabric properties
  - High liquid retention, tear strength, strength-to-weight ratio
  - Breathable, lint-free, sterilizability, resistance to fluid penetration
  - Used mainly for diapers and medical products
- Wide range of characteristics are achievable
  - From paper to woven fabrics
- Highly efficient and cost effective process

Meltblowing

A process of creating nonwovens, where the polymers are extruded using hot air, then the melt blown fibers are collected in a rotating drum or forming belt with a substrate that will generate a nonwoven web.

In this process the creation of the filament and fabric is also combined into one.



Meltblowing: Possibilities in Circular Economy

- This method could process any thermoplastic polymer, including the biodegradable ones
- Creates fine and soft fabric with excellent filtration properties
  - Used in medical masks

Meltblowing: Limitations in Circular Economy

- Meltblown fibers are weaker than spunbonded fibers
  - Low viscosity polymers is need in order for this process to work well

Meltblowing: Effect on Recyclability of Material

- A wide range of biodegradable polymer materials are able to be processed using this method

Yarn Manufacturing

Possibilities and limitations in circular economy

Content: Yarn manufacturing

- Filament yarns
  - Melt spinning
  - Dry spinning
  - Wet spinning
  - Dry-jet-wet spinning
  - Texturizing
- Short-staple spinning (cotton-type yarns)
  - Preparation
  - Ring spinning
  - Compact spinning
  - Rotor spinning / OE-spinning
  - Vortex spinning
  - Friction spinning
  - Air-jet spinning
- Long-staple spinning (wool-type yarns)
  - Worsted spinning
  - Woollen spinning

Filament yarn spinning

Filament Yarns

Continuous, unbroken, and endless length

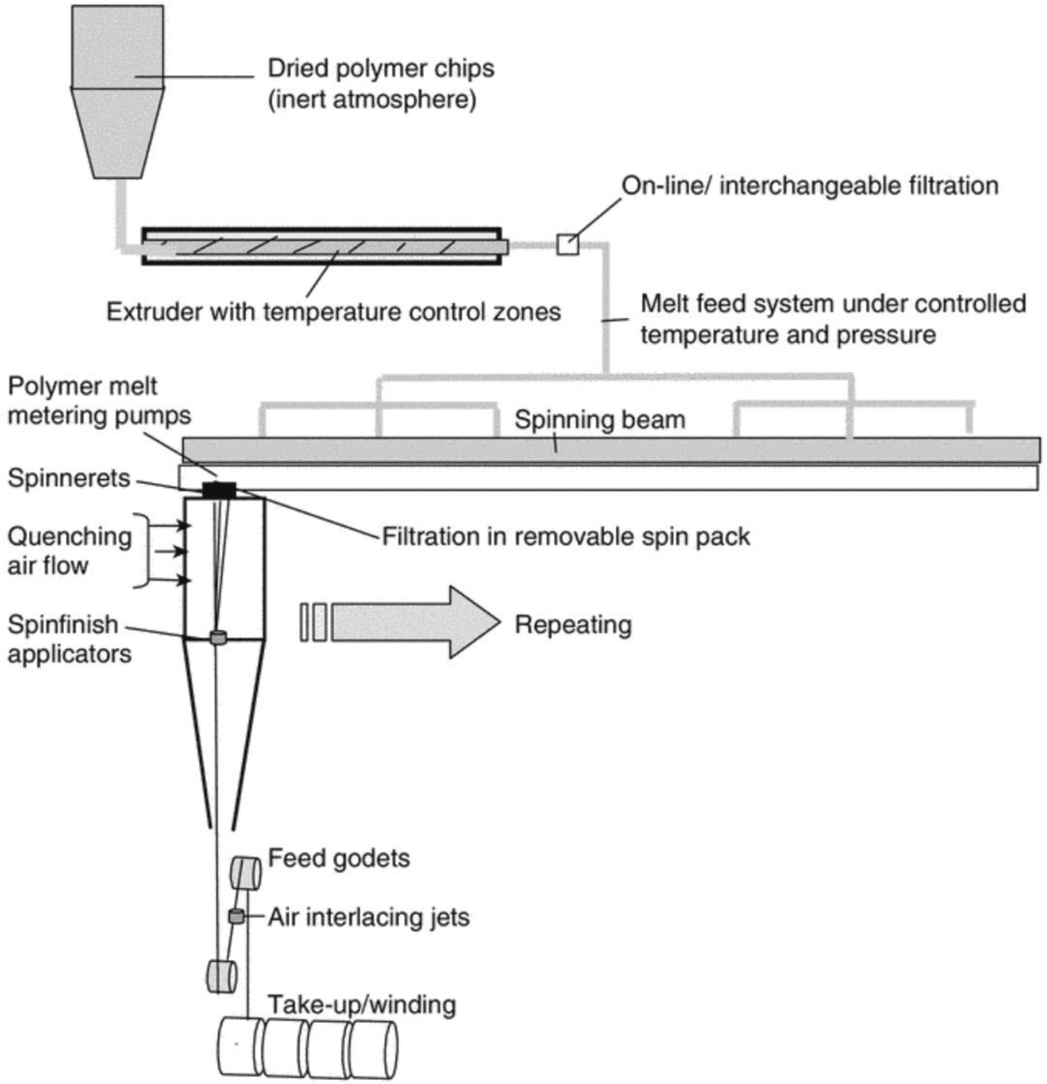
- Man-made synthetic fibers are usually filament
- Silk fibers are considered filament fibers as well

PICTURE: Silk Filament Yarns

PICTURE: Synthetic Filament Yarns

Melt Spinning

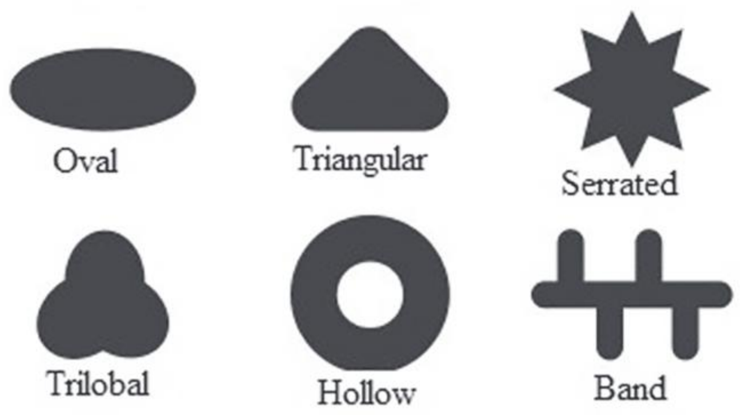
Thermoplastic polymer chips are melted, extruded out the spinneret, and harden by cooled air to form a filament yarn



PICTURE: Melt Spinning Process

Melt Spinning: Possibilities in Circular Economy

- Simple, economical, and fast
- Suitable for thermoplastic polymers like polyester, nylon, and polypropylene
- Various shapes of filaments could be produced



PICTURE: Cross section of various shapes that could be produced by melt spinning

Melt Spinning: Limitations in Circular Economy

PICTURE: Lab Scale Melt Spinning Machine

- Production limited to thermoplastics
  - Unable to process naturally occuring polymers due to them decomposing when heated in such high temperatures

Melt Spinning: Effect on Recyclability of Material

PICTURE: PLA Fiber

- Able to spin PLA (PolyLactic Acid)
  - Composed from 100% renewable resource
  - Biodegradable, biocompatible, non-toxic
- Polyester and nylon are now commonly recycleable although it requires to be mixed with virgin fibers
- No byproduct is produced during the production

Melt Spinning: Utilization of Recycled Materials

- Recycled polyester and nylon products are now common in the fashion industry
  - Used by big fast fashion retailers like H&M and Uniqlo
- PLA based products are used mainly in short term packaging
  - 100% biodegradable

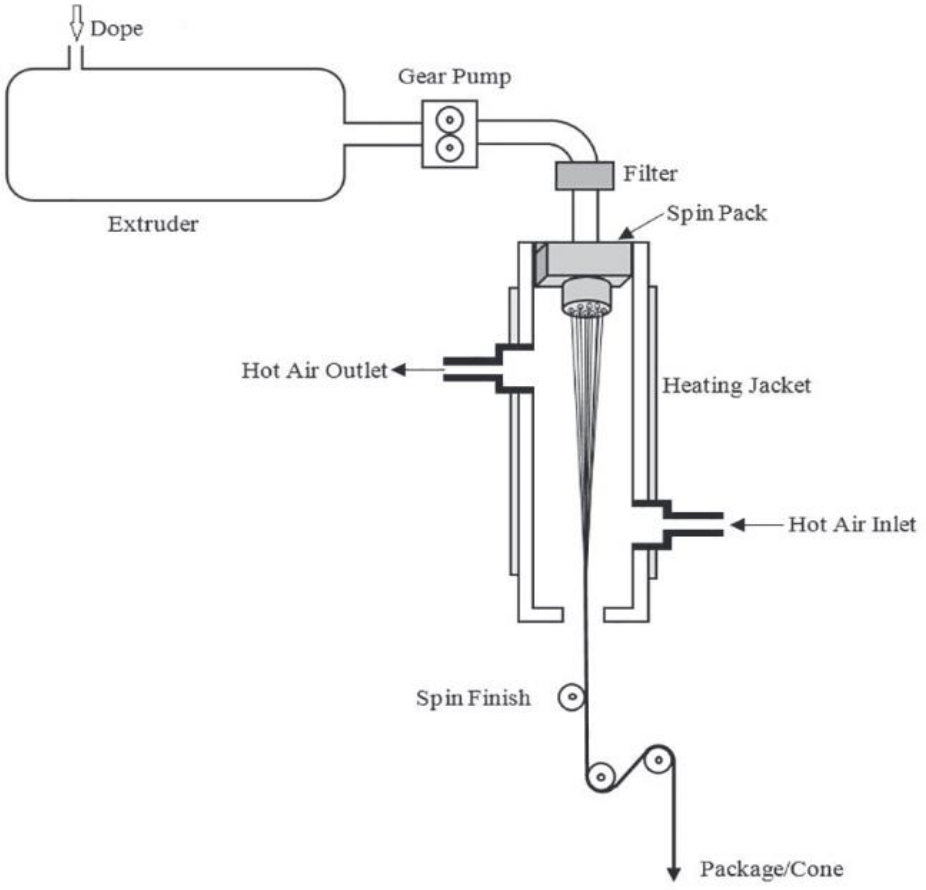
PICTURE: Uniqlo jacket from recycled polyester

PICTURE: Uniqlo tanktop from recycled nylon

Dry Spinning

Polymers are dissolved and mixed in a volatile solvent (dope) and ejected out of the spinneret.

The solvent will be later evaporated, leaving the polymer filament



PICTURE: Dry Spinning

Dry Spinning: Possibilities in Circular Economy

PICTURE: Cellulose Acetate

- Can be used to produce bio-based materials
  - Cellulose acetate
- Most elastomeric fibers are produced using this method
- No need for separate washing
- A faster process compared to wet spinning
  - 500-1500 m/min

Dry Spinning: Limitations in Circular Economy

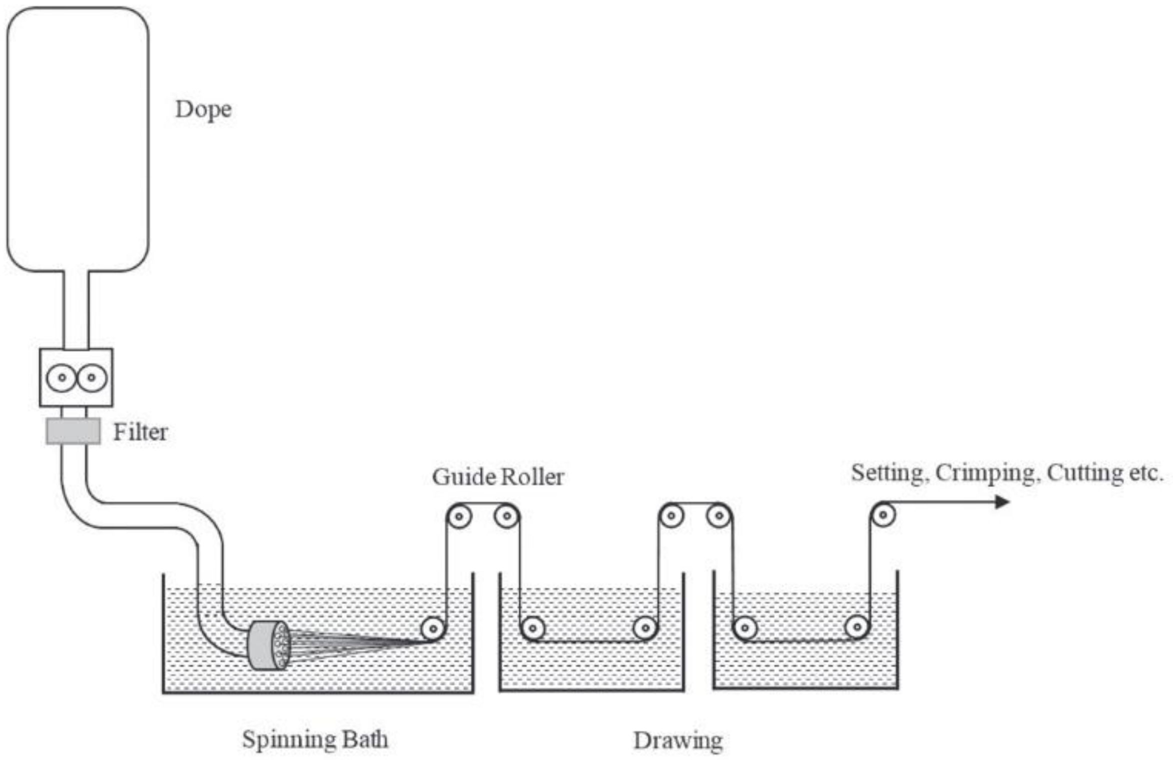
- High equipment and operating cost
  - Costly solvent recovery and recycling
- The solvents used must be gathered and recycled as it could be damaging to the environment
- High energy consumption

Dry Spinning: Effect on Recyclability of Material

- This method is not suitable for recycling natural polymer-based fibers due to the decomposition of the fibers in high heat
- This method produces fibers that are blended with elastane and/or other synthetic fibers causing the fiber's recyclability to decrease
  - Even in a low concentration, elastane could prevent other polymer types present in clothing from being recycled
  - Unable to be mechanically recycled but instead only chemically recycled which uses an excessive amount of chemicals and cause the recovered fiber's polymer chain to be shorter
    - Shorter polymer chain -> reduced quality and strength

Wet Spinning

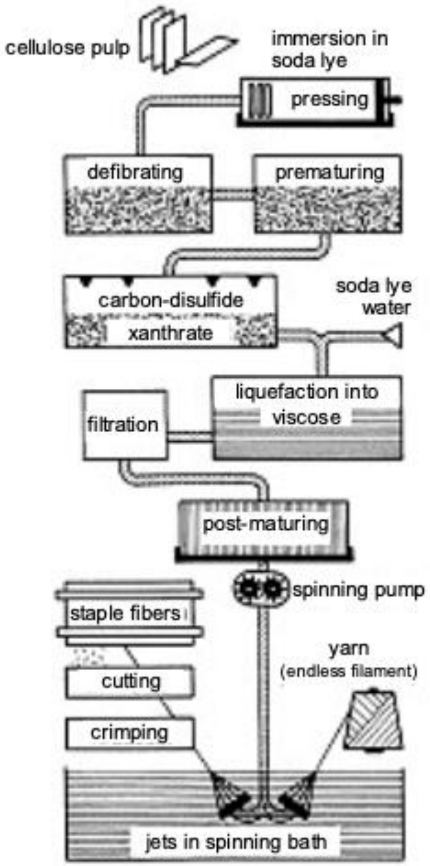
Polymers are mixed into a non-volatile solvent solution (dope) and extruded through spinnerets into a coagulating bath. The fiber is then taken up, washed and dried.



PICTURE: Wet Spinning

Wet Spinning: Possibilities in Circular Economy

- Low operating temperature
  - Less chances of polymer damage or discoloration
- Viscose Spinning Method
  - A flexible method of producing viscose. Chemicals and/or physical process specifications could be modified to accommodate the needed properties.
- Able to produce a large number of fibers at once
  - Multiple filaments/spinnerets in one machine



PICTURE: Viscose Wet Spinning Method

Wet Spinning: Limitations in Circular Economy

- Low dope concentration (5%-30%)
  - Making solvent recovery more costly
- Slow operating speed (50-300 m/min)
  - Due to diffusion of the solvent into the coagulation bath at a low temperature, causing it to be in a semi solid gel state for a longer period of time. Using a higher operating speed will cause the fiber to break.
- The fibers tend to swell.
- It is difficult to improve the fiber's mechanical properties.

Wet Spinning: Effect on Recyclability of Material

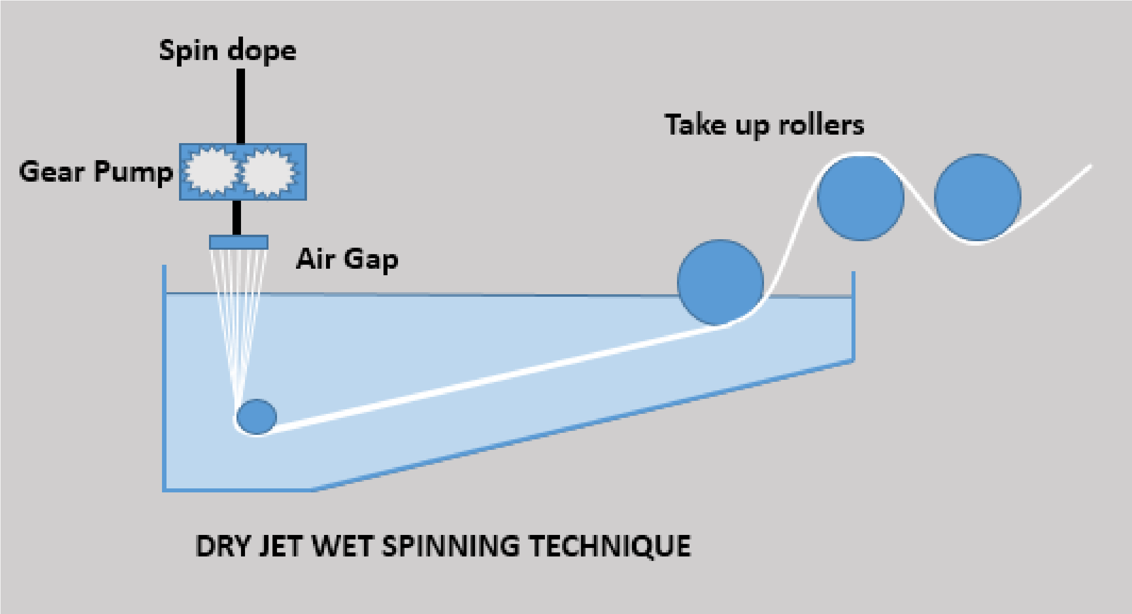
- Wet spun viscose fiber is often blended with other fibers in fabrics
- If wet spun fibers are blended with elastane or synthetic fibers, the fiber’s recyclability decreases
  - Even in a low concentration, elastane could prevent other polymer types present in clothing from being recycled
  - Unable to be mechanically recycled but instead only chemically recycled which uses an excessive amount of chemicals and cause the recovered fiber’s polymer chain to be shorter

Wet Spinning: Utilization of Recycled Materials

- Wet spinning is usually used to spin chemically recycled cellulose fibers
  - Recycled cellulosic waste material can be used as raw material in viscose process

Dry-Jet Wet Spinning

A combination of dry and wet spinning. The polymer is mixed with a solvent and pushed out into an air gap and then into a coagulating bath.



PICTURE: Dry-Jet Wet Spinning Diagram

Dry-Jet Wet Spinning: Possibilities in Circular Economy

- This method is used to produce cellulose-based recycled materials using organic solvents
- Strong, uniform, and soft fiber can be created from recycled materials
- Using this method to spin lyotropic liquid crystalline polymers (LCPs) produces a fiber with superior properties and quality
  - Due to the liquid crystalline phase of the polymers in the dope and the translation of these liquid crystalline domains in an oriented form to the spun filaments

Dry-Jet Wet Spinning: Limitations in Circular Economy

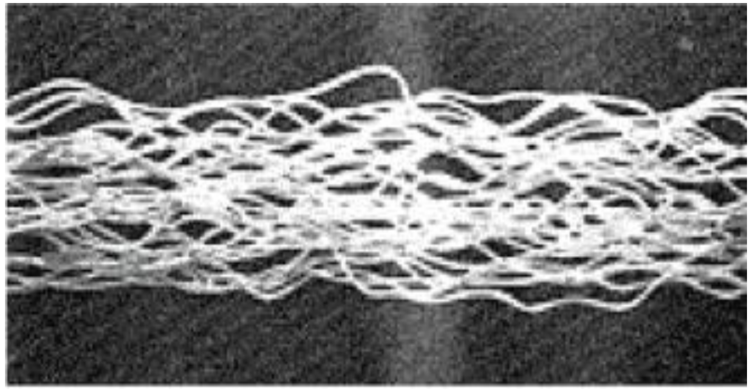
- A low selection of polymers could be used for this method of production
- The fibers are highly fibrillated and could cause wrinkling in the end-product

Dry-Jet Wet Spinning: Utilization of Recycled Materials

- This spinning method could be suitable to spin several recycled cellulose fiber

Texturizing

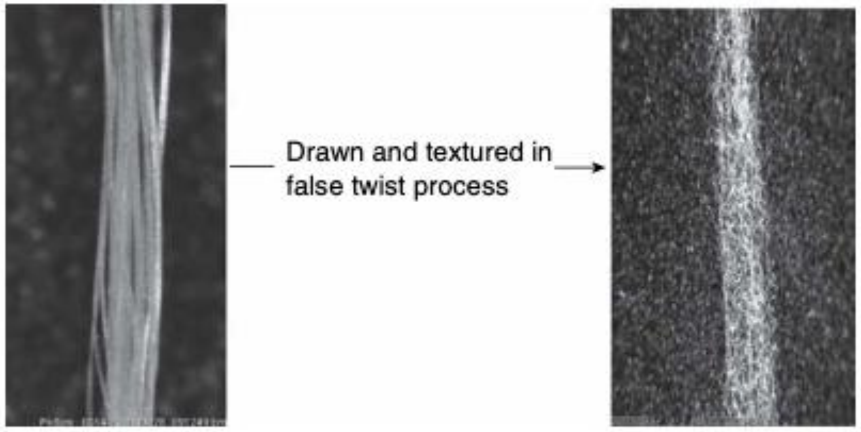
- The curling/crimping of filament fibres and yarns by various methods of heating, cooling, and twisting.



- The most common method of texturizing
  - False Twist Texturizing
    - The fiber is twisted, setted by the heat, cooled, then untwisted
  - Air Jet Texturizing
    - Yarn is overfed into a compressed air jet stream so that loops are forced out of the yarn
- The structure of the yarn is permanently altered.

Texturizing: Possibilities in Circular Economy

- Increases the fiber yarn’s insulation properties, elasticity, volume, and air porosity
- Texturizing allows filament yarn to have properties that are suitable for textile end uses without destroying its continuity
- Air jet texturizing could be used to texturize any continous filament due to the lack of heat in its process
  - Rayon, Glass, and other new high performance fibres



Texturizing: Limitations in Circular Economy

- Texturizing technology has evolved around polyester and nylon continous filament
  - Due to them being the most produced thermoplastic melt spun filament fiber
- Streakiness and a slight change of color could occur to the yarn causing batches to be redone or discarded (False Twist Texturizing)
  - It is undetectable analytically but detectable by the human eye
- Dependent on the feed yarns quality
  - Poor feed yarn could cause easy breakage, broken filaments, and dye variation

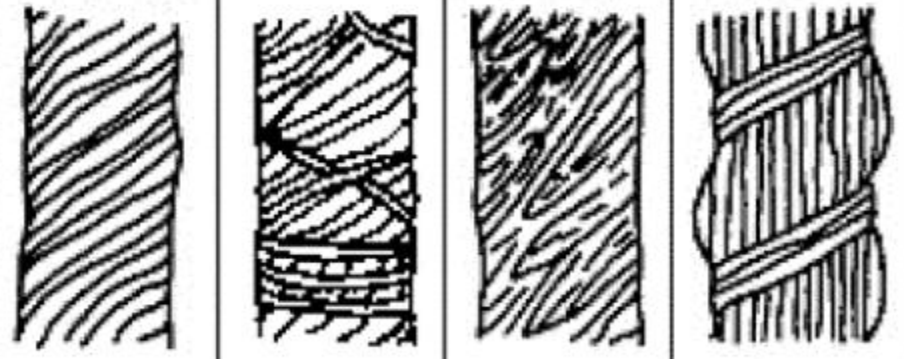
Texturizing: Effect on Recyclability of Material

- Most fibers that are texturized are thermoplastic polymers
  - Recycling might be an issue for polymers other than polyester and nylon, as the technology to do such in an industrial scale is still lacking

Short-staple yarn spinning

Content

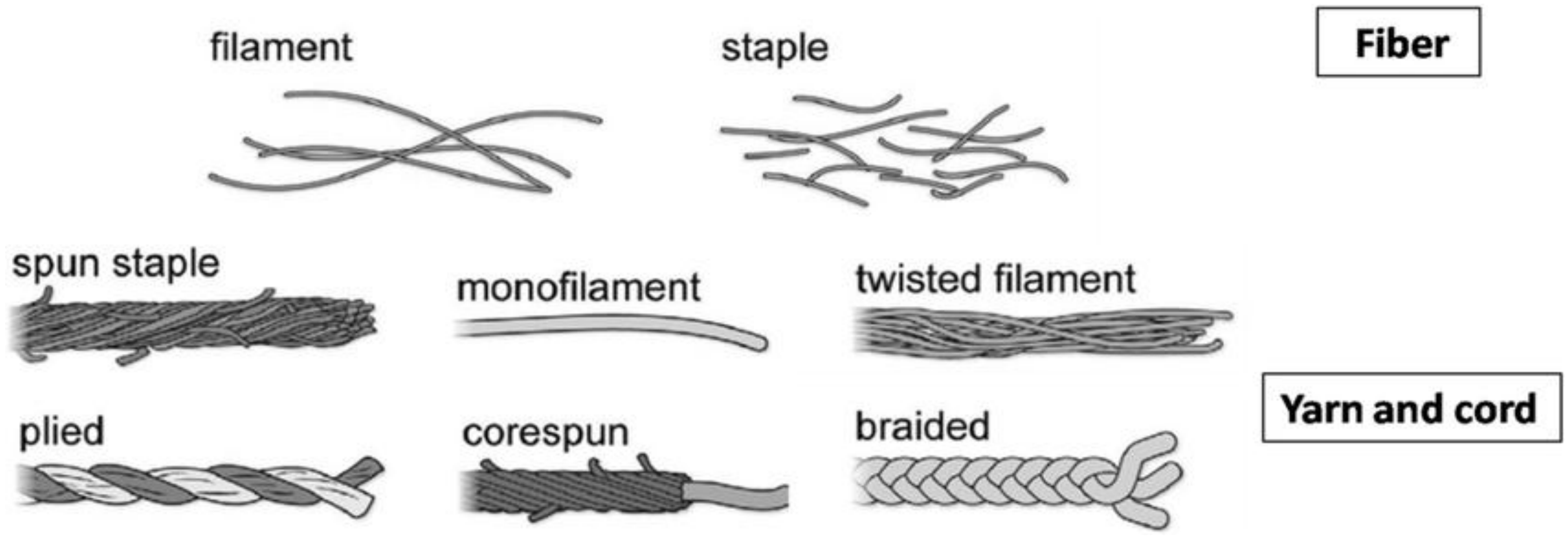
- Yarn manufacturing
  - Short-staple spinning
    - Preparation
    - Ring spinning
    - Compact spinning
    - Rotor spinning / OE-spinning
    - Vortex spinning
    - Friction spinning
    - Air-jet spinning

	Spinning method			
	Ring	OE Rotor	OE Friction	Air false-twist
Characteristics of yarn quality				
Tenacity, elongation	++	+	o	+
Evenness	++	+	o	+
Hairiness	++	+	+	+
Helix angle (twist)	+	+	++	++
Wrapper	-	+	+	++
	++ very high / + average / 0 low / - none			

PICTURE. Flow Chart for Yarn Spinning (Wulfhorst et al., 2006).

Yarn Manufacturing

A process of yarn formation, which generally means assembling fibers into a high aspect ratio aggregation, later used for fabric formation or connection (sewing). Depending on the fiber used in production, yarns can be generally split into two large categories: staple and filament.

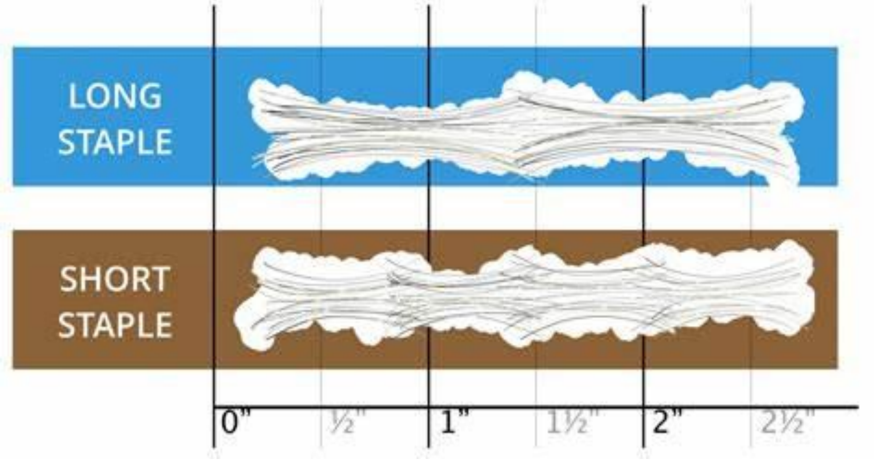


PICTURE. Main fiber and yarn types (Sanchez et al., 2020).

Short-Staple Spinning

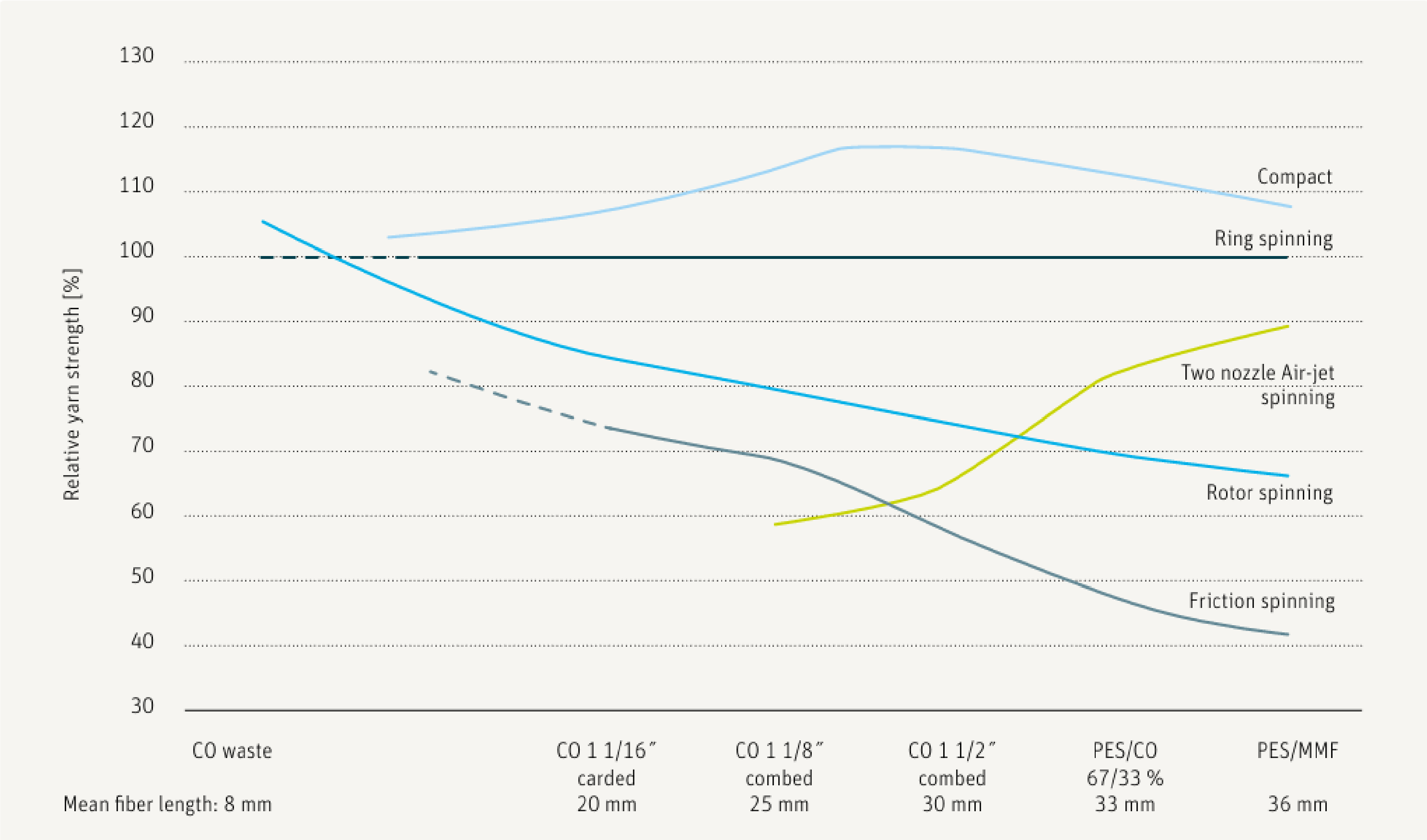
Staple spinning implies spinning staple fibers into a yarn. The imparted twist holds the spun fibers together and increases the yarn's strength and durability. Short staple yarns are commonly called 'cotton-type'. Staple fiber length is generally considered to be 2-50 cm long (but there are exceptions, of course). However, referring to cotton, **short** staple length is identical – 0,32-6,35 cm. There are 6 technologies of yarn spinning:

- Ring
- Compact
- Rotor / OE
- Vortex
- Friction
- Air-jet



PICTURE. Long and short staple fibers.

Short-Staple Spinning



PICTURE. Strength of different yarn types depending on raw material used (Stalder, 2016).

Preparation: definition

Preparation of fiber (spinning preliminary work) is a sequence of steps needed to implement before starting the spinning process. This process generally consists of several steps:

1) Fibers arrive in bales.
2) Opening (a bale opener removes the material layer by layer, separating the bale mass into small tufts) and cleaning up the fibers of debris with such methods as beating, spike screens, air streams etc. The tufts are left in a heap for 24 h to release the packing pressure (before cleaning). If the fibers are synthetic, those don't require cleaning, but, most likely, cutting is needed.

PICTURE. Fiber bales delivered (Fisher, 2020).

PICTURE. Carding process (Aditoadie, n.d.).

Preparation: definition

3) Mixing of different kinds of fibers, if applicable. The obtained mixture is supposed to be homogenous.

4) Carding. The fibers are opened into individual fibers arranged parallel to each other, meanwhile foreign matter, smaller debris and too short fibers are removed. In the last stage, carded web or sliver is produced.

5) For combed yarns: carded sliver is combed to remove even more impurities, get even longer fibers and have them more aligned.

6) Draw frame to equalize thick and thin places of the sliver.

7) Roving frame to impart the sliver a slight twist to prevent breaking in further processing.

NOTE that the actual process may differ depending on the spinning method.

Preparation: Possibilities in Circular Economy

- Short fibers appearing in the preparation stages can be repurposed and used in industries, where the fiber length is not as essential, such as production of nonwovens or viscose, some explosives and plastics. For viscose production, the shorter the fibers – the better, because thus the dissolution goes more easily and quickly. Textile dust can even be used in paper or cardboard production.
- Mechanically recycled fibers can be mixed with virgin fibers, with the final mass as uniform, as possible. Even a diverse composition can be added. The same way, synthetic fibers can be added to the natural ones, or just two different fibers can be mixed.
- Textile fibers can be recycled by different methods, although the mechanical one is more used nowadays as it has lower environmental impact and keeps the fiber form of the recycled fibers.

Preparation: Possibilities in Circular Economy

- The longest fibers are preferably taken, which facilitates their recyclability and longevity as well as of the textiles made of them.
- Textiles made from 100% the same material are easy to recycle into new fibrous material.
- There is reusable waste generated in various spinning preparation processes, called soft waste. This waste is fibers in a relatively open structure, which can be although reprocessed first, used for spinning again further.

Preparation: Limitations in Circular Economy

- The more the fibers are recycled mechanically, the shorter they become, which reduces their spinnability. The yarn's quality reduces correspondingly (especially applicable to hard waste).
- Many textiles contain polyurethanes (PUR, elastane). E.g., elastane complicates mechanical recycling, since it has different properties than, e.g., cotton (the base fiber usually), which makes processing of the mixture more difficult (due to its high elongation, the machine should have different specifications to cut it, than for cotton, and because it blocks the spiked rollers of the opener). Blends typically have various difficulties in other types of recycling.
- Preparation is a multi-stage process, which makes it energy-consuming and expensive. Besides that, it also has high chemical and water consumption, which makes the process less environmentally sustainable.
- Dyes and some other chemicals applied may reduce the recyclability of the material

Preparation: Limitations in Circular Economy

- There's unreusable waste generated in various spinning preparation processes, which includes **cleaning waste** (broken seeds, leaf bits, dust, and short fibers), **hard waste** (which is, in some sources, considered to be not reusable as additional operations are needed to use it with soft waste) and **sweep waste** (basically flying particles which then precipitate and aren't used anyhow further). Reusable in this case implies use as a fiber for further spinning, basically, no restrictions are put in terms of repurposing (e.g. micro dust can be used in paper production, and hard waste – in batting). Minimizing waste requires high investment and factory maintenance costs (educated workers, proper work practices, supervision, good-performance high-quality machines).
- The lint loss increases as the trash content in the material decreases.

Preparation: Limitations in Circular Economy

- To have a good control of the process, product or soft waste, it's crucial to access the waste on the production stages where it's generated at regular intervals through effective supervision, which requires more human resources and efforts, digital technologies and other investments.

Preparation: Effect on Recyclability of the Material

- A significant amount of material is lost in various preparation processes, which reduces the material's traceability and makes the material's reuse/recycling more challenging in the future, since those materials could be reused as such. It easier to obtain clean and uniform fiber preparations, which requires the composition to be rather mono, and the preparation processes designed better (more cost).
- A material formed from two or more different types of fibers mixed might be unsuitable for reuse as a textile material, but is suitable for non-textile applications, for instance, as an insulation material. Increasing trend of use of blends reduces recyclability of textile products. For example, in the ubiquitous cotton/polyester blend, polyester can be remelted, but cotton cannot. On the other hand, solvents for cotton production are not suitable for polyester. Elastane complicates mechanical recycling due to its high elongation. Thus, mechanical, biochemical, chemical and thermal recyclability is affected at this key stage.

Preparation: Utilization of the Recycled Material

- Recycled materials can be used if their spinnability properties are valid. As mentioned before, the recycled material can be mixed with virgin fibers to enhance this characteristic, but fully recycled materials can be used too. The shorter the length though, the lower the quality. Thus, waste fibers are preferably used in a controlled manner and with constant percentage by manufacturers to avoid quality variations.
- Recycled material undergoes all the preparation processes going after the opening stage. Opening takes much more energy and efforts than virgin material, and purity (chemical and fiber-variational) of the original material is important for good quality. The recycled fiber's composition must be known and analyzed, which requires computing power, energy and human resources and so on, which is, however, feasible for large companies.

Preparation: Utilization of the Recycled Material

- Some sources say, that the only waste possible to further reuse is soft waste from production, but this implies reuse with no downcycling. With lower quality, hard waste can be used too.

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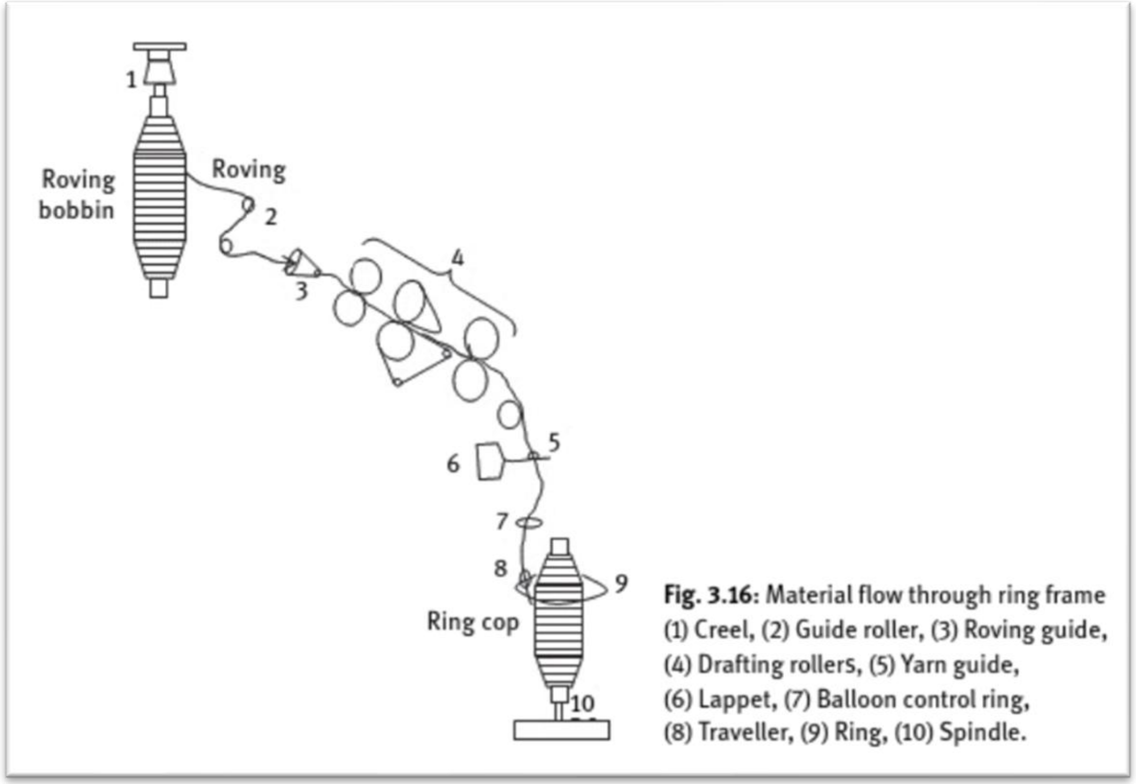
Ring Spinning: Definition

Ring spinning is the most traditional, simple and popular spinning method in the textile industry. It consists of **drafting of the roving** to the desired fineness with rolls, **twisting it by a traveller** rotating along the ring to impart strength by fibers holding up together, and **winding the yarn** onto a suitable package.



PICTURE. Ring spinning (Yasir, 2016).

Ring Spinning: Possibilities in Circular Economy

- Enables production of high quality, strong, durable, thin, and uniformly twisted yarns. This method is considered to give the best quality yarn.
- An adjustable process and can process a variety of fibers, including (not too) short.
- As mostly the longest possible fibers are preferred, the recyclable content of the product is higher.
- Monomaterial yarns are easier to recycle, which the method enables.
- Environmental sustainability can be improved by increase of spinning speed (challenging), use of more efficient engines and driving systems (lower energy consumption), appropriate oiling, lightweight bobbin use, and development of ring traveler's material properties.

Ring Spinning: Limitations in Circular Economy

- Relatively slow (doesn't allow for proper catch-up with the recycling flow in circularity establishment), expensive (due to required preparational processes), and energy intensive (72 % of an average spinning factory's monthly energy consumption, where air conditioning takes 16 % (Koc & Kaplan, 2007, p. 24)).
- Cannot process well too short fibers. The shorter the fibers are, the lower the quality & strength, and higher coarseness are. Thus, spinnability of pure mechanically recycled fibers is usually low, so those often require mixing with virgin fibers. Moreover, ring spinning is sensitive to proportion of recycled fibers in the material used, so the amount of those added can be limited to avoid quality variations.
- Because of the aforementioned factors, ring spinning of self-spun and carded yarns currently faces increasing competition from rotor and friction spinning methods.

Ring Spinning: Limitations in Circular Economy

- Alignment of fibers in ring spinning may be poor occasionally, which reduces the strength of the yarn. The surface can remain fuzzy, and the yarn can easily curl.

Ring Spinning: Effect on Recyclability of the Material

- The spinning method doesn't affect the material's chemical, thermal and biochemical recyclability, but since any waste generated in the process is considered hard, mechanical recyclability is generally considered null. Mechanical recycling typically degrades the fiber length, so the fiber is not further used for ring spinning but still can be reused in yarn production with other methods (rotor spinning). However, according to Esteve-Turrillas, F.A. & de la Guardia, M. (2016), a cotton yarn manufacturer, Hilaturas Ferre, utilizes a certain method of cotton recycling with no fiber length damage (10-15 mm), although involving shredding. There must be some untold damage, as fibers are cut anyways, but it might be inconsiderable for the yarn quality of even ring-spun yarns, however, for a few first cycles. Also, hard waste can be just repurposed instead of being recycled, for example, be used for batting, insulation, nonwovens' etc. (Garnetting machines used for opening).

Ring Spinning: Effect on Recyclability of the Material

- Fiber blends, typically used in ring-spun yarns, complicate recycling.
- Tight structure makes it harder to separate the fibers easily, compared to looser yarn types.
- High twist can cause fiber breakages in spinning.

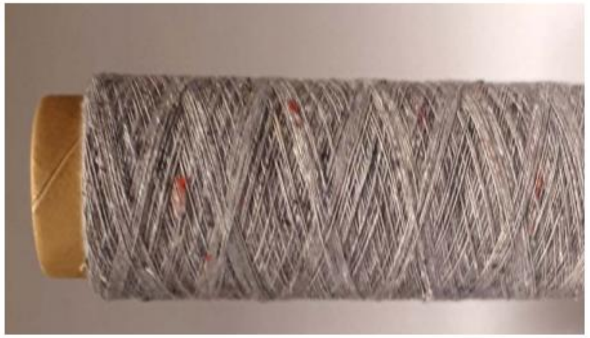
Ring Spinning: Utilization of the Recycled Material

- The method is suitable for the recycled materials, as it can be widely adjusted to different fibers, which enables production of a variety of yarns. In general, a recycled material would require more tender processing.
- Chemically and thermally recycled fibers can be used, as well as mechanically recycled ones, if the length is not damaged. The latter type of fibers, however, may be less preferrable for ring spinning, as fibers' lengths are more likely to be degraded to some extent there.
- Both monofiber materials and blends can be utilized. Recycled fiber often requires mixing it with virgin fiber to improve its properties needed for sufficient spinnability.
- Use of shorter fibers results in lower quality coarser yarns and is challenging, so, preferably, fiber material of mostly long enough fibers is used for this method, which allows for such properties of yarn.

Ring Spinning: Utilization of the Recycled Material

- According to Rieter (n.d.), their ring recycling system Ne 6 to Ne 30 allows production of 100% cotton yarns with up to 30% recycled cotton, and yarns from man-made fiber blends with up to 50% recycled cotton. (Rieter, n.d.)
- Ring spinning process is more sensitive to the proportion of short fibers, than other methods, which limits the amount of recycled fiber used and requires stricter control to avoid quality variations. One of the reasons for this sensitivity is that short fibers tend to form packages in all drafting stages. The Rieter ring Com4recycling system "optimizes the control of the short fibers in the drafting units along the complete process to maximize the share of recycled fibers also for quality yarns". (Rieter, n.d..)
- VTT have done laboratory researches on different compositions of cotton mixed with virgin and recycled fibers (See the next slide) (Heikkilä et al., 2019).

Ring Spinning: Utilization of the Recycled Material



50 % r-CO (6) / 50 % virgin CV

Yarn

30 % r-CO (5) / 70% virgin CV

Yarn and knitted material

PICTURE. Ring-spun yarns of different fibre compositions (Heikkilä et al., 2019).

Cotton opened 5 or 6 times, mixed with virgin cotton & viscose, and post-consumer r-PET

Fibre composition	Outcome
100 % r-CO	Sliver was formed, but spinning required blending (with used machine)
50 % r-CO (6) / 50 % CO	A yarn was difficult to spin, resulted only small and weak samples
50 % r-CO (6) / 50 % CV	Spinning worked well and resulted yarn (88 tex and 650 twists/meter) – see next slide The yarn was test knitted, but it was too thick for a lab scale knitting machine
30 % r-CO (5) / 70% CV	Spinning worked well and resulted yarn (66 tex, 650 twists/meter) The yarn suited well for knitting – see next slide
40 % r-CO (5) / 40 % r-PET / 20 % CV	Roving was formed, but it was uneven and yarn spinning was not possible

PICTURE. Ring spinning outcomes with different fibre compositions (Heikkilä et al., 2019).

Ring Spinning: References

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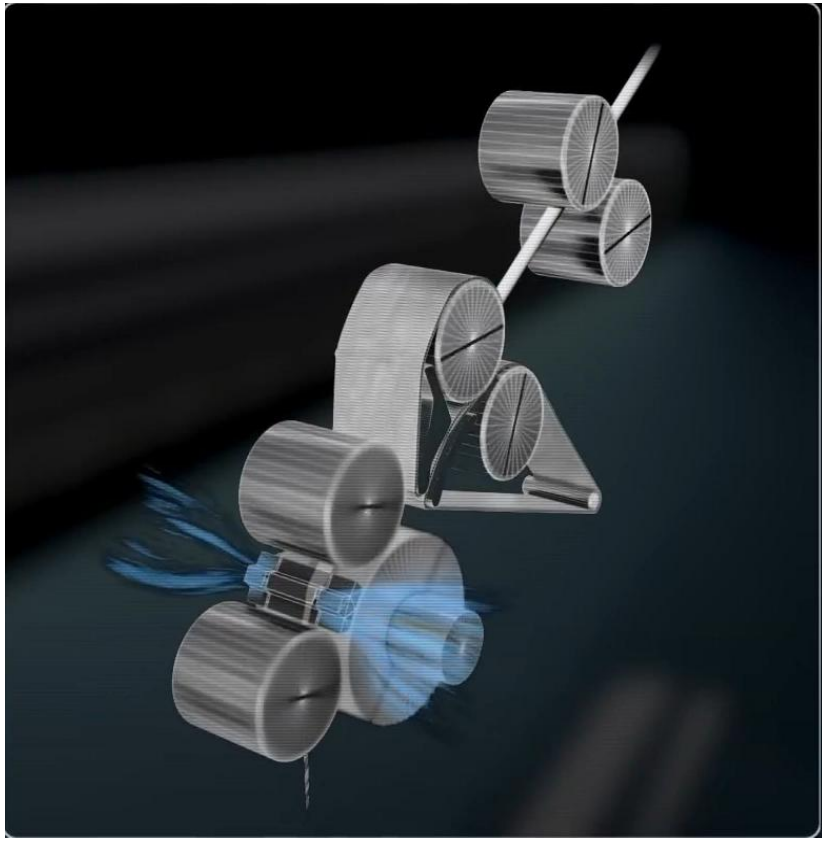
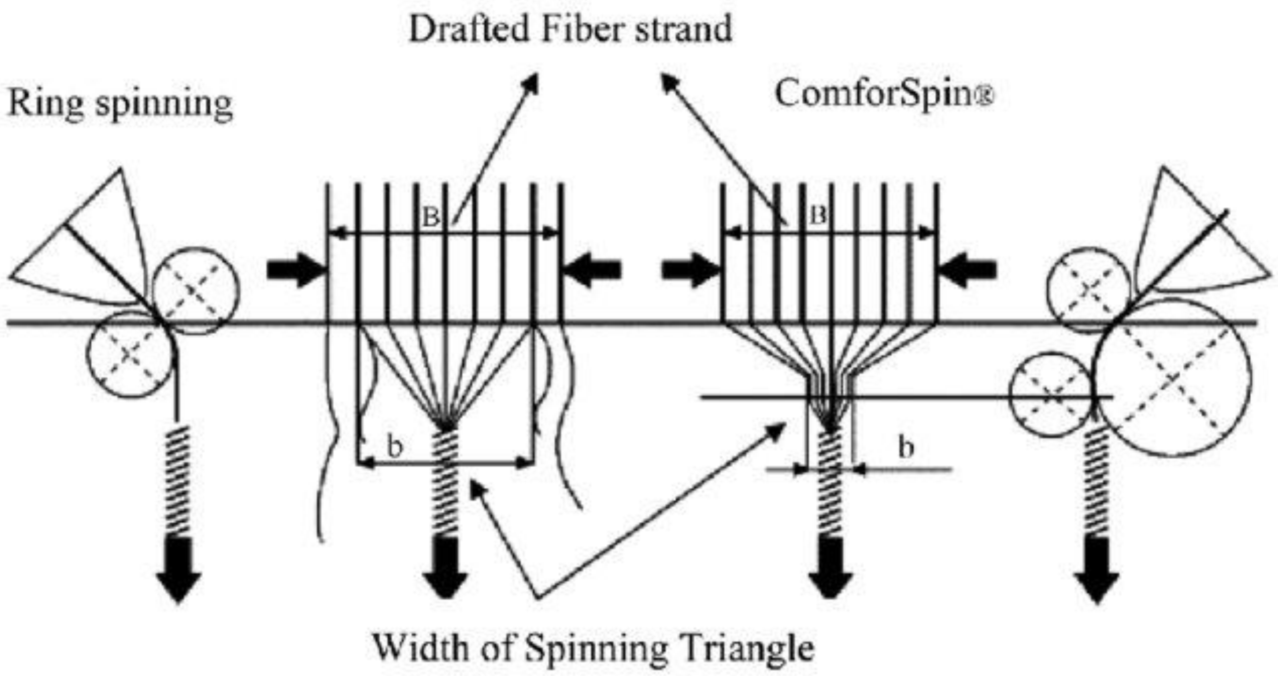
Compact Spinning: Definition

Compact spinning is a relatively new spinning process, which is a modification of the basic ring spinning frame. The roving entering the drafting unit is drafted to the required yarn count, and the fibers get compacted by air suction and a perforated roller (methods of condensing are aerodynamic, mechanical and magnetic). The hairiness is thus reduced, as protruding fibers are bonded. Then, like in normal ring spinning, the roving is twisted by a spinning/twisting triangle (reduced in size, though). The quality is higher (more durable and even and less fuzzy, compared to ring-spun yarns.



PICTURE. Compact spinning frame (Rieter, 2015).

Compact Spinning: Definition



PICTURE. Compact Spinning in Comparison To Ring Spinning (Khan et al., 2020).

Compact Spinning: Possibilities in Circular Economy

- The yarns produced have significantly higher tenacity, elongation, work to break, and abrasion resistance, lower hairiness and better fiber alignment. Compact yarns are up to 20% stronger than ring-spun yarns (El-Sayed & Sanad, 2014). The textiles produced last longer because of higher durability of yarns, which also increases opportunities for the secondary market.
- Recycled fibers from compact yarns are high quality because of good yarns' properties. This is also why it can be used widely.
- The spinning process consumes less energy (higher efficiency). E.g., less twisting is required, around 14,6% (Gokarneshan et al., 2005), because the fibers' tenacity is used better. This saves energy in total, despite higher energy consumption by the condensing modification, which would result in higher total energy, if the same twist were imparted, as in ring spinning.

Compact Spinning: Possibilities in Circular Economy

- As the tenacity is better, cheaper raw material can be used.
- Less waste during production and wear, so the fibers are used in the maximum amount from the input, and thus with maximum benefit.
- Less (up to 50 %) or no sizing/waxing is required (Beg, 2015). This also saves energy to size and desize the yarns.
- Compact yarns improve weaving efficiency by 3-5% due to their high strength, which reduces weaving cost (El-Sayed & Sanad, 2014).

Compact Spinning: Limitations in Circular Economy

- Generally suitable for long and fine fibers only, and short fibers are a challenge, which decreases opportunities in circular economy (see the "Utilization of the Recycled Material" slide).
- The machines and maintenance are more expensive, which is reasoned by a more complicated mechanism.
- Due to high quality, it is more difficult to open a yarn or a fabric made of it, which requires more energy.
- More expensive, than ring spinning in maintenance and investments, but so are all the other techniques. At the same twist level, consumes more energy because of the negative pressure generator: according to Yin et al. (2021).

Compact Spinning: Limitations in Circular Economy

- The improvements compact spinning is supposed to make for yarns, are not always drastic. Although, of course, use of blends is possible, advantages of compact spinning can be reduced. Compact yarns made of cotton, viscose and their mixes have advantage over ring-spun yarns made of the same raw materials. Polyester, however, doesn't allow for proper fiber condensing, and thus, the yarns are not significantly different from ring-spun yarns. This improvement reduction can also happen for cotton/viscose yarns too, though.

Compact Spinning: Effect on Recyclability of the Material

- Despite the difficulty of opening the compact yarns because of their high strength, due to high alignment and even distribution of fibers in a yarn and its low hairiness, the stress applied in mechanical recycling can be distributed into opening the fibers, instead of tearing them. This, however, requires quite precisely set machines. The compact yarns' good abrasion resistance helps to preserve the fibers during use better.
- The process does not affect the chemical, thermal and biochemical recyclability of the material.

Compact Spinning: Utilization of the Recycled Material

- The advantage compared to ring spinning is only apparent with use of only long and fine fibers, as the production of coarse fibers is not as efficient, and short fibers may clog the compacting rollers' holes. This problem is generally typical for mechanically recycled fibers. However, there are opinions that short fibers can also be used, probably, requiring an optimized mechanism. Another reason to say so is that fibers don't move freely, so recycled fibers could be put in a yarn's core for bulk, for example.
- On Rieter machines, fine compact yarns with almost 40 % recycled fibers can be spun (Rieter, n.d.). This is good, since possible, but, on the other hand, cannot be improved much due to short fibers in the recycled fiber mass.

Compact Spinning: Utilization of the Recycled Material

- Due to the better use of fibers' tenacity, not only cheaper material can be used for compact spinning, but also lower quality recycled material (shorter or weaker fibers), than in ring spinning to reach the same result. Theoretically, compact yarns from recycled cotton can be even stronger than virgin cotton ring-spun yarns.
- Dependence of the yarns on length and fineness of fibers and types of fibers implies high sensitivity of the process's result to the raw material content and quality, which is commonly hard to meet with use of recycled mass, especially without good sorting.

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Rotor OE Spinning: Definition

A spinning technique that produces yarn using a rotating kind of cup, called rotor. First, the sliver is fed into the machine and is opened to individual fibers aligned parallel with an opening roller. The trash including too short fibers is thus removed. Then the fibers go into the rotor and are displaced on its edges (groove) due to a centrifugal force, forming a ribbon of fibers there. They are then pulled out into a yarn. The twist is formed by the rotation of the rotor, which's high speed creates partial vacuum.

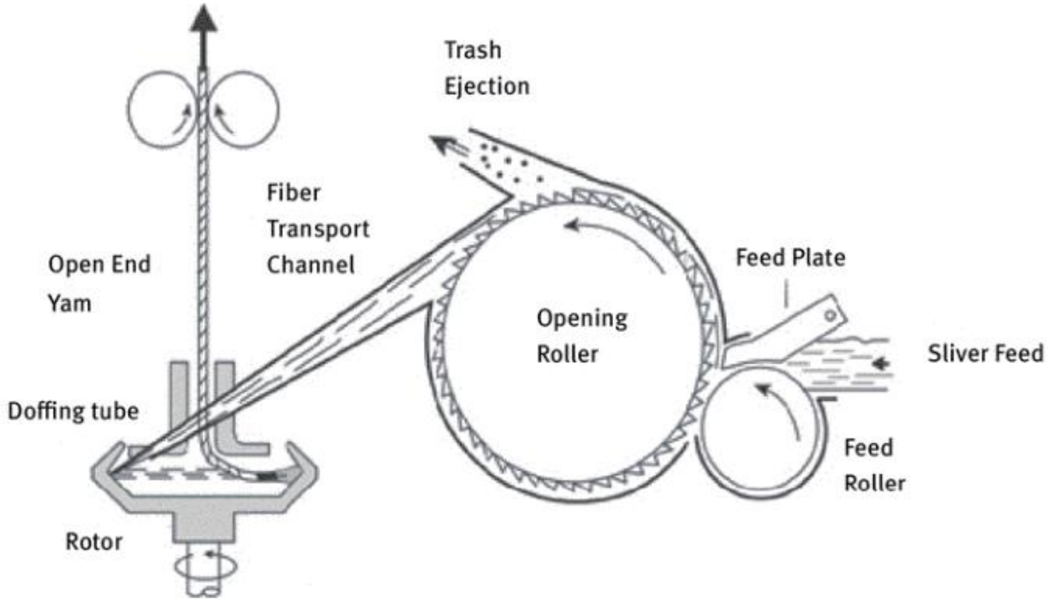

Fig. 3.19: Material flow through open end rotor machine.

PICTURE. Open End Rotor Spinning (Yasir, 2016).

Rotor OE Spinning: Possibilities in Circular Economy

- The process suits well for fibers with high short-fiber content, and, therefore, for mechanically recycled fibers. End-of-life textiles are only suitable for this method.
- Fine and uniform threads with a low number of nodes/knots can be produced for a wide variety of applications. With the process's affordability and possible quality, can be used for popular denim, for example.
- The method is fast (5-10 times faster than ring-spinning (Muthu, 2017)), cheap, and easier, than ring spinning, as no preprocessing is required, such as roving and its additional winding, which saves energy and lowers expenses for equipment. However, totally, the process is energy-intensive.
- Amount of twist and thickness can be adjusted by changing the speed of the rotor's rotation and draw speed of the yarn.

Rotor OE Spinning: Possibilities in Circular Economy

- Many different raw materials can be used, and very different yarns can be produced. A large number of spinning components is available on the market (easy adjustment).
- Considered the best process for short (e.g., recycled) fibers.

Rotor OE Spinning: Limitations in Circular Economy

- Threads as thin as ring-spun are not possible, and they are fluffier, weaker (tensile strength), have low abrasion resistance + pills easily (especially decreases durability), stiffer and not tightly threaded (as no stress in spinning).
- Impurities present in a fiber mass can affect the yarn quality. Also, quality is sometimes told to be not even and lower, which can be explained by using recycled fibre and, from some sources, the manufacturing process itself, which doesn't provide good yarn evenness.
- Different materials and different yarn characteristics require adjustment of different system's elements in shape and material (as well as process's settings), which limits using of fiber blends (depends on a specific case).

Rotor OE Spinning: Limitations in Circular Economy

- End-of-life textiles' fibers should be strengthened by mixing with virgin fiber.

Rotor OE Spinning: Effect on Recyclability of the Material

- No effect on chemical, biochemical or thermal recycling, except for increased purity of the material caused by the combing roll. The mechanical recyclability stays unchanged, but the resulting recycled fibre is even shorter than already short fibers used for yarn production.
- The fibers in a yarn are not parallel, especially considering the wrapping fibers. This affects the yarn's mechanical recyclability, as some fibers will be torn/cut apart instead of getting opened.

Rotor OE Spinning: Utilization of the Recycled Material

- Rieter's rotor recycling system Ne 3 to Ne 25 allows production of 100% cotton yarns with up to 50% recycled cotton, and yarns from man-made fiber blends with up to 70% recycled cotton, which is 20 % higher in both cases, than the ability of their ring recycling system Ne 6 to Ne 30 (Rieter, n.d.). Polyester, cotton and viscose are the main used fibers.
- Fineness and strength of the fiber are more important than length, but long fibers are, of course, suitable too. As short fibers are suitable, so are mechanically recycled fibers.
- As the process is adapted for use of short recycled fibers, the resulting quality is uneven and lower, in general. This is because of shortened, contaminated, divergent (mixed composition of raw material from blends or bad sorting), and, sometimes, damaged fibers. Also, impurities can be present in a recycled fiber mass, however, the same thing goes for virgin fiber mass too.

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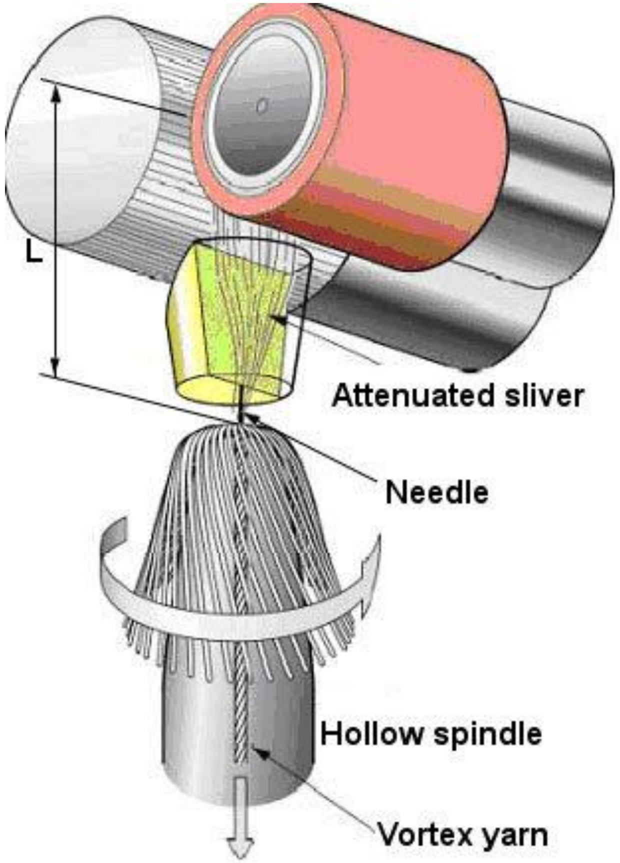
Vortex Spinning: Definition

- A spinning method developed from air-jet spinning that can be categorized as either an OE spinning method or a surface spinning method. The second one can be, for example, the air-jet spinning method. In the OE variant, which is the air-jet method's advanced version, a sliver is opened to individual fibers and is fed through a nozzle with an airflow, which spins them into a yarn inside out, forming a structure similar to ring-spun yarn and anchoring them to the yarn's core.



PICTURE. Vortex Spinning (Mouckova et al., 2015).

Vortex Spinning: Possibilities in Circular Economy

- Uniform, abrasion resistant, less pilling, less hairy, and withstands washing better – high durability and longevity.
- Extremely fast production – up to 550 m/min (Vortex, n.d.). For comparison, ring spinning is around 30 m/min (Räisänen et al., 2017), and the abovementioned 5-10 times faster rotor spinning is around 150-300 m/min (Muthu, 2017).
- Suitable for different raw materials and fiber blends (e.g., PES, CO, CV, their blends, LI, PAN and elastane sheath), and is used in e.g. apparel and home textiles.
- Prior combing can reduce the waste fiber amount (formed during spinning), and those fibers can be effectively used in, e.g., rotor spinning, as then the proportion of longer fibers is higher, and besides that, there is a fewer risk to the vortex-spun yarn quality.

Vortex Spinning: Possibilities in Circular Economy

- For medium and long staple cotton spinning (unperishing recycling, which is not common yet, however), a serious alternative to rotor spinning, as yarn count doesn't affect the production speed, but for ring and rotor spinning, there are limits of it.
- As there are no rotating mechanical twist-imparting elements in the system, the machines require less maintenance related to, for example, wear and tear, comparing to most other methods.
- The process is fully automated, which also reduces cots.
- The technology's flexibility is a lot higher than of false twist spinning, at least.
- Generally stronger than rotor-spun yarns, which, along with the possibility to use recycled fibers, makes it competitive for that method in certain applications in circular economy.

Vortex Spinning: Possibilities in Circular Economy

- Fewer stages: cheaper (also because of speed) than rotor or ring methods, more energy-efficient, faster.

Vortex Spinning: Limitations in Circular Economy

- Fibers must be of high quality: uniform, clean, strong, and with minimum length of 28 mm. Shorter fibers lead to fibre waste (loss), but prior combing increases the total cost of production. Fiber loss is related to variations in yarn quality undetectable by conventional evenness testers, so, sometimes, problems are identified only by weak/defected points in the fabric. (Kiron, 2013.) That is why some sources say that cotton results in inadequate yarn quality (as natural fibers can't ideally follow the planned trajectories by air-jets), but it depends on the initial quality and prior treatments like combing.
- Some sources say that fabrics made of vortex-spun yarns can achieve the same characteristics (softness and smoothness) only using the abovementioned high-quality (relatively) fibers. It may be because of higher ring-spun yarns' hairiness.
- Weaker and stiffer, than ring-spun yarns, generally.

Vortex Spinning: Effect on Recyclability of the Material

- As relatively long fibers are used, too short fibers are removed, and vortex yarns are durable, recyclability of the yarns is quite high.
- Chemical, biochemical or thermal recyclability is not affected by the method, at least, if one-fiber feedstock is used. As the method suits well for blends, it might reduce the yarn's recyclability, and, in some cases, increase environmental impact due to, for example, if more toxic chemicals are used to separate two fibers from a mix.
- The method itself doesn't affect the recyclability.

Vortex Spinning: Utilization of the Recycled Material

- Use of recycled fibers is a challenge, as the yarn quality deteriorates (from mechanical recycling and wearing), which is the opposite of what vortex-spun yarns require. In this case, either the fibers are removed by suction, or the quality deteriorates, so it's better to provide a proper feedstock.
- Might require mixing with virgin material.
- Various materials and blends are suitable.

Vortex Spinning: References

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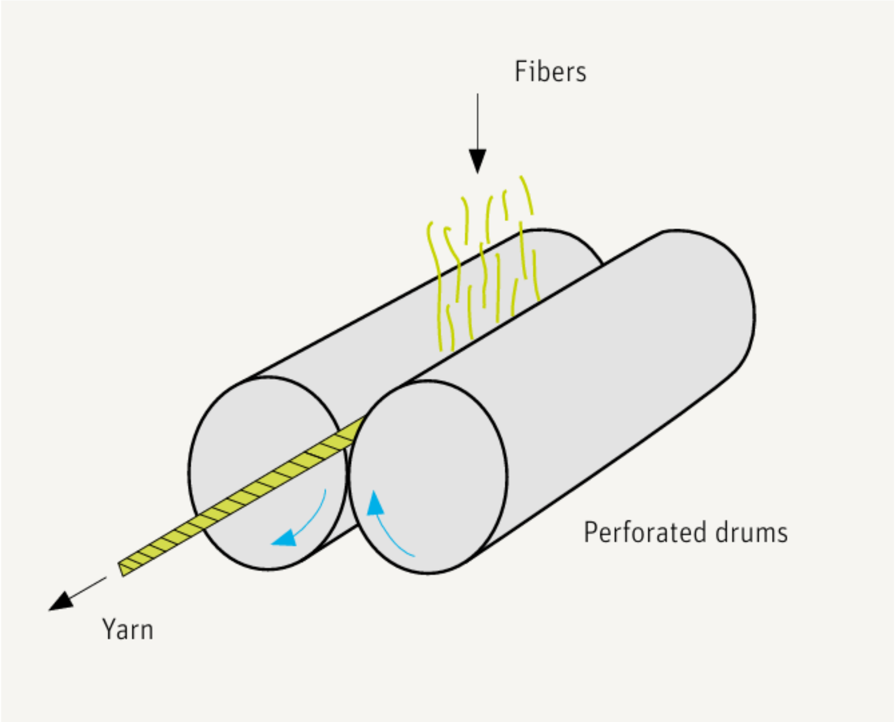
Friction Spinning: Definition

- Another method of OE spinning, in which the twist (and cohesion) is generated with the friction of 2 perforated rollers, rotating in the same direction. Multiple slivers are opened to individual fibers and carried by air into the wedge between those two rollers. Fibers are held in the system with a help of the suction through the rollers, which also removes impurities. The yarn is wound directly onto a cone.



PICTURE. Friction Spinning (Stalder, 2016).

Friction Spinning: Possibilities in Circular Economy

- High twist insertion speed (about 250 m/min for decent quality, depending on fiber type and yarn count) and cheap – cost efficient (DREF, n.d.).
- Effective for very short fibers (down to 1 mm), which can't be processed with other methods, but can use long fibers too (up to 120 mm) (DREF, n.d.).
- Soft, smooth, not very hairy, visually even and regular yarn.
- Only economical for thick yarns for industrial and technical applications, such as coarse yarns from wool and synthetic fibers, commonly used for carpets. Also, can be used in fire- and cut-resistant fabrics, geotextiles, composites, filters, etc.
- Fewer stages, e.g., no rewinding, which saves energy.
- Suitable for a wide range of fibers and blends, including recycled. Can produce hybrid yarns, for example, core-spun, to combine properties of different materials.

Friction Spinning: Possibilities in Circular Economy

- Despite general low tenacity of friction-spun yarns, DREF 2000 machine is stated by the producer (DREFCORP) to be capable of producing stronger and more uniform yarns, and DREF 3000 – even high tenacity yarns, which, however, requires longer staple length of at least 32 mm (DREF, n.d.).
  - It's important to keep in mind, however, that these statements are not supported by numbers and can be with respect to common impression of friction-spun yarns, and the DREF 3000's high tenacity yarns may be still inferior compared to ring-spun yarns.
- If the speed of feeding fibers could be somehow balanced closer to the yarn pull-off speed, the orientation of fibers in the yarn would increase, and, therefore, the overall strength. This is a problem of at least the earliest DREF systems and balancing that might have been the reason for high tenacity of yarns produced with DREF 3000 system (the latest one) (DREF, n.d.).

Friction Spinning: Limitations in Circular Economy

- The velocity of fibers hitting the rollers and open yarn end is much higher than the yarn pull-off speed, which causes the fibers to buckle and get oriented randomly. This disarray of fibers decreases the yarn's tensile strength and quality (weaker than rotor-spun yarns). Because of this, friction spinning is rarely used for spinning cotton or other yarns for apparel or interior textiles.
- Fiber length should be sufficient for appropriate quality.
- Yarn has high tendency to snarl.
- Maintaining consistent spinning process is difficult. A speed increment affects yarn's uniformity and strength.
- Despite high transmission drum-to-yarn ratio, which is an advantage because of lower rate of drums' rotation, the yarn takes up only 15-40% of that drum rotation (Stalder, 2016).

Friction Spinning: Effect on Recyclability of the Material

- Possibility to use of blends and make hybrid yarns with this system may affect further recyclability of the yarns. Also, core-spun yarns are more difficult to open.
- The method itself doesn't affect recyclability.

Friction Spinning: Utilization of the Recycled Material

- Suitable for recycled fibers, since effective for short (down to 1 mm) (DREF, n.d.). Also suitable for a wide range of fibers and certain blends, which alleviates the sorting issue and extend the opportunities of use.
- Shortened recycled fibers make the yarn quality even worse, than with ordinary fibers.

Friction Spinning: References

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Air-jet Spinning: Definition

- A wrap/cover spinning method, in which air nozzles with opposite directions, which twist fibers as a sheath (jet 1) around a core and creates a false twist, which is formed by some fibers, separately guided by the airflow (jet 2), which untwists the false twist. This method locks the fibers relatively tightly together, which results into fewer protruding fibers on the yarn surface. The sliver is priorly combed and stretched by at least 3 passages. Another method possible with this system is called "filament coating". It is twisting an outermost layer of filaments around a parallel sliver-core (80-90% of the yarn) (Räisänen et al., 2017). In this case, cotton is the most common core material, and for sheath – polyester.

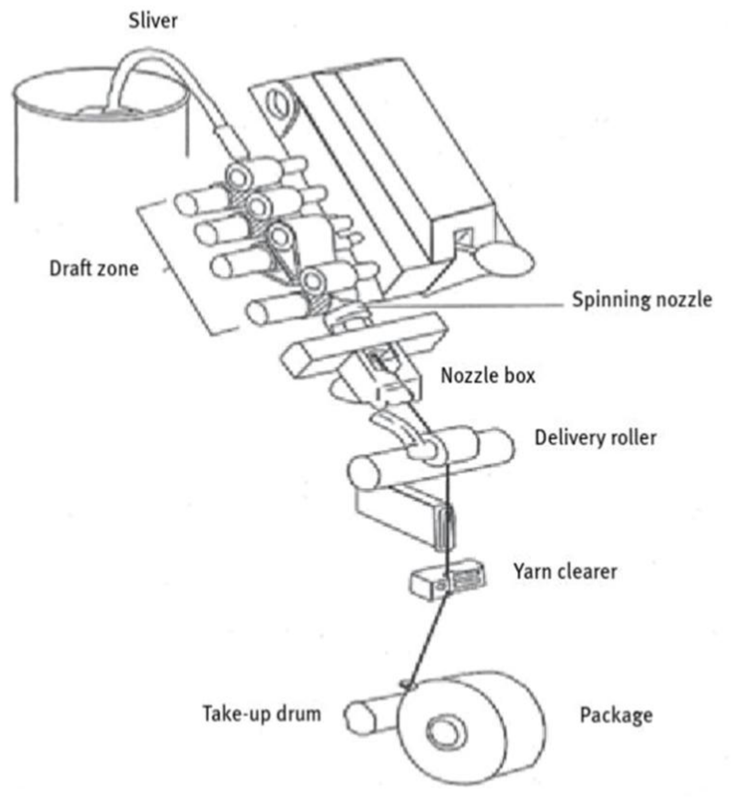
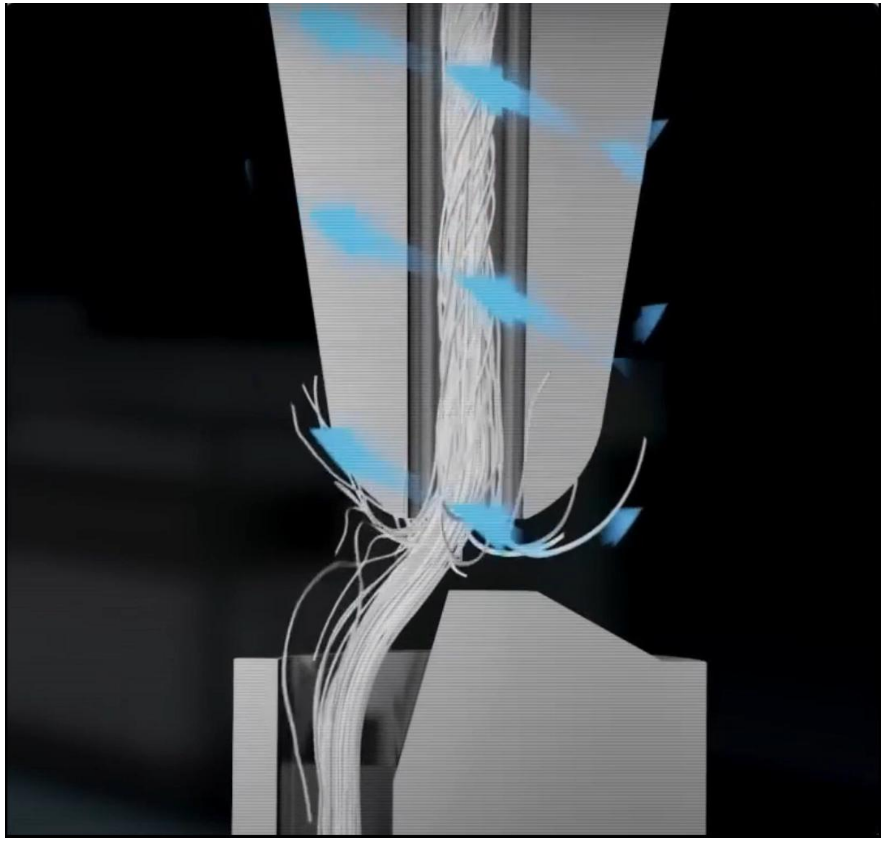


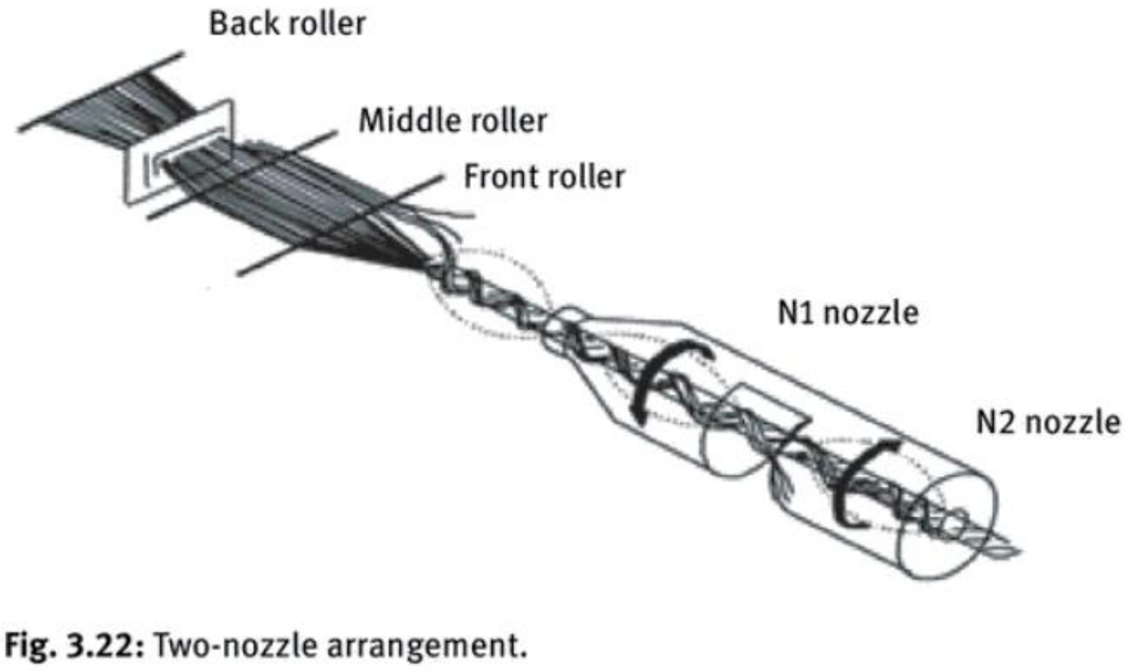
Fig. 3.21: Material flow through air jet spinning machine.

PICTURE. Air-jet Spinning (Yasir, 2016).

Air-jet Spinning: Definition



PICTURE. Air-jet Spinning Close-Up (Rieter, 2015).



PICTURE. Two-Nozzle Arrangement in Air-jet Spinning (Yasir, 2016).

Air-jet Spinning: Possibilities in Circular Economy

- Particularly suitable for short fibers, producing a fine yarn (from 59 tex down to 7,4 tex (Räisänen et al., 2017)). However, mostly medium count yarns are produced.
- Inexpensive and fast (600 m/min (Rieter, n.d.)) as no pre-processing and rewinding are required and the production is fully automated. Similar cost level as rotor spinning, and much cheaper than ring spinning.
- Suitable for viscose, Lyocell and modal microfiber. Blend yarns can be produced (e.g., CO/PET or CO/CV).
- Uniform, good abrasion resistance, low pilling and snarling tendencies. All of these facilitate the yarns' longevity.
- Filament-coated yarns are smooth, soft, more uniform, stronger and less hairy than ring-spun. They potentially extend the lifecycle of textiles they are used in.

Air-jet Spinning: Possibilities in Circular Economy

- Long and fine fibers improve almost all the properties of the yarn.
- The system can be adjusted for specific raw material: for example, the twist level can be regulated by the width of the sliver fed, the twist relationship between the first and second jets, pressure in the nozzles or switching the nozzles themselves.
- Space needed for modern air-jet machines is 25% less than for ring-spinning machines with the identical capacity, which reduces the building/rent costs, including climate control systems and energy spendings overall (Muthu, 2017).
- Among ring, rotor and air-jet spinning, the air-jet technology and yarns have the lowest level of environmental influence. Any improvement can be done with increase of spinning speed, decrease of energy consumption, use of more efficient engines and driving systems, and better engineered system components.

Air-jet Spinning: Possibilities in Circular Economy

- As there are no rotating mechanical twist-imparting elements in the system, the machines require less maintenance related to, for example, wear and tear, comparing to most other methods (same as the vortex spinning method).
- With their softness, the yarns produced from modal microfibers can be used in e.g. underwear, where high strength is not needed, but fineness is welcomed.
- Good washing resistance and comparatively less shrinkage allow for longer life cycle and nicer quality.

Air-jet Spinning: Limitations in Circular Economy

- Lower strength compared to ring-spun yarn.
- High energy consumption.
- Filament-coated yarns are expensive because of high cost of thin filaments (and the thinner, the more expensive).
- Filament-coated yarns use different fiber materials, for example, a cotton core and CV/PET/PA sheath, which might affect recyclability.
- There are restrictions for suitable materials, which imply use of only either synthetic fibers or their blends with each other or cotton. Pure cotton only can be used, if combed, and still gives only 50-70% of the ring-spun yarn strength, meanwhile synthetic fibers or their blends (at least 50% of synthetic) with cotton give about 80% or more. That is the reason for wide use of air-jets in USA, but poor in Europe and Asia, where predominantly cotton is produced. (Stalder, 2016.)

Air-jet Spinning: Limitations in Circular Economy

- Maintaining consistency in the spinning process is challenging, which affects the yarn's uniformity and strength. Has lower quality than rotor-spun yarns.
- Dirt in the fiber material disturbs the process.
- Fibers to use need to be strong, bendable, easily twistable, with small proportion of short fibers and high enough friction to each other. These factors narrow down the range of suitable fibers, including not only their nature, but also quality. High quality of fibers is required to get a yarn with descent properties. The same thing goes for ensuring proper length of fibers, despite the method's suitability for short fibers.
- Wrapping fibers are not uniformly distributed along the yarn's length, which causes differences in abrasion resistance and strength, reduces general regularity and recyclability.
- Coarse yarns cannot be produced, limiting use of shorter fibers.

Air-jet Spinning: Effect on Recyclability of the Material

- Possibility to produce filament-coated or core-spun yarns, which always use different fiber materials, and the possibility to use blends in the core or in the sheath affect further recyclability of the yarns
- Wrapping fibers (which vortex-spun yarns don't have) might cause difficulties in opening: core typically has no twist, meanwhile edge/sheath fibers have some, which improves the yarn's strength and coherence of fibers.
- The method itself doesn't affect the recyclability, except the abovementioned points.

Air-jet Spinning: Utilization of the Recycled Material

- Recycled materials can be used, as particularly suitable for short fibers.
- Previously mentioned long and fine fibers, which improve the yarn's properties, are also a limitation, because it's difficult to meet with mechanically recycled textiles. The same thing goes for general high quality of fibers required.
- Blends of known compositions can be used, which reduces sorting costs. A good advantage there is increased strength with use of synthetic fibers and their blends compared to cotton or its blends with synthetics. This allows for efficient use of recycled post-consumer textiles with high synthetic contents (especially, in the US), as does the need for long and fine fibers, possible to achieve with chemical or thermal recycling of synthetics, for example. In the contrary, in both recycling and spinning, dirt is a nuisance, and it's typical for post-consumer goods.
- As mentioned above, suitable for use of a range of synthetic fibers and viscose, Lyocell and modal microfibers, which enables efficient use of recycled materials. Generally, there's no problem with use of chemically, biochemically or thermally recycled fibers, if their strength is not affected, as it will weaken the yarn even more.

Air-jet Spinning: References

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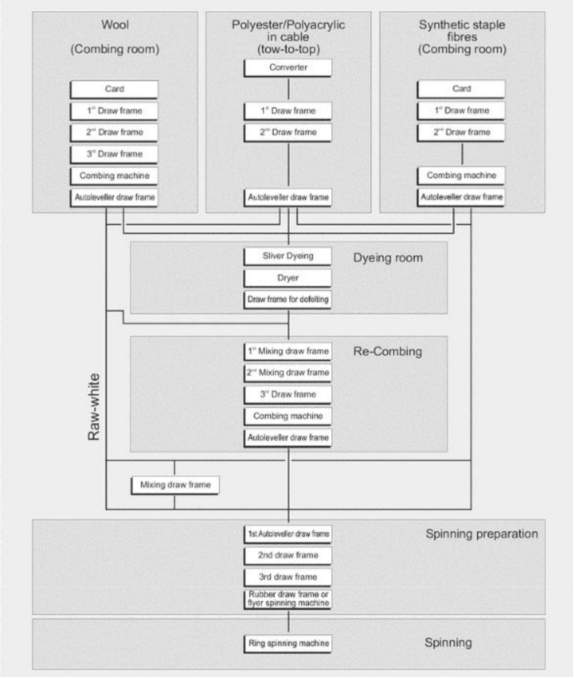
Long-staple yarn spinning

Worsted Spinning: Definition

- Virgin long-staple wool and synthetic fibers (especially, PET, PA and PAN) are processed.
- The method was originally created for wool, a long-staple fiber.
- Wool is scoured, dried in perforated tumble dryers, and opened. Then fibers are oiled to alter frictional properties and prevent electrostatic charging and put to the mixing chamber. Synthetic fibers are opened, oiled and fed to the card. Then the process is like in the picture. Then a roving is made and ring-spun (most commonly).

PICTURE. Worsted yarns (Aliexpress, n.d.).



PICTURE. Flow Chart for Worsted Spinning (Wulfhorst et al., 2006).

Worsted Spinning: Possibilities in Circular Economy

- Provides uniform yarns with high tenacity and elongation, low hairiness, low pilling during wear.
- High-quality yarns and woven fabrics can be produced.
- Most of the waste (from carding, gilling&combing and spinning) generated during production of worsted yarns is utilized by the supporting woollen system, with which the worsted method forms a synergy. This not only saves money for worsted producers and resources but enables circular economy at this stage.
- Wool is a durable and highly spinnable fiber because of its surface structure. Wool can have active first life of 20-30 years (Woolmark Learning Centre, n.d.c). Thus, this material, precious to consumers, is also more likely shared to others by people than thrown away. Worsted spinning is even more durable than woollen. Washing is needed less frequently, reducing water and chemical use.
- Pure wool garment is 100% biodegradable, enabling circular economy, returning important nutrients back to the soil, thus supporting other living systems.
- Ring spinning is more efficient than for woollen spinning, and it is more efficient itself than mule spinning because of its continuousness.

Worsted Spinning: Limitations in Circular Economy

- Raw wool scouring systems are very expensive and under strict environmental protection laws. Sustainable processing of raw wool requires eco-friendly use of chemicals by their nature of the methods utilized. This requires high investments. More applicable for woollen spinning.
- Requires longer fibers longer than 60 mm (Woolmark Learning Centre, n.d.a).
- Preparation for worsted spinning takes up to 18 operations, compared to woollen spinning's 3 (Woolmark Learning Centre, n.d.b). This increases the cost of the yarn production, although, for synthetic materials, the number is lower.
- Dyed wool fibers always have lower tensile properties, making the spinning process less efficient.
- Commonly, wool is blended with SE, WM, WS, PET, PA, PAN, EA or CV or their 3-fibre blends. This not only decreases quality but also compromises recycling.
- Many spindles are required for a reasonable productivity due to low productivity of a single spindle.

Worsted Spinning: Effect on Recyclability of the Material

- The wool fleece used for worsted yarns is long enough to be suitable for woollen spinning even after being mechanically opened. Although this is a bit of downcycling process, it is a very good solution, conventionally used.
- As mentioned before, it is common to blend wool with other materials. Compared to woollen yarns, it is more complicted and hard to work with. Some blends may be unsuitable for woollen yarns or would require adding some other fibers. Pure woolen garments are recyclable, depending though on their condition.
- End-uses of recycled material obtained from worsted yarns are limited because of their compactness and lack of softness, less air entrapped, and less bulk.

Worsted Spinning: Utilization of the Recycled Material

- Mechanically recycled material is typically not suitable, unless the case is about filaments (such as elastane) to add to the wool used. Since the top-making processes are still included in the preparation, long fibers still can be obtained by mechanical recycling of clothes, but it is a minute fraction and most of the recycled mass would be discarded and directed to woollen spinning.

Worsted Spinning: References

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Woollen Spinning: Definition

- Ring-spinning of short wool fibers, which are not as well aligned with the yarn axis as long wool fibers in worsted yarns.
- Woollen spinning allows for processing of other fibers of similar length. In the process, carded sliver is fed into a fine spinning machine, such as mentioned above ring-spinning machine or a mule spinning machine (drafting, twisting and winding are done discontinuously).

PICTURE. Woollen yarn (Temu, n.d.).

Woollen Spinning: Possibilities in Circular Economy

- Flexible and versatile, allowing processing of a wide range of fibers: wool, animal hair, synthetic fibers, fiber blends etc.
- Fiber length is not as significant, maximizing fiber use. Fibers shorter than 50 mm and of varying lengths are utilized. Wool from other parts of the sheep than fleece is utilized, which is although traditional, significantly contributes to circular economy resource-wise. (Woolmark Learning Centre, n.d.a.) By-products of worsted spinning, as well as card waste and noil, can be utilized too, which makes it a very important complementary system for the worsted system.
- Preparation for woollen spinning takes three operations, compared to worsted spinning's up to 18 (Woolmark Learning Centre, n.d.b). This advantage is not as vivid with synthetic materials, but the cost of this spinning is anyways always lower.
- There is a possibility of drafting against twist on woollen spinning, which provides better control of the drafted fibers, offering a higher yarn uniformity and strength.
- Pure wool garment is 100% biodegradable, enabling circular economy, returning important nutrients back to the soil, thus supporting other living systems.
- Wool is a durable and highly spinnable fiber. Wool can have active first life of 20-30 years (Woolmark Learning Centre, n.d.c).Thus, this material, precious to consumers, is also more likely shared to others by people than thrown away. Washing is needed less frequently, reducing water and chemical use.

Woollen Spinning: Limitations in Circular Economy

- Adding virgin wool fibers is often required
- Normally, only blends of wool with PA or PAN (less commonly, CV in 3-fibre blends) are used. As well as in worsted yarns, quality and recyclability of woollen yarns are compromised.
- Dyed wool fibers always have lower tensile properties, making the spinning process less efficient. More common for woollen as it is more subject to yellowing.
- Raw wool scouring systems are very expensive and under strict environmental protection laws. Sustainable processing of raw wool requires eco-friendly use of chemicals by their nature of the methods utilized. This requires high investments. More applicable for woollen spinning because of its higher contamination levels.
- Use of ring-spinning is limited because of high short fibers content. Besides, mule spinning is less efficient because of its discontinuity.
- Not as durable as worsted yarns, even though more durable than e.g. cotton.

Woollen Spinning: Effect on Recyclability of the Material

- The method itself doesn't affect recyclability.
- Commonly used fiber blends compromise recycling, but this is case-specific and still not as complicated to work with, compared to worsted yarns. Pure woolen garments are recyclable, depending though on their condition.
- Since the fibers entering the system are already short, their recyclability is not as high as that of worsted yarns.
- High hairiness and fiber entanglements make the yarn disassembly challenging.

Woollen Spinning: Utilization of the Recycled Material

- Use of recycled fibers is possible. Recovered from woolen garments by mechanical 50% blending. This allows for processing recycled fibers from worsted yarns, which even if mechanically open, can be efficiently utilized in woollen system. Despite this, especially speaking of woollen recycled yarns, mechanically recycled fibers lead to generation of more waste, thus requiring adding more virgin fibers. Even though shorter fibers can be processed, not all the additional materials would be desirable, so, even when using worsted recycled fibers, this should be considered, as the quality and properties are typically affected with a higher fibre material variety.
- Fibers used for woollen spinning are usually with highly contaminated with, e.g., vegetable matter and unscourable stains, the first of which (since possible) facilitates use of previously landfilled clothes with potential contamination (also from the ocean), and the last also supports use of used contaminated clothes. Although it is a common fact about wool fibers, this can also apply to other materials.

Woollen Spinning: References

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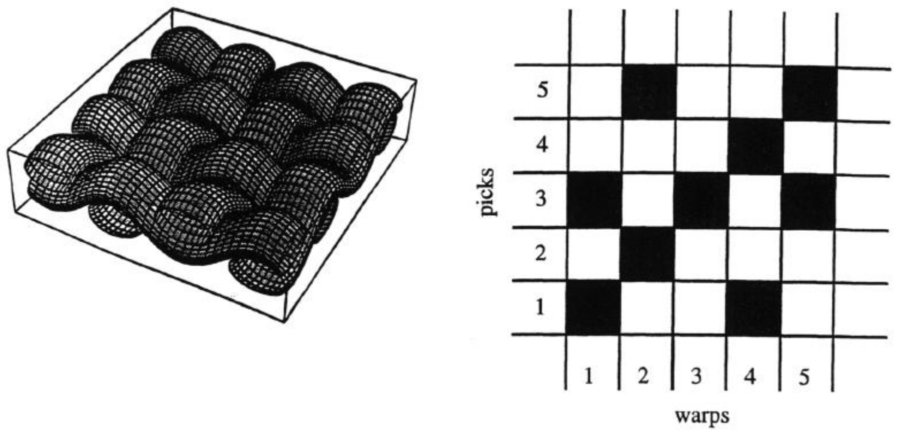
Weaving

Possibilities and limitations in the circular economy

Weaving: Definition

- Weaving is the method of interlacing the warp and filling yarns to form a fabric.
- Woven fabrics are made of two sets of yarns: warp and filling. These yarns are interlaced at 90° to each other.
- The warp yarns (ends) are parallel to each other and run lengthwise through the fabric or along the weaving machine direction.
- Filling yarns (picks) run perpendicular to the warp yarns.
- Order of interlacing of a fabric is called the weave.

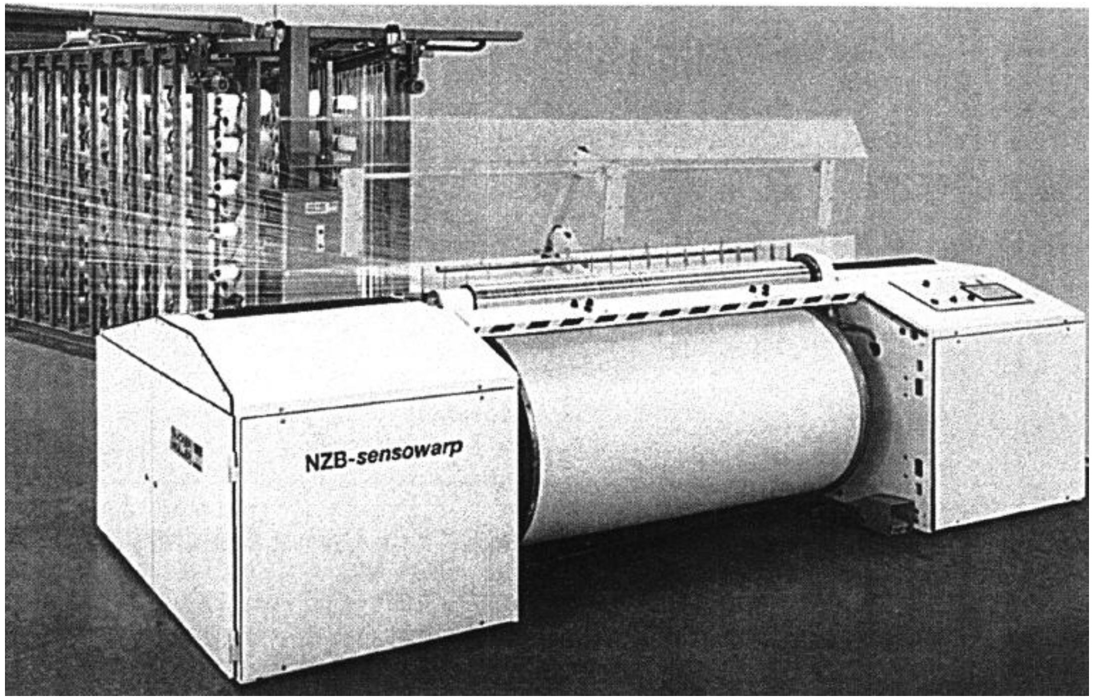


PICTURE. Interlacing of warp and filling yarns in plain weave.

[Weaving Process]

Warping: Definition

Warping involves transferring multiple yarns from a creel to form a parallel sheet wound onto a beam. Modern machines handle various yarn types, often with static eliminators. The weaving machine's beam, called a weaver's beam, contains thousands of ends, with different processes and regional terminology variations.



PICTURE. Warping process.
Warping process

Warping: Possibilities in Circular Economy

- Warping machines can be calibrated to minimize waste by precisely measuring yarn usage, ensuring only the necessary amount is processed, which reduces material waste.
- Modern warping machines are often energy efficient and can process multiple materials simultaneously, reducing energy and resource consumption.
- A well made warp beam is the basis of the fabric and enables its durability and better recycling time.
- The warping process helps organize the yarns in order, preventing knotting and thread damage.

Warping: Limitations in Circular Economy

- Natural fibers like cotton and wool can be prone to breaking and stretching under tension, which can disrupt the warping process and result in material waste.
- Warping machines are built for large scale production, making them inefficient for processing smaller or customized batches.
- Warping often involves combining different types of yarns, making it hard to separate materials later.
- The application of sizing agents during warping can introduce non biodegradable chemicals, hindering the recyclability of materials.

Warping: Effect on Recyclability of Material

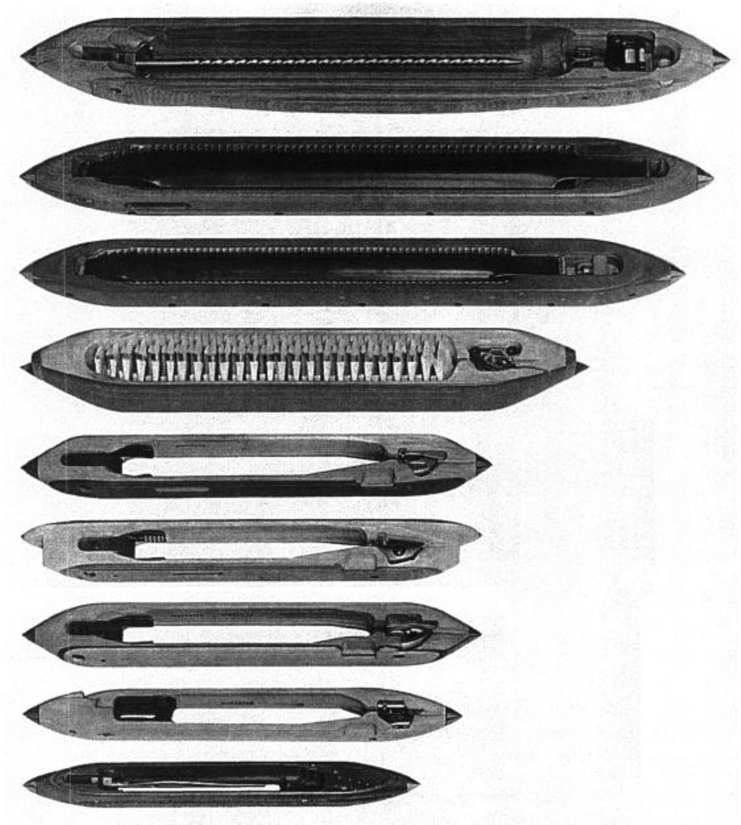
- Warping often involves combining different yarn types on a single beam, making it challenging to separate these materials later for recycling. This blending can hinder the ability to reclaim individual fibers.
- The warping process tightly aligns and binds yarns in parallel, creating a durable structure. This can limit recyclability because the tightly wound yarns are difficult to disassemble, requiring additional processing to break down the material.
- During the warping process tension controlled by tension devices, it will maintain the yarn tension and sustain the fiber properties.
- Fiber properties may be altered or damaged due to the sizing process during warping.

Warping: Utilization of Recycled Materials

- Theoretically in weaving, the warp and weft can both be made using recycled yarn, but quality reduces so much it will not make a product that lasts. The warp endures a lot of tension in production, so it is difficult to have a high percentage of recycled cotton in the warp. (Kate 2019).
- Recycled yarns often have shorter fiber lengths or variable quality, which can lead to breakages during warping. This results in material waste and may discourage the use of recycled content in warping processes.

Shuttle Weaving: Definition

Shuttle weaving is the traditional method of inserting the filling (weft) yarn across the warp threads using a shuttle. This system, used for centuries, originated with manual looms where the warp was tensioned with individual weights, and the filling was initially inserted with a stick.



PICTURE. Various Shuttles.
Shuttle weaving process

Shuttle Weaving: Possibilities in Circular Economy

- Shuttle looms are durable machines capable of withstanding heavy use, producing consistent, high-quality fabrics. Their sturdiness allows them to last for decades, making them a valuable long-term investment for textile production companies.
- A key advantage of shuttle looms is their low production cost. Their simple design makes them easy to operate and maintain, with fewer parts to replace and minimal upkeep required. This simplicity leads to lower operating costs compared to modern weaving machines.
- Shuttle looms have a lower environmental impact, as they typically produce less waste compared to modern weaving machines. This makes them a favorable option for companies aiming to reduce their carbon footprint.

Shuttle Weaving: Limitations in Circular Economy

- Shuttle weaving uses a heavy shuttle (approximately 450g) to carry a small amount of weft, which leads to significant energy waste during each pass.
- The shuttle's free flight can cause it to strike parts of the loom, leading to damage on the reed, shuttle, and pirn, and often resulting in inconsistent weft tension.
- Conventional shuttle looms can be very noisy, reaching up to 110 dB during operation, which is problematic for worker health and comfort.
- The limited space within the shuttle restricts pirn size, leading to frequent stops for thread changes, increased maintenance needs, and additional labor for monitoring and restarting the loom.

Shuttle Weaving: Effect on Recyclability of Material

- The high tension applied during shuttle weaving can indeed affect the recyclability of the material. This aspect introduces additional challenges, particularly with mechanical recycling processes.
- The use of shuttles introduces more knots and overlaps in the fabric, complicating the recycling process and requiring additional steps to break down the material.
- The selvedge waste is unavoidable waste in weaving machine. The fibers are separated by the garnetter who uses them for stuffing of pillows and quilts. Also, this waste can be used for making fancy composites for floor covering. (Goyal 2021, 78).

Shuttle Weaving: Utilization of Recycled Materials

- Theoretically in weaving, the warp (fibres going lengthwise on the grain) and weft (fibres going across) can both be made using recycled yarn, but quality reduces so much it will not make a product that lasts. The warp endures a lot of tension in production, so it is difficult to have a high percentage of recycled cotton in the warp. On a large scale, many companies operates for recycled polyester or virgin cotton in the warp.
- For sustainability practices weaving industry started incorporate recycled materials with their products blending with lyocell, recycled polyester.

Shuttleless Weaving: Definition

Shuttleless weaving is a textile production method where the weft yarn is inserted without a traditional shuttle. Instead, methods like air-jets, water-jets, rapiers, or projectiles carry the yarn across the loom. This process increases weaving speed, reduces noise, and enhances fabric quality by minimizing yarn tension, making it ideal for high speed, efficient textile manufacturing.

- Air-jet - weaving is a type of weaving in which the filling yarn is inserted into the warp shed with compressed air.
- Water-jet - weaving is a type of weaving in which the filling yam is inserted into the warp shed with compressed water.
- Rapiers - in this type of weaving, a flexible or rigid solid element, called rapier, is used to insert the filling yam across the shed.
- Projectiles - projectile weaving machines use a projectile equipped with a gripper to insert the filling yam across the machine.

Shuttleless Weaving: Possibilities in Circular Economy

- Shuttleless looms, using rapiers or air-jet insertion, reduce yarn waste and energy consumption by optimizing the weaving process and limiting material loss.
- The rapier loom has the feature of easy color change, suitable for multi-color weft fabrics, and is ideal for producing yarn-dyed fabrics, double-layer velvet, terry fabrics, and decorative fabrics.
- The water jet loom has high speed and high output and is mainly suitable for hydrophobic synthetic fiber filament fabrics.
- Projectile weaving is suitable for weaving multi-color weft fabrics, fine and thick fabrics, wide fabrics, and fabrics woven by special yarns.

Shuttleless Weaving: Limitations in Circular Economy

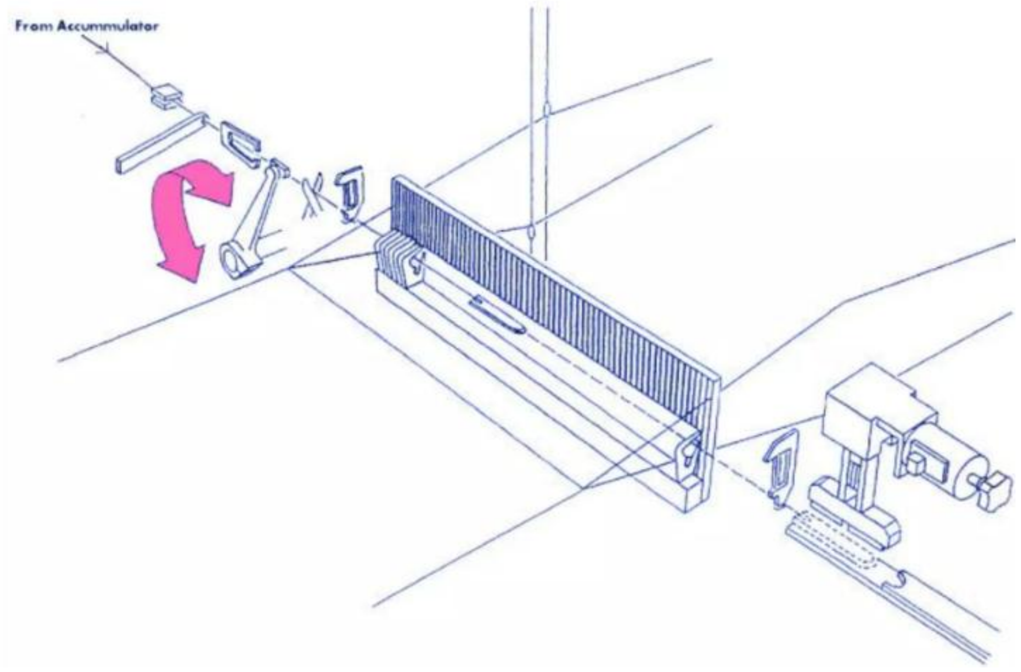
- A limitation of shuttleless looms is their high consumption of energy and, in some cases, water, which can elevate operational costs and impact environmental sustainability despite their efficiency in other areas.
- In shuttleless looms, the high speed of weft insertion can sometimes cause damage to warp threads, potentially lowering fabric quality and reducing overall efficiency.
- Shuttleless looms come with a high initial cost, which can be a barrier for smaller manufacturers despite their long term operational advantages and efficiency.

Shuttleless Weaving: Effect on Recyclability of Material

- Since the high speed and tension of shuttless weaving process materials can be damged the weaving process.
- Fabrics produced via shuttleless weaving tend to have consistent quality and composition, which are ideal for mechanical or chemical recycling methods.
- The properties of fibers can be altered when using a water jet machine.
- Shuttleless weaving produces less waste during production, contributing to more efficient recycling processes and less material loss.
- The precise interlacing in shuttleless weaving maintains better fiber alignment, making it harder to recycle mechanically and reuse fibers in the material.

Shuttleless Weaving: Utilization of Recycled Materials

Studies have observed that shuttleless weaving can effectively incorporate recycled materials, and shuttleless weaving, as a modern weaving method, is well suited for these materials. Some industrial machine manufacturers have integrated support for recycled materials in their advanced shuttleless weaving machines.



PICTURE. Projectile weaving.

Jacquard Weaving: Definition

The jacquard machines offer the highest level of warp yarn control. This versatility is due to the separate control of each warp end or groups of similarly interlacing warp ends within the pattern repeat across the fabric width. They enable the most sophisticated patterns, such as pictures, to be produced in the woven fabric.

PICTURE. Jacquard woven fabric.

Jacquard Weaving: Possibilities in Circular Economy

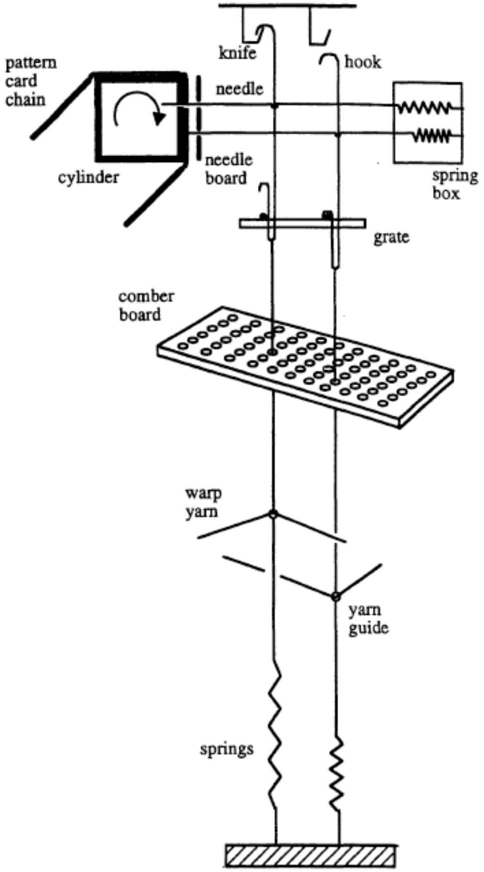
- The jacquard textile machine can automate the process of creating complex patterns, reducing the time and labour required compared to manual methods.
- The jacquard loom machine allows for high precision and accuracy in producing jacquard fabrics, resulting in improved quality and consistency.
- The jacquard power loom can increase productivity and reduce the need for manual labour, leading to cost savings in producing a jacquard weave.
- The jacquard loom enables the creation of intricate and unique designs, differentiating the finished fabric and adding value.

Jacquard Weaving: Limitations in Circular Economy

- Jacquard mechanisms are more liable than dobby or cam shedding to produce faults in the fabric (Adanur 2021, 152).
- Large scale moving parts makes the machine and its harness relatively costly to install and maintain (Kiron 2012).
- Pattern change is a time consuming process (Kiron 2012).
- Until recently, the jacquard machine had tended to impose limitations 300 picks/min (Kiron 2012).
- Jacquard fabrics are much more costly to produce (Kiron 2012).

Jacquard Weaving: Effect on Recyclability of Material

- Jacquard fabrics can be recycled using chemical techniques, which break down fibers for high-quality reuse, or mechanical methods, which shred and respin fibers for a lower cost, sustainable alternative.
- Due to the intricate pattern designs in Jacquard fabric, separating the fibers can be challenging.
- As well as this, if there are many colors, it is difficult to segregate them.



PICTURE. Schematic principle of single lift, single cylinder jacquard machine.

Jacquard Weaving: Utilization of Recycled Materials

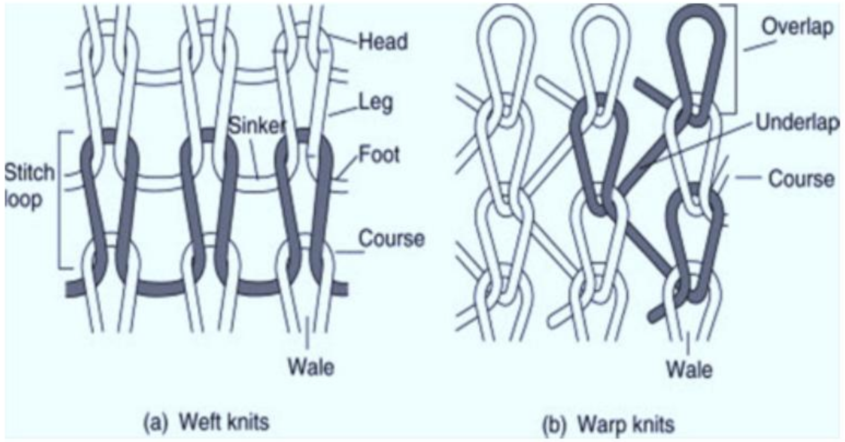
- By using recycled materials and reducing waste in the production process, manufacturers can create high-quality fabrics with a lower environmental impact. This aligns with the growing consumer demand for sustainable fashion and responsible manufacturing practices.
- Modern Jacquard machine manufacturers have advanced their technology to incorporate recycled textile materials, promoting sustainability in fabric production.

Knitting

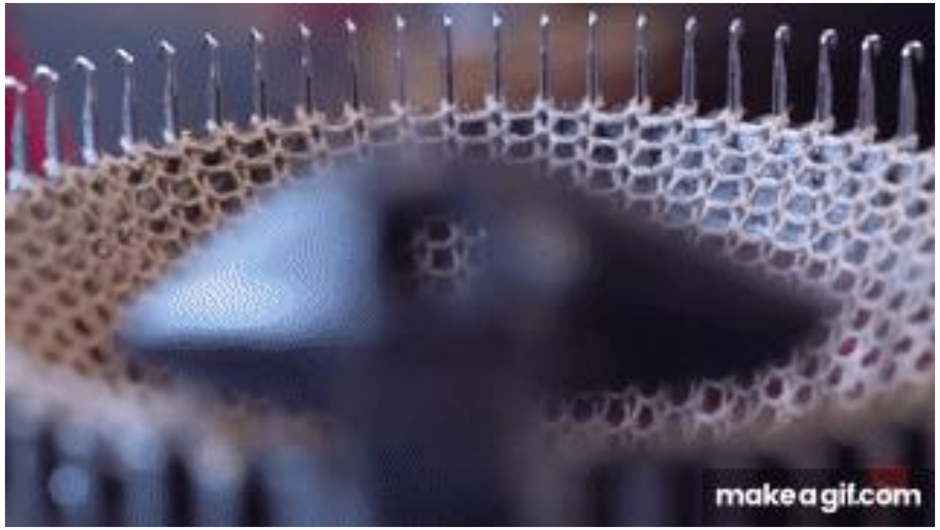
Possibilities and limitations in the circular economy

Knitting: Definition

- Knitting is a textile technique that creates fabric by looping a continuous yarn into interconnected vertical columns.
- In knitting, loops are organized in rows, similar to the weft and warp in woven fabrics. These rows are called "courses," while the vertical columns are known as "wales".
- According to the looping direction knitting can be devided Warp and Weft knitting.
- Knitted fabrics are more stretchable than woven fabrics.



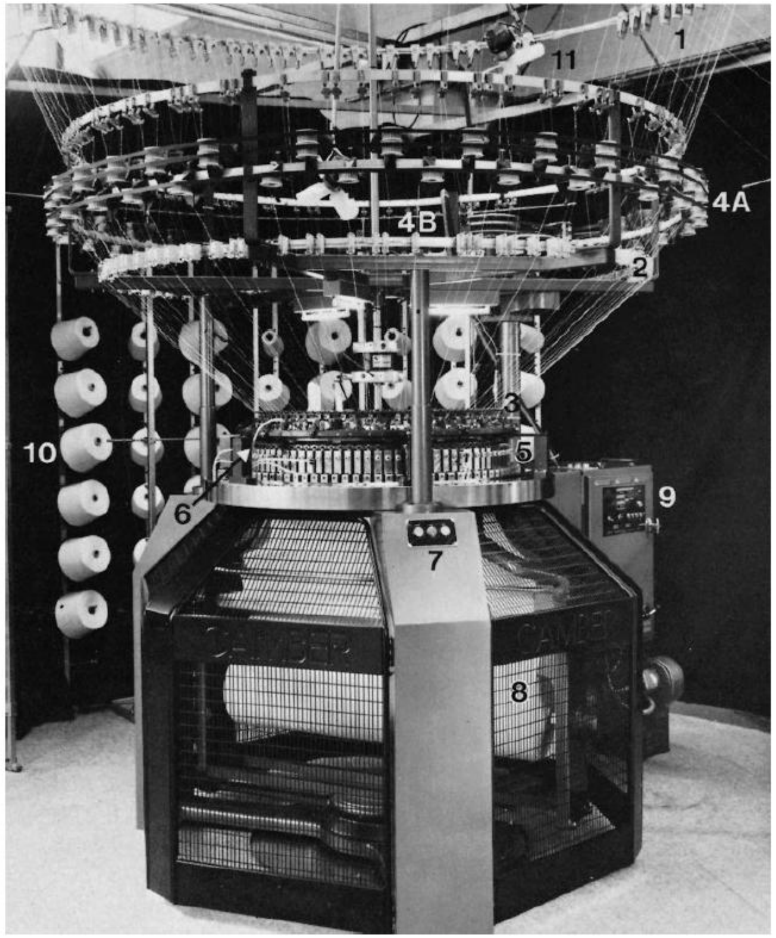
PICTURE. Knitting Fabric structure.



PICTURE. Circular Knitting process (Make a GIF).

Circular Knitting: Definition

Circular knitting creates a continuous tube of weft-knit fabric, often cut open to produce flat fabric for garment patterns, similar to woven production. This method is commonly used for single-jersey fabric, popular for T-shirts and underwear, and can be made from various fibers, from microfibers for activewear to organic cotton for fashion. By adjusting knitting cams and needle arrangements, circular knitting machines can also produce diverse structures and stitches like rib, double jersey, purl, tuck, and miss stitches that add both aesthetic and functional qualities to the fabric.



PICTURE. Modern Circular Knitting Machine.

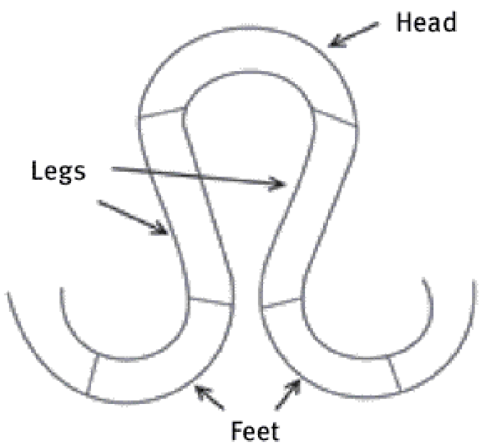
[Circular Knitting Process]

Circular Knitting: Possibilities in Circular Economy

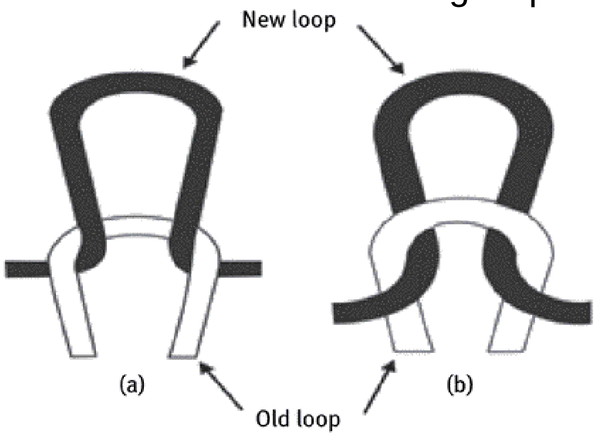
- Circular knitting is an efficient fabric manufacturing method, and further into apparel or other products
- The development of large-scale circular knitting machines with extended production runs improves efficiency
- Circular knitting machines can create a wide range of fabric types and patterns, including single jersey, rib, and double jersey, allowing for diverse applications and aesthetic possibilities.
- Since circular knitting produces fabric in a continuous tube, it minimizes fabric waste, especially for tubular garments, compared to flat knitting.
- Circular knitting produces a tubular structure without seams, which is beneficial for comfort in garments like T-shirts, socks, and underwear.

Circular Knitting: Limitations in Circular Economy

- The most important limitation of seamless knitting machines in circular form is the poor flexibility of these types of machine for producing fabrics in different diameters.
- High-speed knitting machines are classified as the limitation of friction occurrence in knitting elements and tension control in the yarn feeding system.
- Circular needles come in fixed lengths, complicity to produce small diameter fabrics.



PICTURE. Parts of a knitting loop.



PICTURE. Fabric sides: (a) Technical face, (b) Technical back.

Circular Knitting: Effect on Recyclability of Material

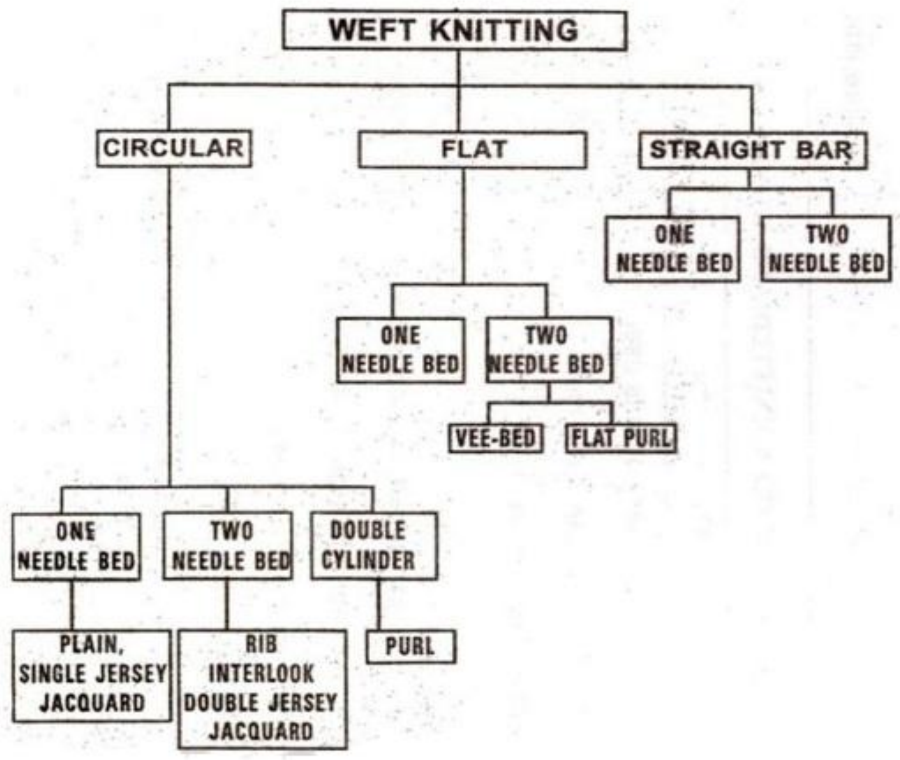
- Circular knitting fabrics can be recycled through deconstruction, either mechanically or chemically. When compare to weaving circular knitting fabrics are easier to deconstruction.
- Knitted fabric recyclability challenge lies in the development of efficient and cost effective recycling technologies. The process of deconstructing fabric and spinning recycled fibers can be complex and expensive.
- Fabrics with complex structures, multiple colors, and intricate loop patterns are more challenging to recycle due to the difficulty in separating and processing the various yarns and materials.

Circular Knitting: Utilization of Recycled Materials

- Knitted fabric recycling technologies open up new possibilities for sustainable fashion. By incorporating recycled yarns into their designs, brands can reduce their environmental impact and meet the growing demand for eco-friendly products. (XINJINGLONG 2024).
- Circular knitting machines are well-suited to support sustainable production technology due to their high level of automation and precise production processes. The use of sustainable materials, such as recycled yarns or organic fibers, can be integrated into the production process with minimal waste. (Chinahanma 2023).
- Modern circular knitting machine manufacturers incorporate technology to utilize recycled materials.

Weft Knitting: Definition

A weft knitted fabric contains horizontal / parallel row of courses of yarn are knitted. It requires just a single yarn to form a fabric, but a greater number of yarns is fed with respect to machine capacity. Weft knitted fabrics is used widely in the clothing industry for example hosiery, sweaters, foundation garments and active wear. The most important benefit of weft knitted fabric is its construction techniques.



PICTURE. Weft knitting classification.

Weft Knitting: Possibilities in Circular Economy

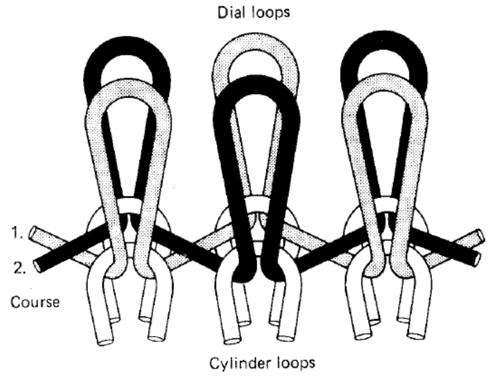
- Weft knitting machines are popular among small manufacturers for their versatility, affordability, compact design, rapid adaptability to pattern and machine changes, and efficiency in short production runs with minimal yarn and fabric storage needs.
- Weft knitted loops can easily distort under tension, allowing yarn to flow freely between loops with varying tension. This characteristic enhances form-fitting and elastic recovery, contributing to improved durability.
- Weft knitting machines, through selective needle operation and loop transfer, enable the creation of shaped garment parts directly on the machine, promoting sustainability by reducing fabric waste and minimizing material and energy use.

Weft Knitting: Limitations in Circular Economy

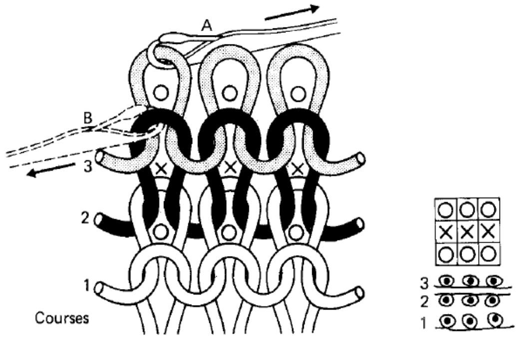
- Weft knitted structures can generally be unroved, a course at a time, from the end of the fabric knitted last and this, together with a tendency for loop breakdown to cause laddering, can create problems.
- Weft knitting machines have restricted number of yarn feed positions and the need for varying yarn feed rates, which can limit design complexity and production efficiency, though the adaptability of circular or straight needle beds helps meet specific application needs.
- Fixing problems due to machine function can take lots of time and become a great aggravation.

Weft Knitting: Effect on Recyclability of Material

- These fabrics are made with a single yarn looped in a horizontal direction. They have a simpler, less tightly bound structure, making them easier to unravel and break down into individual fibers during mechanical recycling.
- Fabrics with complex structures, multiple colors, and intricate loop patterns are more challenging to recycle due to the difficulty in separating and processing the various yarns and materials.



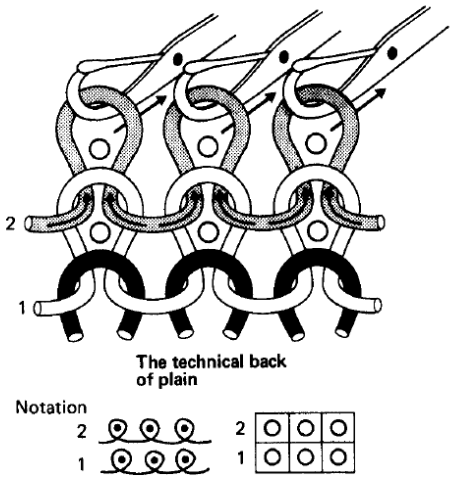
PICTURE. Interlock knitting structure.



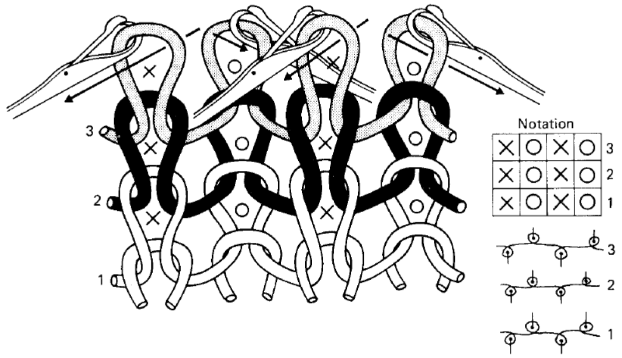
PICTURE. Purt knitting structure.

Weft Knitting: Utilization of Recycled Materials

- Recycling yarn from knitted garments is a great way to repurpose materials for new projects. Natural fibers like wool are easier to unravel and reuse, while synthetic fibers may stretch or degrade, making them harder to recycle.
- The slightly more textured feel of recycled yarn provides a higher grip on needles and hooks.



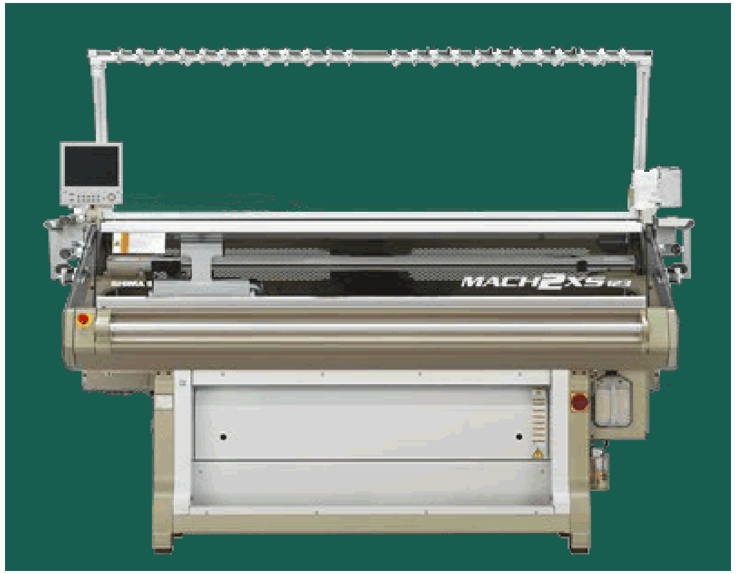
PICTURE. Plain view knitting structure.



PICTURE. 1x1 Rib knitting structure.

3D Knitting: Definition

3D knitting, or whole garment knitting, is a technology that uses computer-programmed knitting machines to produce seamless, three-dimensional garments directly from yarn. This method eliminates traditional cutting and sewing steps, creating a finished garment in one process. It also allows for the incorporation of intricate knit designs and has become more accessible with advancements in machinery and programming.



PICTURE. 3D knitting.

3D Knitting: Possibilities in Circular Economy

- 3D knitting helps brands reduce overstock and save costs by tailoring production to customer needs.
- 3D knitting uses precise coding to create on demand garments, reducing fabric waste by 30% and minimizing landfill contributions.
- 3D knitting automates garment production, reducing time, labor, and inventory risks while enabling rapid response to fashion trends.
- 3D knitting consolidates garment production into a single machine, reducing energy use by 43% compared to traditional methods.
- 3D knitting produces seamless garments, enhancing quality, durability, and consistency while reducing defects from human error.

3D Knitting: Limitations in Circular Economy

- The 3D wholegarment knitting machine is expensive to adopt due to its high initial investment and advanced software costs, making it accessible primarily to larger companies.
- The rapid advancements in 3D knitting technology require designers to continually update their knowledge of fibres, textiles, and programming methods, posing a challenge to widespread adoption due to the ongoing need for training and retraining.
- Difficulty of recycling 3D-knitted garments, as their complex fiber blends and seamless constructions can complicate material separation and reuse.

3D Knitting: Effect on Recyclability of Material

- The structure of knitted products makes it possible and facilitates the recycling of yarns: using this technology yarns are not damaged, therefore it is possible to unravel the fabric to recover them easily and use them for creating a new product (Cerulo et al., 2022).
- However, complex fiber blends and seamless constructions may complicate material separation and reuse.
- During the finishing process, there is a risk of raw material damage in 3D knitting due to its differences from conventional sewing. Special finishing techniques are required, and these can sometimes lead to material damage.

3D Knitting: Utilization of Recycled Materials

- With the use of computerized machinery for 3D knitting, recycled yarns can be effectively utilized. These machines allow for controlled tension and friction, reducing yarn breakages and enhancing the overall efficiency of the process.
- Modern 3D knitting machine manufacturers, such as Shima Seiki, have integrated features to support the use of recycled materials, promoting sustainability in 3D knitting.
- Blending recycled materials with virgin materials is recommended to achieve fabrics with improved physical properties and better overall quality.

Jacquard Knitting: Definition

Jacquard knitting is highly valued in the textile industry for its ability to produce intricate and detailed patterns on knitted fabrics. By leveraging the Jacquard mechanism, it provides precise control over individual needles, enabling the creation of complex designs, multicolored motifs, and diverse textures. This innovation enhances creativity and customization, allowing designers and manufacturers to craft unique and visually striking textiles. The importance of Jacquard knitting lies in its potential to revolutionize textile design, enhancing both the aesthetic appeal and functional versatility of knitted fabrics.

PICTURE. Jacquard knitted fabric figured by Hashan Disanayakage using AI.

Jacquard Knitting: Possibilities in Circular Economy

- Jacquard knitting excels in integrating multiple colors into fabric, enabling the creation of intricate patterns, gradients, and color blocks for visually stunning textiles.
- Jacquard Circular Knitting Machines provide unparalleled design flexibility, enabling precise control over stitch structure, density, and yarn placement to create customized fabrics with textures, patterns, and motifs tailored to specific design needs and customer preferences.
- Jacquard knitting machines produce high-quality fabrics with intricate patterns, precise stitch control, and smooth color transitions, enhancing aesthetics, durability, and overall fabric integrity.
- Jacquard Circular Knitting Machines combine complex pattern capabilities with efficient production, using advanced technology and automation to increase speed and output, making them ideal for large scale manufacturing.

Jacquard Knitting: Limitations in Circular Economy

- The creation of patterns in jacquard machines is limited to a number of knit elements: the yarn feeder system, the needle selection system and the dial needle bar gauge.
- Machines with smaller diameters, such as the 4-inch diameter machine, are better for creating prototypes but are not suitable for large-scale production. This restricts their utility in mass production.
- Different jacquard patterns or fabric types (e.g., striped jerseys) require specialized machines, making it necessary to have multiple models for diverse needs.
- The needle-by-needle selection system, while allowing high flexibility in jacquard pattern application, must be compatible with high-speed machines, posing a potential limitation for performance optimization.

Jacquard Knitting: Effect on Recyclability of Material

- Like other knitted fabric structures, Jacquard knitting can also be recycled through mechanical and chemical processes. However, compared to simpler structures, the recyclability of Jacquard fabrics is more complex due to their intricate patterns.
- If there are many colors in Jacquard knitting, it will be difficult to recycle the material, as separating and processing the different yarns and dyes can be complex.
- The combination of different fibers, especially synthetic and natural blends, can complicate recycling processes, as separating these materials is challenging.

Jacquard Knitting: Utilization of Recycled Materials

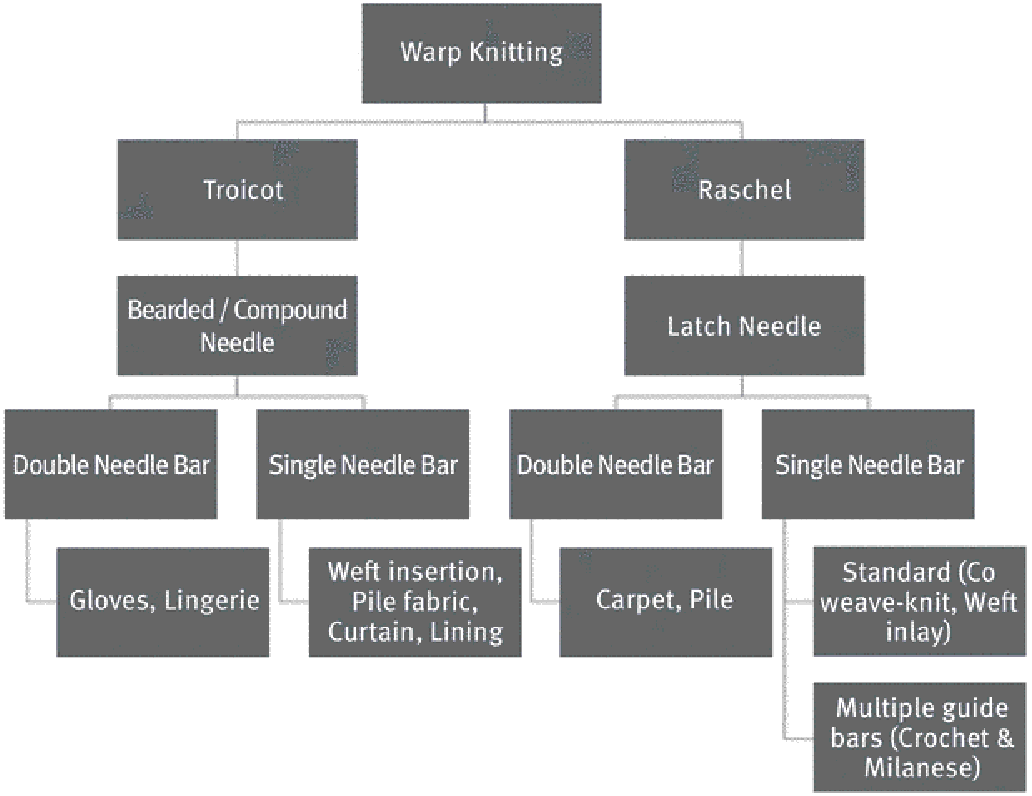
Jacquard knit fabric manufacturers utilize recycled fibers in their products, often blending them with virgin materials. Modern Jacquard machines are specifically designed to accommodate recycled materials, resulting in a wide variety of recycled Jacquard fabrics now available in the market.

PICTURE. Jacquard knitting machine.

Jacquard knitting process

Warp Knitting: Definition

Warp knitting is a fabric loop formation process where loops are created along the warp (lengthwise) direction. In this method, a sheet of yarn, supplied from a warp beam (similar to weaving), feeds individual needles. Each needle forms new loops by drawing yarn through existing loops created during the previous cycle. The yarn also passes through guides on a guide bar, enabling lateral movement between needles. Warp knitting machines are flat and employ a more complex technique than weft knitting.



PICTURE. Classification of warp knitting machines and their structures.

Warp Knitting: Possibilities in Circular Economy

- The warp-knitted fabric is dimensionally very stable due to overlapping and underlapping of yarns (Nawab 2016).
- The application area of warp-knitted fabric is not only apparel but also have huge demand for domestic, industrial and technical applications (Nawab 2016).
- Warp knitting is a highly efficient manufacturing process that provides quick, large-scale production. This benefit is crucial in the automotive and medical industries, where stakeholders rely on mass production.
- Warp knits can be produced in wide dimensions, while weft knits are generally made more narrowly.

Warp Knitting: Limitations in Circular Economy

- Warp knitting often relies on filament yarns, which can limit the selection of raw materials, making it less suitable for applications requiring natural fibers or spun yarns that provide a softer or more textured feel.
- The warp-knitted fabric are less stretchable and mostly they stretch in the weft direction (Nawab 2016).
- Yarn supplied to machine from warp beam, so additional warping process is required to prepare warp beam (Nawab 2016).
- The filament yarn is used in warp-knitted fabric according the end application. Antistatic oiling is required to avoid static charge (Nawab 2016).

Warp Knitting: Effect on Recyclability of Material

- Warp knitted fabrics can be recycled, but the recycling process depends on the type of fibers used in the fabric and its construction.
- Since mostly filament yarns are used for warp knitting, it is difficult to recycle due to their synthetic composition and the tightly interlocked structure of the fabric, which complicates the separation and processing of materials for reuse.
- Due to the presence of chemicals like antistatic agents, warp knitted materials may be susceptible to damage and may become unsuitable for use.

Warp Knitting: Utilization of Recycled Materials

The circular economy in warp knitting is supported by using recycled yarns, promoting the reuse and repurposing of materials. This approach enables fabrics to be recycled or upcycled into new products, reducing the need for new materials and minimizing waste. Companies may also adopt closed-loop systems, ensuring fabrics can be fully recycled repeatedly, creating a sustainable lifecycle and significantly lowering the environmental impact of production

PICTURE. Warp knitted fabrics.

Tubular Knitting: Definition

Tubular fabric is a type of textile designed in the shape of a hollow cylinder, as its name suggests. Unlike conventional fabrics woven flat on a loom, tubular fabrics are created using circular knitting machines. This method results in a seamless tube without side seams, offering enhanced flexibility and stretch in all directions.

PICTURE. Tubular knit wear figured by Hashan Disanayakage using AI.

Tubular Knitting: Possibilities in Circular Economy

- Tubular knitting machines can create more than one tube and join the tubes together on a machine. The complete garments knitted on circular machines may also only need a minimal cutting operation.
- Eliminates the time gaps between the successive knitting and assembly production phases, thus saving production time and costs.
- For clothing and paraclothing (e.g., medical textile accessories worn on the body), it provides the user with greater comfort and a better fit, as it eliminates the need for seams.
- An environmental point of view, the most important advantage is the possibility of waste-free production potential.

Tubular Knitting: Limitations in Circular Economy

- Seamless knitting machines in circular form is the poor flexibility of these types of machine for producing fabrics in different diameters.
- One of the most important problems for the knitting industry is the instability of fabrics after knitting, and particularly after their first laundering.
- The capital cost of production time alone on a full-body garment machine can still exceed the price that a cut and sewn knitted garment could be purchased for in China.
- There are also design limitations to the full-body knitting machines; intricate designs cannot be applied to cylinders during knitting.
- In some cases knitted constructions do not have appropriate physical properties and are therefore not suited for certain end uses.

Tubular Knitting: Effect on Recyclability of Material

- Tubular knitting has an interlocked and seamless structure, which can be advantageous for recycling as there are no cut edges or seams that generate additional waste during fabric processing.
- The density and tightness of the knit may affect shredding and fiber recovery. Tightly knitted tubular fabrics may be harder to mechanically break down compared to looser knit fabrics.
- When the recycling process requires cutting and altering the tubular structure, it can potentially affect the properties of the material.

Tubular Knitting: Utilization of Recycled Materials

- Recycled materials can be effectively utilized in tubular knitwear production, offering excellent friction properties during the knitting process (Au et al 2011).
- Significant problem is that some of these stiff yarns are almost inextensible, which causes tension peaks with breakage of the yarn or single filament in the yarn bundle, especially in high speed knitting operations (Au et al 2011).
- Modern tubular knitting fabric manufacturers have embraced advanced technologies to incorporate recycled materials, promoting sustainability in their production processes.

Dyeing and Printing

Dyeing: Definition

Dyeing is a process of producing a uniform coloration into a material (fiber, yarn, fabric).

There are various methods used to apply color into textiles, the most common one being exhaust dyeing (batch), continuous (padding), and printing.

There are also various types of dyes that are used according to the material being dyed and the achieved result.

Dyeing: Possibilities in Circular Economy

- Increases the commercial value of a textile product
- Natural dyes and mordants could be a great alternative to its synthetic counterparts
- Chemical involved in the dyeing process as well as the type of dye itself could be labelled to ease the end-of-life recycling of the product
  - The are more than 10,000 different dyes used in textile manufacturing and identifying the exact chemistry of it during the end of its life could be hard
- Some types of dye baths are recyclable
  - Saves on dye stuff, water, and auxiliary chemicals
  - Usually done on dye baths with minimal auxiliary chemicals
    - Direct dyes for cotton, dyeing of acid dyes, and disperse dyes for polyester

Dyeing: Limitations in Circular Economy

- Textile dyeing could use up to 150L of water per kg of textile
- The dyeing process could cause water pollution
  - Could come from oxidizing agents, salts, dyes, etc.
  - Heavy metals like arsenic or chromium might be dispersed in the water
  - Color must be removed from the wastewater which is an expensive process
- Most dyes are lost in the effluent (wastewater) due to the inefficiency of the dyeing process
  - Out of 700,000 tons of dyes, 200,000 tons are lost in the process

Dyeing: Effect on Recyclability of Material

- Color must be removed before the textile is chemically recycled as it is considered as impurity
  - This is due to the uncertainty of the type of dye used in the textile and its chemical structure
- Researchers in Aalto university are able to recycle post-consumer denim fabric while retaining its color through the Ioncell process
  - It shows that it is possible to recycle post-consumer textile without decolorization while maintaining an attractive and marketable colour

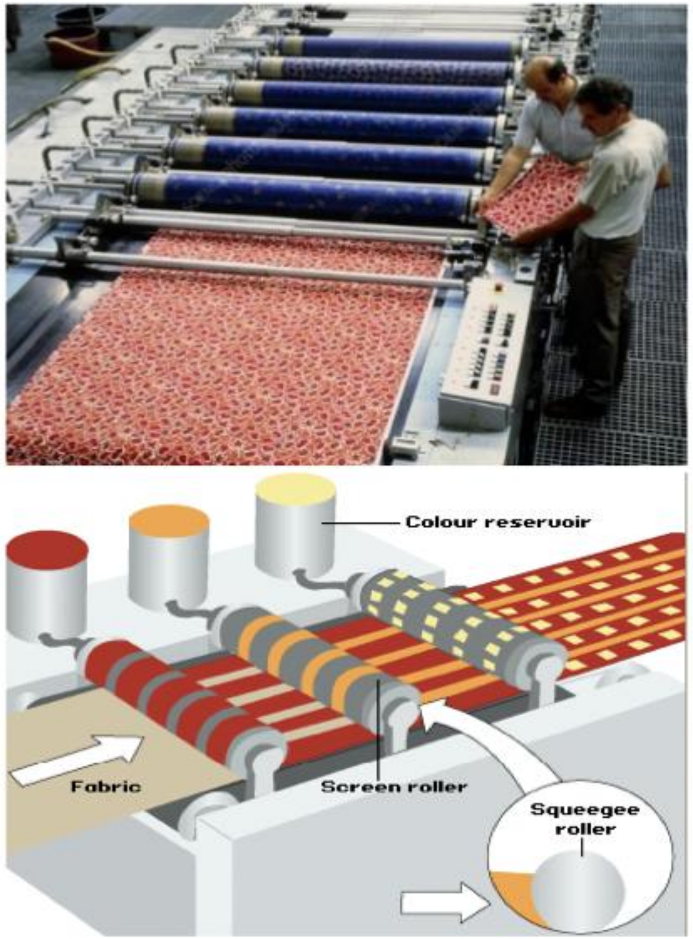
Dyeing: Utilization of Recycled Materials

- Materials that uses vat dyes and reactive dyes with anthraquinone units have the greatest potential to be re-used in dry jet wet spinning
- It is possible to upcycle post-consumer and pre-consumer cotton waste without removing its color
  - The color remains bright which is suitable for the commercial market
  - Still a lab-scale process

Rotary Screen Printing: Definition

The fabric is stretched on a constantly moving belt and color is transmitted to the fabric using lightweight metal foil screens that are shaped in a cylinder, it usually made of stainless steel or nickel.

Each color in a pattern is designated its own cylinder and up to 24 cylinders can be used for a single pattern.



Picture 1: Rotary Screen Printing Machine Diagram and Actual Machine

Rotary Screen Printing: Possibilities in Circular Economy

- High production rate
- High versatility and custom ability in regard to the patterns
  - As much of 24 colors are able to be printed at once
  - No joint marks
  - Continuous patterns are achievable
- Pigments/dyes could be stored for later use
  - Unless it is alkali based reactive dyes which has a short shelf life

Rotary Screen Printing: Limitations in Circular Economy

- The cylinders and belt must be washed before every color change
  - A production of patterns with multiple colorways or the production of a wide array of patterns could be water consuming.
- Generates a considerable amount of chemical wastage and effluents
  - The use of chemicals such as urea, thickener, alkali in the pigment makes effluents hard to treat
  - Studies in Bangladesh show that 42% of printers are not properly treating their effluents
  - A study show that a production of a 16-color print on 1000m of woven cotton generates 96kg of chemical waste

Rotary Screen Printing: Effect on Recyclability of Material

- The use of pigments, inks, and dyes that contain volatile organic chemicals (VOCs) may affect the recyclability of the textile at the end of its life cycle
  - Might be a difficult task to chemically recycle due to the variety of combination of chemicals in the thickener, dyes, pigments, etc that could be use and it also might pose some problems to the fiber during mechanical recycling

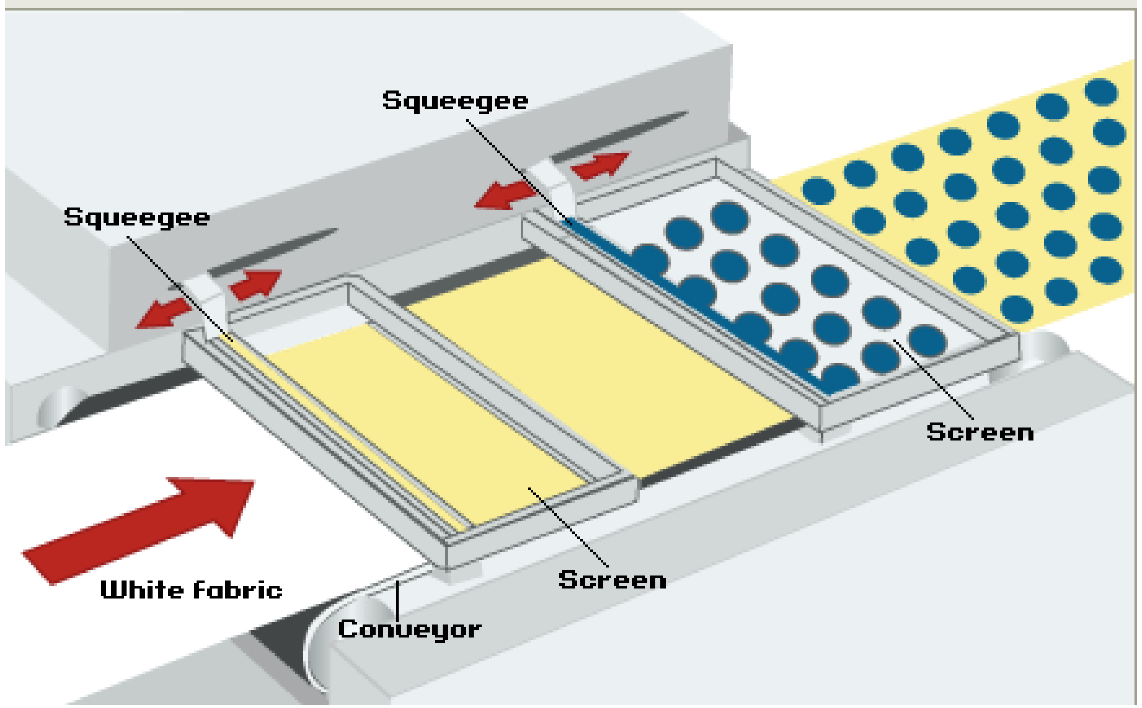
Rotary Screen Printing: Utilization of Recycled Materials

- Cuttings from rotary screen printing or wastes from post consumer textile wastes could be regenerated and recycled
  - Materials that are unable to be spun into new fibers could be recycled as pigments and dyes
  - Most of the cuttings and unsorted waste could be sold as fuel or insulation.
  - In 1000m run about 10 m of fabric cutting is obtained

Flat Screen Printing: Definition

The essence of flat screen printing is that it is a technique in which the fabric is extended and stretched to taut in a frame, a screen with an image/pattern cut on it is placed above the fabric and a squeegee is used to apply ink, pigment, or dye unto the fabric evenly.

This process could be done manually by hand, but semi-automatic and automatic machines are available as well.



Picture 1: Diagram of Industrial Screen Printing Machine

Flat Screen Printing: Possibilities in Circular Economy

- Good color definition and penetration
  - Depending on the type of dye used and the material but in general it is better than other methods
- Rapid change of design and color is possible
- Relatively low-cost production, with a low initial investment cost
- Pigments/dyes could be stored for later use
  - Unless it is alkali based reactive dyes which has a short shelf life

Flat Screen Printing: Limitations in Circular Economy

- Excess paste could be wasted due to the pigments needing to be pre-mixed
  - More color in the pattern meaning more unique mixtures of dyes and shades
  - Most pastes are stable and could be stored except for reactive dyes with alkali (limited shelf life)
- A slow process with limited designs
  - Design repeat size is limited to the width and length of the flat screen and continuous designs are not possible
  - 6-8 colors available
- Screens and belt must wash after every color change, and this could consume a lot of water especially in big productions

Flat Screen Printing: Effect on Recyclability of Material

- The use of plastisol ink (a PVC based ink), which is one of the most used screen-printing ink, could cause some issues in regards of recyclability of the textile and microplastic dispersion.
  - Due to the phthalates mixed in with the ink

Flat Screen Printing: Utilization of Recycled Materials

- Cuttings from flat screen printing or wastes from post consumer textile wastes could be regenerated and recycled
  - Materials that are unable to be spun into new fibers could be recycled as pigments and dyes
  - Most of the cuttings and unsorted waste could be sold as fuel or insulation.

Digital Printing: Definition

The most common method of digital printing is inkjet printing in which a nozzle sprays ink unto the substrate. In this process no coloring apparatus makes contact with the substrate.

The design can be transferred directly from the computer to the substrate without the need for modifying machinery or stencils for different patterns

Picture: Mimaki’s Direct Textile Inkjet Printer

Digital Printing: Possibilities in Circular Economy

- Environmentally friendly
  - Development of water-based inks with little volatile organic compounds
  - Need for less water, energy, and less effluent discharge
- Shorter print runs and sampling is more economical and profitable
- Highly efficient
  - Engraving a new design/pattern of a rotary screens might take 3-4 days while with digital printing there is not need for such downtime

Digital Printing: Limitations in Circular Economy

- Fabrics used for digital printing especially inkjet printing must be pre-treated especially for this process.
  - Unable to print on stretchy knits or performance fabric
- Lower durability and colorfastness compared to other printing methods
  - Due to it being a non-contact dyeing method, the lack of pressure causes a lack of dye penetration
  - Post printing finishes for digital printing are not yet in the level of other printing.

Digital Printing: Effect on Recyclability of Material

- As flat or rotary screen printed material

Digital Printing: Utilization of Recycled Materials

- As flat or rotary screen printed material

Plastisol Printing: Definition

Fabric decoration with printing ink containing thickeners and binders, which swell and get cured at around 180°C (The Watchtower, 2022) and form a uniform PVC surface, when dried, which is often raised. Utilized both as a coating and as a textile ink for screen, heat transfer or direct-to-garment printing methods. They are the most used inks for printed designs and work especially well with opaque bright prints on dark materials.

PICTURE . Plastisol Printed Fabric (Melmarc, 2014).

Plastisol Printing: Possibilities in Circular Economy

- Plastisol phthalate-free inks are much environmentally friendlier and enable product recycling. This implies that thus, common toxic plasticizers (phthalates) are eliminated from recycling cycles because of their toxicity.
- Printing can cover irregularities on the fabric surface, thus extending the possibility to use recycled lower-grade fibers (or waste fibers). Also, discarded PVC can be utilized (not used or used but pure and not cured).
- Plastisol is water-insoluble and is not absorbed by fibers but adsorbed.
- Plastisol ink mixes well with many different materials. This allows for use of some side-stream materials of restricted use opportunities.
- Cheaper than water-based printing methods.

Plastisol Printing: Possibilities in Circular Economy

- Consumes no water, but oil, and thus, doesn't air-dry in the silkscreen stencil in screen printing, which reduces waste and makes screen printing a more ecological option for plastisol, and plastisol a more ecological option for screen printing. Also, residual non-used ink can be collected back into a container and reused later.
- Garments don't need to be washed after printing.
- Can keep vibrant colors for many years with suitable maintenance.
- PVC used is durable, versatile and resistant to acids and bases, which is also reflected in plastisol. However, the latter one is weaker in all strength parameters, than the original PVC. Its durability also increases chances for successful reuse or recycling.
- Plastisol emits fewer VOCs when being cured, compared to solvent-based inks.

Plastisol Printing: Possibilities in Circular Economy

- Can be removed with, for example, solvents containing acetone, which is more efficient, than mechanical removal. Also, there are researches on developing of more sustainable options for chemical solution of plastisol. For instance, solvents could be bio-based and/or exploit enzymatic action.

Plastisol Printing: Limitations in Circular Economy

- Different bans and restrictions for PVCs and used phthalates have been imposed in many countries (generally, US and some EU countries) because of its toxic threats (CHEJ, n.d.) to health and environment – PVC and its plasticizers. For one, common phthalates have different effects on health such as endocrine disruption, asthma, damage to fertility and reproductive system. 0,15% is the maximum concentration for short chain chlorinated paraffins (SCCP) for production, placing on the market, and use of such goods. (Kamppuri et al., 2019.)
- Doesn't dry at room temperature and requires heat, which takes more energy than normal printing.
- Thick prints compromise recyclability (see latter slides). Mechanical removing them takes more energy and is not efficient as the chemical method, which utilizes chemicals, water and sometimes heat, and may cause safety, health and environmental concerns.

Plastisol Printing: Limitations in Circular Economy

- Microplastics may be emitted during the product's lifecycle, which contributes to environmental pollution.
- Poor use resistance, in processes such as ironing, washing and heavy wear because, for instance, although PVC itself is quite strong, the plasticized variant is less tensile.
- Despite the advantages for recycled-fiber fabrics, plastisol is only recommended for long-lasting products, as it's long-lasting itself and commonly considered not reuseable.
- Recommended for printing on colored fabric, as its vivid and distinct picture works better on them, and, on white fabrics, there's no need for such print's properties, and lighter ink would be preferable for more comfortable use. This, however, requires dyeing: use of dyes, chemicals, water, etc.

Plastisol Printing: Limitations in Circular Economy

- PVC packaging is generally restricted from recycling and goes to mixed waste – the best option nowadays. Plastic products which are not packaging, also are treated as mixed waste. As plastisol is both made of PVC and not a packaging, it is not recyclable. Recycling and reuse of PVC plastics have been developed, however, to overcome the current problems in those processes, which will change the position of PVC in circular economy drastically, if successful.
- Incineration of PVC is problematic as it causes corrosion of boilers on power plants and produces toxic chlorine compounds, so it's not eligible as energy waste.
- PVC is not biodegradable and, if contains phthalates, can release harmful chemicals, when heated (VOCs; more, compared to water-based inks).
- The print may fade or peel off (with time or improper maintenance) but still leave marks (plastic/glue) that can be difficult to remove.
- Despite low initial investment, environment-related expenses might be high.

Plastisol Printing: Effect on Recyclability of the Material

- Thick prints are unsuitable for mechanical recycling as they clog the processing equipment. Printing thus must be removed mechanically before recycling, but thin (and/or small) prints can be left. This also minimizes amounts of harmful plasticizers in the textile waste stream.
- The print (or glue) may be difficult to remove, additionally. But if separated, the fabric can be reused.
- Since plastisol prints are non-breathable, they absorb body liquids more, which may contaminate the fibers and complicate recycling.
- The more breathable a printed material is, the easier it is to remove the print chemically, as breathability means better penetrability for both plastisol and solvents.
- Presence of textiles with plastisol prints in the end-of-line textile stream makes necessary use of such technologies, which increases the cost of recycling.

Plastisol Printing: Utilization of the Recycled Material

- As mentioned before, use of recycled materials gives better results than for unprinted fabrics, as prints can cover irregularities. However, plastisol is only recommended for long-lasting products.
- Theoretically, a plastisol print could be removed carefully from the fabric, without damage to it, and put on a new fabric with adhesive or a layer of fresh uncured plastisol, so that it makes fabric and print adhere to each other after getting cured. This is a reuse technology, which seems potentially viable to the author, but is not commonly used today. Also, as a pre-treatment for this method, the fabric could be dissolved with certain solvents to get pure print separated from the base material (not suitable for every case, of course).
- Plastisol currently doesn't go to recycling, but mixed waste, so cannot be used recycled.

Plastisol Printing: References

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Finishing

Resin Finishing: Definition

Resin finishing is primarily used for cellulosic fabrics such as cotton and viscose. The purpose is to prevent wrinkling during washing and use, and shrinkage during washing, and make ironing easier. Also, can be used to set permanent pleats/wrinkles. This helps the pile of pile fabric stay upright. The mechanism behind involves creation of cross-links between cellulose molecules. Cross-linking agent often contains urea, melamine, formaldehyde. Catalyst – magnesium chloride, ammonium salts. Additives – softeners, water repellents, surfactants etc. The process is a traditional dip-dry-bake method (bath with resin monomers).

PICTURE. Winkle-Free Finished Fabric (Baleaf, 2023).

Resin Finishing: Possibilities in Circular Economy

- Formaldehyde-free solutions are under development. They include polycarboxylic acids such as butanetetracarboxylic acid (BCTA) and citric acid. One of completely formaldehyde-free wrinkle-resistant chemicals is DMeDHEU (dimethyldihydroxyethyleneurea). (Räisänen et al., 2017.)
- Citric acid/xylitol combination is environmentally sustainable as it is created of entirely renewable raw resources (and is a replacement for formaldehyde). There has been researched and established a cost-efficient scale-up strategy comparable to solutions using formaldehyde, and it is more efficient than alternative green solutions. (Kiron, 2021.)
- Among other chemicals, DMDHEU (dimethylol dihydroxyethyleneurea) is a cost-effective option providing good wrinkle resistance even at low concentrations and excellent wash resistance.
- The chemicals and chemical mixtures can be adjusted to achieve formaldehyde levels down to 50 ppm, which meets the requirements of almost all products, mentioned by Finlex, except for products for children under 2 years (Räisänen et al., 2017).
- Wrinkle-free finishing reduces flexibility/elasticity, and makes the surface stiffer, which makes the product more durable.
- Reduced shrinkage after washing helps extend a fabric's lifespan, imparts a smooth and quick drying property, and improves fastness to light. Specific properties, however, depend on the chemical used.
- If a textile is washed before used, formaldehyde level drops down to permitted, according to limitations in Finland, besides the established allowable levels.(Räisänen et al., 2017.)

Resin Finishing: Limitations in Circular Economy

- Finished fabrics may release formaldehyde, causing allergic reactions, eye irritation, coughing and headache, and is harmful to one's DNA, very reactive and, suspected to be carcinogenic. Due to this, there is a regulation in Finland concerning the maximum amount of formaldehyde in textile products (Finlex, 2012). Especially, when sealed in a package, formaldehyde cannot evaporate to the environment and remains in the product.
- It's challenging to identify products containing harmful substances, analyze them and determine their concentrations. Those substances pose health and environmental hazards, and formaldehyde complicates recycling. Also, most of the chemicals used in the finishing process (cross-linking agent, catalyst, additives) are harsh and their environmental impact should be taken into account carefully.
- Finished fabric may turn gray during washing and chlorine-based detergents can cause yellowing. Reactive-dyed fabrics may lose some color strength. All of these increase the chances that a textile product will be discarded. Also, as per reactive dyes, they cannot be printed with on a wrinkle-free finished fabric.
- Abovementioned DMDHEU releases formaldehyde, in the contrary of its advantages.
- DMeDHEU is more expensive and has worse wash and chlorine resistance, so the fabric may yellow.
- In the finishing process, if the baking temperature is too high, the fabric's strength decreases, it yellows and becomes hard. Elastic fibers may also be damaged. A too low temperature can increase the release of formaldehyde and produce an unpleasant odor, which is almost completely removed after the first wash, however.

Resin Finishing: Limitations in Circular Economy

- A finished fabric feels hard/stiff, and, sometimes, to improve its feel and elasticity, they add softeners and surfactants to the finishing treatment, which is not only additional use of chemicals, but also, in case of silicone-based softeners and cationic and nonionic surfactants, potential toxicity to aquatic life and low biodegradability. The REACH regulation restricts some substances, used as softeners, such as APEOs. When they break down, they can form nonylphenols, toxic to aquatic life and accumulating in the food chain. Also, silicone-based softeners can contain VCs, contributing to air pollution. Certain cyclic siloxanes can act like estrogen and disrupt hormonal systems. (Räisänen et al., 2017.)
- After multiple washing cycles, the wrinkle-free property perishes, which goes along with release of formaldehyde or other chemicals into wastewater, as well as leads to additional chemical use in order to restore the finish. Therefore, softeners should be biodegradable, even if they are wash-resistant.
- The fabrics pills less, as pills come off more easily, when formed. This increases material loss and decreases its traceability.
- Chemical residues in textiles prior to recycling (with wrinkle-free finishing applied) might limit the use of recycled fiber, excluding some applications. For example, if a fabric was treated with a formaldehyde-containing chemical, there's a much higher probability that it's not suitable for children's clothing, than for some technical textile because of the aforementioned regulation.
- The properties imparted by the finishing don't necessarily stay after recycling, which, in case of loss of the property, requires additional chemical use.
- Wrinkle-free finishing reduces tear strength and abrasion resistance of a fabric, reduced durability and a textile's life cycle.
- Energy-intensive because of drying and curing (baking).

Resin Finishing: Effect on Recyclability of the Material

- Residual chemicals in the product can pose risks to workers in textile waste facilities and harm the environment during recycling and complicate the very recycling (e.g., formaldehyde), for instance, by adding more refining processes due to the strict requirements for chemicals, which sometimes makes it unsuitable for reuse/recycling (if recycled, can have limitations in use in certain products, e.g., children's clothing) or just less worth to recycle (if chemical recycling is too complex/expensive/etc.). Therefore, recyclability depends on the chemical used. Also, residual chemicals can cause unwanted reactions, but there are opinions that those chemicals are unlikely to cause problems in chemical (or biochemical/thermal) recycling because of their small concentrations meeting the regulations in Finland, which depends on a specific case. The EU's regulations restrict use and recycling of certain chemicals, but such substances may still be present in the textile waste stream.
- There are no troubles in mechanical recycling, but the recycled fiber should be safe and cause no problems in further chemical treatments with its residual substances.
- The resins fill the fibers' cells and react chemically with cellulose, which makes recycling questionable, as it may be difficult to remove substances used.
- The treatment is resistant to washing (and, therefore, water), which might make removal more problematic.
- Recyclability is higher, if the chemical used for finishing is known, which is difficult to identify, but should be somehow indicated (a label or QR codes to DPP).
- Presence of textiles with resin finishing in the end-of-line textile stream makes necessary use of such technologies, which increases the cost of recycling.

Resin Finishing: Utilization of the Recycled Material

- There are no restrictions on use of recycled cellulosic materials, but any previous treatments should be considered, especially if the fiber to finish is mechanically recycled, so that there are no unwanted reactions, when applying wrinkle-resistant finishing. An unwanted reaction can, for example, be poor adhesion of the finishing chemical to the fibers.
- Use of recycled fabric finished with resins, safer for human health and environment, is safe too, but the point above is still valid.

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Flame Retardant Finishing: Definition

A textile is treated with a flame-retardant chemical to reduce its flammability and slow/hinder the spread of fire at the beginning of inflammation. Chemical finishing of a fabric is the only option for natural fibers to achieve flame retardancy, but for synthetic fibers (during their production), it can also be achieved by modifying the polymer structure or adding flame retardant additives, although they are finished largely with the 1st method. Flame retardant chemicals are primarily based on phosphorus or halogen compounds and may also include nitrogen in phosphorus compounds and antimony – in halogen, to enhance flame retardancy. The most well-known brands are Proban and Pyrovatex CP for cellulose fibers, and Zirpro – for wool.

Flame retardants absorb heat, preventing the material from reaching its ignition temperature. Then the material chars as it decomposes, which slows combustion and prevents ignition. The decomposition is also guided to produce fewer combustible gases, and flame-retardant gases are released that limit the textile's oxygen supply, preventing combustion. There are 70 different brominated flame retardants used in the industry (was in 2001, when the source was created, and new options were coming to the market at that moment, for example). They have very diverse properties, including toxicity levels and potential for bioaccumulation in organisms and ecosystems. (Ryynänen et al., 2001.)

PICTURE. Flame-Retardant Finished Fabric (Zhognshi, 2023).

Flame Retardant Finishing: Possibilities in Circular Economy

- Proban flame retardant treatment of cellulose reduces the fibers' shrinkage during washing which can extend the fabric's lifespan.
- Pyrovatex-treated fabrics can be dyed with comparatively cheaper reactive dyes, which also allow for wider variations of color and have good abrasion and wash fastness, prolongating a textile's lifespan.
- Vat dyes used for Proban-treated fabrics are highly eliminable from wastewater as they are insoluble and have excellent fastness to washing and light, which aligns well with circular economy principles.
- Wool fibers naturally have high levels of moisture and nitrogen, decreasing the need for chemical treatment (amounts or even presence). Abovementioned Zirpro utilizes fluorinated (hexafluoro) zirconate ad titanate salts for wool.

Flame Retardant Finishing: Possibilities in Circular Economy

- Although many flame reatardants are easily washed out from textiles, there are permanent options, such as utilizing flame-resistant fibers, modifying fibers during production to enhance flame resistance, or applying a more durable flame retardant. Textiles with permanent flame-retardant properties have them lasting for the product's lifetime if care instructions are followed, and it is the most ecological option.
- Since, as a common example, public spaces require flame-retardant textiles, recycled finished textiles, which save their properties, can be used for this application, without involving unfinished fibers, and, therefore, excessive use of chemicals. On the other hand, the requirements (quality and technical) for PPE, such as firefighter overalls, are stricter, which might reflect on the recyclability.

Flame Retardant Finishing: Possibilities in Circular Economy

- Nanoparticles are now increasingly used as flame retardants (as additives or as finishes), and they allow for reduction of chemicals required. They are relatively safe, when imbedded within fibers and cannot be rubbed off the textile surface.
- Substitutes for prohibited substances have been developed. Those new brominated flame retardants don't accumulate in the food chain (which PBDEs typically do).
- There are bio-based nylon fibers for textiles made of renewable resources, which have imbedded moisture absorption and flame retardancy properties, with the purpose to replace PE-based fabrics.

Flame Retardant Finishing: Limitations in Circular Economy

- Flame retardant finishes are based on chemicals containing phosphorus and nitrogen, and synthetic fibers – phosphorus or bromine. These chemicals are toxic to different extents and pose various health and environmental risks. For example, phosphorus burdens water systems and causes biodiversity loss and eutrophication. Halogenated compounds in general (such as bromine) can be carcinogenic, cause toxidrome, environmentally persistent, or act as endocrine disruptors. That's why their use is either banned, restricted, or are substances of very high concern under the REACH regulation. Nitrogen increases production of tropospheric ozone and fine particle pollution, which adversely impact on terrestrial ecosystems, aquatic ecosystems, and human health.
- Proban-treated fabrics must be vat-dyed. Besides this, vat dyes are comparatively expensive, have limited color variations, don't have good fastness to rubbing, and require high pH.

Flame Retardant Finishing: Limitations in Circular Economy

- Reactive dyes for Pyrovatex-treated fabrics are unfixed, readily soluble in wastewater and difficult to eliminate.
- Blends can sometimes be more flammable, than fabrics made of those components separately. For example, cotton/polyester 50/50 blends are more flammable than pure cotton or polyester fabrics themselves. A fabric made of flame-retardant wool and polyester, which are fire-safe individually, burn readily if mixed. Overcoming these joint properties requires use of more chemicals.
- The abovementioned increased use of nanoparticles has such disadvantages as potential negative effects on lungs, when inhaled (if the treatment is abraded off), or accumulation in other body parts, particularly cells (and cellular changes), and release during a textile's lifecycle (e.g., in washing). This makes use of nanoparticles questionable and requires a deeper research.

Flame Retardant Finishing: Limitations in Circular Economy

- The abovementioned new brominated compounds are not completely safe, as they have shown causing of harm in animal studies too. There is limited information on the toxicological and epidermological properties of these compounds, so it has not been possible yet to assess the quantitative risk. There's an assumption, however, that at least some of the new brominated flame retardants will be restricted in the future due to suspected harm.
- As some brominated compounds are still permitted, only banned ones cannot be identified in the end-of-life textile stream based on the total bromine content (using, e.g., XRF method). Thus, the permitted compounds have to be removed from the stream too, but rapid bromine detection may practically be the only viable method for detection of banned PBDEs. Otherwise, identification of certain compounds and determination of their concentrations requires sampling from every textile item and a chemical analysis in a laboratory.

Flame Retardant Finishing: Limitations in Circular Economy

- Not only nanoparticles are washed out in washing cycles, but many flame-retardants too, as they are water-soluble. In order to maintain flame protection, the treatment has to be renewed after washing with water. This not only leads to increased chemical use but also release of toxic chemicals into water bodies.

Flame Retardant Finishing: Effect on Recyclability of the Material

- Mechanical recycling is possible, if the fiber doesn't possess any risk and further chemical treatments will not be problematic.
- Chemical (or biochemical) recycling is possible if there are no incompatible residual substances in the textiles that can cause unwanted reactions.
- Recyclability is limited as the chemicals may get released from the product, causing health and environmental harm. That's the reason to remove the products with too high bromine content (higher than the limit value). In practically used methods, there's no distinction between banned and permitted bromine compounds, but if there was, the recyclability of the textile mass would be higher (most preferably that the chemical used is known), especially for newly produced textiles (under the EU's POPs regulation).

Flame Retardant Finishing: Effect on Recyclability of the Material

- For better determinability, the chemicals used should be somehow indicated (a label or QR codes to DPP). As per limit values, there are maximum allowable concentrations, individual for each compound, which are set by the EU in REACH (ECHA, 2024), but generally, the amount of Substances of Very High Concern (SVHC) must not exceed 0,1% of the total product weight (QIMA, 2024). The same number applies for articles and preparations made partly or entirely of recycled materials, 0,001% - if PBDEs are present as contaminant residues. 0,15% works the same way for short chain chlorinated paraffins (SCCPs) for production, placing on the market, and use of such goods. (Kamppuri et al., 2019.)
- Presence of textiles with flame retardant finishing in the end-of-life textile stream makes necessary use of such technologies, which increases the cost of recycling.

Flame Retardant Finishing: Utilization of the Recycled Material

- There are no restrictions on use of recycled materials, but any previous treatments should be considered, especially if the fiber to finish is mechanically recycled, so that there are no unwanted reactions, when applying flame retardant finishing. An unwanted reaction can, for example, be poor adhesion of the flame-retardant chemical to the fibers.
- Recycling of flame-retardant textile waste is problematic because of potential chemical risks posed by banned compounds, so all textiles with bromine are removed from the recycling stream, so flame-retardant textiles are typically not used recycled.
- If a textile is recycled mechanically and doesn't require washing or chemical treatments, it might not require reapplication of a flame retardant.
- As mentioned above, there are limitations in use of blends.

Flame Retardant Finishing: References

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Soil Repellent Finishing: Definition

A chemical finishing process that repels soils (powdered and liquid substances) (and always water), simplifies cleaning and facilitates stain release during washing by reducing the surface tension of the fabric (for wet or greasy soils), preventing absorption of soils into the fabric. Dirt repellency is typically achieved by using fluorocarbons (perfluorinated polyacrylate polymers that form a thin film on the fiber surface). Surface tension of water is 72,8 mN/m, and, to repel it, a fabric needs a lower value. The surface tension for oil is 32 mN/m, which is much lower. This means that usual water-repellent treatment is not enough to repel oils but can work vice versa. (Bechtold & Pham, 2023.) Conventional soil resistance worsens soil release, but dual action fluorocarbons can fix it.

PICTURE. Soil-Repellent Finished Fabric (Mikhail Iavkin with help of AI, 2024).

Soil Repellent Finishing: Possibilities in Circular Economy

- As textiles are kept cleaner, and stain removal is easy, the number of washing cycles lowers correspondingly. This reduces consumption of energy, water and chemicals (used in detergents), and prolongs the textile's lifespan.
- The textile will be in use longer, as it will be protected and kept clean normally, up to the moment when it's technically not suitable for use anymore (mechanical damage). This benefit, however, is not as drastic, since it's more important for normal clothing, but this finishing is normally applied to textiles of specific purposes.
- Most FC products are padded, dried, and cured with heat. Low curing fluorocarbons have been newly developed, and they don't require heat in the applying process, drying at just room temperature, which saves cost and energy.
- Caused by concerns about the safety of perfluorinated chemicals, new, entirely fluorine-free chemicals have been developed, such as silicones or hydrocarbons, which can give favorable water repellency to the finished textiles. Silicone-based water repellency can be improved with adding fluorine atoms to create fluoroalkylsiloxanes. As their durability is limited and main purpose is water repellency, they could be used in a laminated textile material too. Also, natural waxes can be used as water repellents, with some properties poorer, however, but usually, they are the cheapest option. In the contrary, popular fluorocarbon-based compounds are usually the most durable and high-performance: they cover well both water and oil repellency needs.

Soil Repellent Finishing: Possibilities in Circular Economy

- There is a solution for lack of fixation of fluorocarbons, which utilizes activation of isocyanine (at different temperatures depending on the kind of blocking groups), reacting with the functional groups of the fluorocarbon, fiber or itself. This fixation on the fiber surface provides durability to washing, dry cleaning and rubbing, all of which prolong the textile's lifespan.
- Water repellency normally implies also repellency to the soil dissolved in it, especially, if its quality and condition are good. However, it is possible, as one example, that dirt particles adhere to the surface because of stronger interactions with the fabric than water (or another carrying liquid, which could be a similar case for oils/fats), which can be, e.g., chemical or electrostatic. Overall, although it means that the performance of such a finishing is generally worse and repels only aqueous soils, excluding greasy substances, it still can be a good option for soil-repellent finishing, especially, if no greasy soils are expected in the intended application.
- Shorter-chain perfluoroalkyl compounds, like C4 or C6 (more common), do not release harmful PFOS or PFOA compounds under normal conditions and, despite the decreased oil repellency (nevertheless, it still is there), have good water repellency. (Bechtold & Pham, 2023.) They are safer to human health and friendlier to the environment (e.g., biodegradable). They also provide good air circulation through the fabric, which reduces its contamination with body liquids, thus prolonging the textile's lifespan and increases recyclability.
- Some repellents can be applied during dye cycle, as they are exhaustible, which saves energy, as all subsequent treatments are done at the same time thus.

Soil Repellent Finishing: Possibilities in Circular Economy

- A so-called self-cleaning textile can be made, by creating a nanostructure by use of nanoparticles and/or engraving nano-scale grooves onto the fabric surface. Dirt particles do not adhere to the nanostructure, and water droplets carry them away. Nanoparticles, such as silica (silicon dioxide), quartz, or titanium dioxide can be used. They allow for reduction of chemicals required to make a finishing and are relatively safe, when imbedded within fibers and cannot be rubbed off the textile surface.

Soil Repellent Finishing: Limitations in Circular Economy

- Fluorocarbons cause safety concerns, which limit the application of treatment with those, and they are the most expensive option. This counteracts with circular economy practices, especially for older products that typically contain longer and more harmful chains of banned compounds. Widely used "C8" PFOS and PFOA (currently, of very high concern in the REACH list) compounds (e.g., PTFE films) are persistent, bioaccumulating (and can get into the food chain) and have toxic effects. However, shorter-chain fluorocarbons, despite their advantages, provide decreased oil repellency. High chemical load may pose risks to the user and compromise recycling too. All of these are the reasons why European commission banned those (POPs regulation) (Euroopan komissio, 2014). 0,1% is the maximum allowed concentration of PFOS and its derivatives as contaminant residues in semi-finished products and/or articles.
- An alternative value, commonly applied to coatings, is 1 µg/m2. 0,15% works the same way for short chain chlorinated paraffins (SCCP) for production, placing on the market, and use of such goods (Kamppuri et al., 2019).

Soil Repellent Finishing: Limitations in Circular Economy

- Low curing fluorocarbons have a disadvantage (although it's considered evitable) of their low durability, because they are not fixed by cross-linking as well.
- The abovementioned natural waxes, used as repellents, have relatively poor wash durability and reduced fire safety. Also, silicones have limited durability and comparatively high costs. Both options can only provide water repellency, but not oil.
- Washing (including use of surfactant) and dry cleaning disturb the orientation of performance side chains of the finishing chemicals, which reduces the finish performance. This orientation, however, should be recovered by newly applied heat treatments, such as ironing, pressing, or tumble drying. Although this allows for maintaining of proper performance of the finish, it requires more energy and, therefore, cost for the user.
- The lamination and coating options, suggested above, might decrease recyclability.
- The abovementioned nanoparticles have such disadvantages as potential negative effects on lungs, when inhaled (if the treatment is rubbable off), or accumulation in other body parts, particularly cells, where they cause changes, and release during a textile's lifecycle (e.g., in washing). This makes use of nanoparticles questionable and requires a deeper research.

Soil Repellent Finishing: Effect on Recyclability of the Material

- Soil-repellent treatment affects the recyclability significantly, as the treatment process involves the use of fluoro-carbons and -chemicals, silicones, resins, triazine or waxes and their derivatives. These chemicals, if residual, make the treated material unsuitable for recycling (unwanted reactions/ unremovability /complexity /inefficiency/cost/various hazards/etc.), especially, if chemical load is high. That is why the POPs regulation restricts recycling of textiles containing perfluorinated compounds, so they go to mixed waste. The recyclability depends on the chemical used.
- Presence of textiles with soil repellent finishing in the end-of-life textile stream makes necessary use of such technologies, which increases the cost of recycling.
- The water repellency of the treatment might make removal more problematic.

Soil Repellent Finishing: Effect on Recyclability of the Material

- Recyclability is higher, if the chemical used for finishing is known, which is difficult to identify, but should be somehow indicated (a label or QR codes to DPP).
- There are no troubles in mechanical recycling, but the recycled fiber should be safe and cause no problems in further chemical treatments with its residual substances. It can, for instance, repel the finishing to apply to the recycled material. Also, the applications are limited, as for some end-uses, water repellency is rather a disadvantage (e.g., towels or mops).
- Although some repellent chemicals can be washed off during washing, it rather results in higher chemical consumption to restore the finish and sooner discarding, than higher chemical purity of the material.

Soil Repellent Finishing: Utilization of the Recycled Material

- There are no restrictions on use of recycled materials, but any previous treatments should be considered, especially if the fiber to finish is mechanically recycled and not treated chemically, so that there are no unwanted reactions, when applying wrinkle-resistant finishing. An unwanted reaction can, for example, be poor adhesion of the repellent chemical to the fibers.

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Coating and Lamination

Coating: Definition

Application of single- or double-sided coating compounds or foam films on the textile's surface (any kind), so that a plastic surface created simultaneously as it is bonded to the fabric by its adhesive properties or an adhesive.

The most common raw materials are natural and synthetic rubbers, PVC, PU and acrylic. The purpose of coating is to impart certain properties to a textile, which can be water/dirt-repellency, strength, abrasion resistance, appearance qualities (including prints), light blockage or even to cover electronic elements of smart textiles, etc.

Coating could also be seen as a lamination, but more limited. Liquid polymers, like **PVC** and **PU**, can be spread (direct or reverse, depending on the textile), printed, sprayed,
or impregnated into a fabric, whereas thermoplastics (**PU**) can be extruded with a wide flat nozzle.

PICTURE. Solid Vinyl Coated Plyester Fabric (LOOKOUT MOUNTAIN TARP, n.d.).

Coating: Possibilities in Circular Economy

- **Natural rubber** has good tensile strength, and its flexibility and pliability remain excellent even at low temperatures. This prolongs the textile's lifespan.
- **Synthetic rubbers** (e.g., **SBR**, **NBR**, **EPM**, **CP**, **butyl rubber**, **silicone rubber**) have better heat, aging and oil resistance, compared to **NR** (**natural rubber**), which prolongs their lifespan (both technically and by reducing chance of being discarded).
- **PVC** is a common coating material because of its affordability and favorable properties, such as excellent resistance to fire, weather and solvents.
- **PU** has good tensile, tear, and abrasion strength. It feels soft, flexible and drapes well even at low temperatures. This is what makes **PU** versatile and long-lasting.
- **Acrylic** has excellent resistance to UV light, heat, ozone, chemicals, and water, and it withstands dry cleaning well. This extends its lifespan.
- Out of solvent-based, water-based and thermoplastic polyurethanes, water-based and thermoplastic options are environmentally the best.

Coating: Possibilities in Circular Economy

- One of the methods to make artificial leather is coating with **PVC** or **PU.** (Textile) **PU** is recyclable and has bio-based options, which reduces reliance on petroleum-based chemicals. Also, some manufacturers are developing methods to recycle PU-coated fabrics, minimizing waste and environmental impact (Jiezhixin Textile, n.d.). Although production of synthetic leather utilizes more toxic chemicals, it doesn't utilize water and doesn't have effluents like usual leather production, which, has a much higher carbon footprint (almost 7 times) and utilizes a very high land area. Overall, synthetic leather is considered more preferable and sustainable, in comparison to the traditional option, even if it is vegetable-tanned. (LaBarbera, n.d..)
- All possibilities of specific finishes must be considered, when they are applied as coatings, as they are also reflected in the final product. Coating in general, if carries a chemical finishing, is more long-lasting than the same finishing applied by other methods (except for fiber modification).
- In a waterborne technology, PU is delivered and processed with no solvents, providing a safer working environment, less pollution, and high efficiency, since water consumption decreases for 95 %, and energy – 50 % (as drying is unnecessary), compared to conventional technologies. From this, a base layer of a coating can be created. (Muthu, 2017.) This is utilized in powder coating, a more environmentally friendly option. Also, it generates low amounts of waste or hazardous chemicals. Unique characteristics are obtained because of high surface area of particles. It's possible to create rich coatings with minimal penetration. Also, melting is easier because of better heat absorption. Mostly, metal particles are used in this coating technology
- Thin coating can be applied with nanoparticles, such as different methods (e.g., silver). They potentially reduce use of chemicals.

Coating: Limitations in Circular Economy

- Impossible to recycle into new material because of separation difficulties.
- They use phthalates as plasticizers to make **PVC** softer and flexible. Those are toxic for human health and the environment and can lead to cracks and hardening of the coating material with time, as some phthalates evaporate easily from plastic.
- **PU** is more expensive than **PVC**.
- **Acrylic** has poor frost resistance, which makes it less suitable for clothing in, e.g., Finland's weather conditions.
- All currently used materials, except for **NR**, are made from non-renewable raw materials. Besides this, coatings in general consume water, energy and materials excessively, leave carbon footprint and generate toxic wastes.
- Solvent-based **PU**s release VOCs into the atmosphere, contributing to air pollution, besides their effects on human health.
- **PVC** or **PU**, used for production of synthetic leather, are non-renewable and non-biodegradable resources, their production utilizes chemicals and has environmental impact, and thermal or mechanical recycling of **PVC** is impossible. Also, some microplastic emissions are possible, as well as chemical hazard too human health.
- All limitations of specific finishes must be considered, when they are applied as coatings, as they are also reflected in the final product.
- The abovementioned nanoparticles have such disadvantages as potential negative effects on lungs, when inhaled, or accumulation in other body parts, particularly cells, where they cause changes, and release during a textile's lifecycle (e.g., in washing). This makes use of nanoparticles questionable and requires a deeper research.

Coating: Effect on Recyclability of the Material

- **PVC** is generally considered not recyclable, partially, due to use of phthalates and, sometimes, cadmium (also limited by the REACH regulation, with their maximum concentrations for heavy metals), and **PVC's** strong resistance to solvents. The same thing goes for plastisol. Although PVC itself is self-extinguishing when the ignition source is removed, plasticizers added can increase its flammability, so flame-retardants may be added, complicating recyclability even more. When burned, **PVC** produces dioxins and hydrogen chloride, the last of which, for example, causes corrosion in incinerators, making **PVC** unsuitable for burning.
- Organic solvents in solvent-based **PUs** pose risks to workers' health, which restricts their recyclability.
- **Acrylic's** resistance to chemicals might complicate recyclability too, and the process can be quite energy intensive, besides the need of specialized facilities and environmental impact concern.

Coating: Effect on Recyclability of the Material

- One of the restrictions for recycling of coated fabrics is contained prohibited compounds, which, if exceed the concentrations, allowed by POPs regulation, must be removed from the end-of-life textile stream, as it was stated regarding other finishes. Plastic-coated home textiles only account or about 4% of the total Chemical risk fraction of end-of-line textile stream tested mass (from the VTT report). For example, 0,15% is the maximum allowed concentration of short chain chlorinated paraffins (SCCP) for production, placing on the market, and use of such goods. The same way, textile coatings must have content of PFOS below 1 µg/m^2. It's quite commonly applied to PTFE films. Possible groups of harmful substances found in back-coated upholstery fabrics are considered phthalates, SCCP, fluorinated compounds and flame retardants. The estimated amount of HBCD in the background coating is 25%, and in the whole textile – 8%. (Kamppuri T. et al., 2019.)

Coating: Effect on Recyclability of the Material

- Coatings prevent material identification, so the most suitable sorting and identification method is manual sorting, but identification technologies will develop. Presence of coated textiles in the end-of-line textile stream makes necessary use of such technologies, which increases the cost of recycling.
- Coating can be applied not to fabrics and nonwovens only, but yarns, all of which have varying recyclability. Coated yarns, compared to coated fabrics and nonwovens made of the same uncoated yarns, have more contact of protruding fibers with the coating, which complicates removal. Besides that, if a fabric is made of coated yarns, first yarns should be separated to enable effective removal, and just in general, this structure is more difficult to operate with compared to even flat surfaces (fabrics and nonwovens). Thus, although fabrics, nonwovens and yarns are considered not recyclable, within certain recycling opportunities (chemical removal of plastisol coating), yarns always will have lower recyclability in this sense.

Coating: Effect on Recyclability of the Material

- Coated fabrics are generally considered not recyclable (especially, with liquid coating polymers), but there are developments around the world to overcome this. However, it's also case-specific due to the wide variety of fabrics (structures, materials, finishings, blends, etc.) and coatings, and thus, their combinations, which complicates the sorting and recycling processes a lot. Even if the polymeric layer is recyclable, one needs to check, what effects the recycling process will have on the textile layer (e.g., its recyclability), and vice versa. Although various composite materials are impossible to recycle mechanically or chemically, they are suitable for thermal conversion (pyrolysis or gasification), so the easiest way currently is to put coated fabric to the mixed waste stream. However, in the future, the sorting could be alleviated by using labels and/or QR codes leading to DPP, which would also increase the recyclability of such products.
- Coated fabrics are not as breathable as uncoated, which increases absorption of body liquids, which may contaminate the fibers and complicate recycling.

Coating: Effect on Recyclability of the Material

- All negative and positive impacts on recyclability of specific finishes must be considered, when they are applied as coatings. For example, although drawbacks of flame retardants or grease repellents do not refer to coating as such, they are reflected in the final product.
- If nanoparticles are used, besides their potential hazards to human health and environment, their removal may be difficult chemically, inflicting damage to the treated textile. Also, they adhere to the textile rather chemically, than mechanically, so mechanical recycling is not interfered, and, in chemical, with proper selection of chemicals, damage to textile is lower, than for plastic coating, so the recyclability increases. Also, nanoparticle coating enables lower amounts of chemicals used, facilitating to recyclability. Improper removal, though, may cause release of nanoparticles into the environment, adding to the environmental hazard, primarily. Some nanoparticles, like metal oxides, can strongly adhere to textiles, challenging the removal.

Coating: Effect on Recyclability of the Material

- Mechanically recycled coated textiles could be used as a batting in suitable applications (e.g., boxing bags or some composite materials).
- In chemical recycling, concentrations and composition of the chemicals used to make the coating determine recyclability largely.
- Since all currently used materials (for coating), except for **NR**, are made from non-renewable raw materials, the need for high recyclability of the coated materials is of increased importance.
- Recycling is possible, if the textile base and the coating are made of the same material (polymer), provided that this polymer is recyclable as such.
- **PVC** can be recycled with solvent with VinyLoop process (see later slides).

Coating: Utilization of the Recycled Material

- Thermoplastics, such as polyester, used in hydrophilic coatings, can be used recycled, which reduces resource consumption, waste generation and carbon footprint (and other impacts on land, air and water), compared to virgin raw material. Despite this, some thermal and/or oxidative degradation will happen to that coating, so all the strength parameters will decrease.
- Coating can be applied to recycled textile materials, provided that the same material originally is suitable for this finishing and the material's degradation doesn't prevent adherence of the coating (mechanically or chemically). Also, potential chemical incompatibilities must be taken into account, especially for previously finished and/or impure textiles (e.g., post-consumer textiles). As well as other finishings, coating can add more value to recycled textile materials.
- PVC coatings can be recycled with VinyLoop process which allows separation of PVC from other materials (and elimination of contaminations), using a solvent, which is then recycled in a closed loop. This recycled PVC can be used in place of virgin PVC in various applications, including coatings. The process is mainly supposed for recycling of PVC composite waste which cannot be satisfactorily recycled by traditional mechanical recycling processes. VinyLoop R-PVC has a 46% lower primary energy demand. (VinyLoop Ferrara SpA, 2012.)

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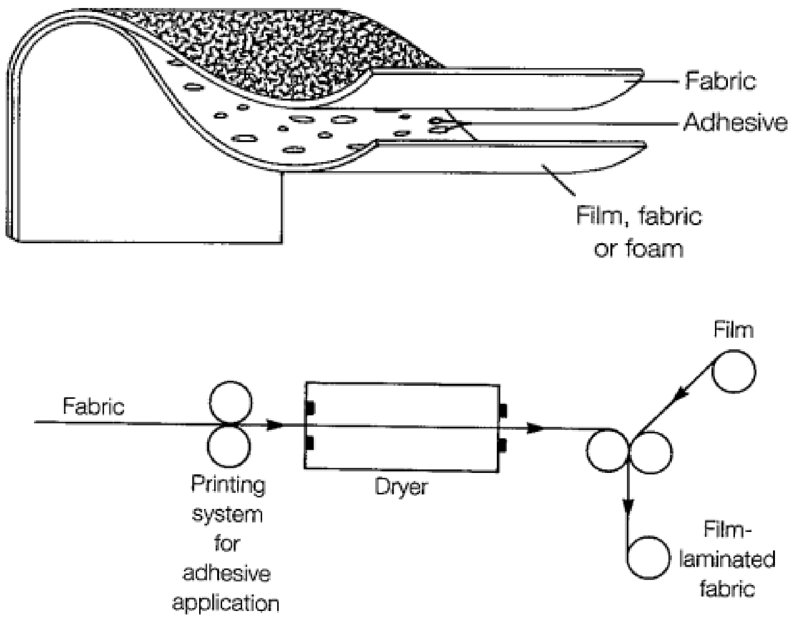
Lamination: Definition

Fabrics with plastic surfaces can be not only coated but also laminated. In laminated fabrics, the plastic film is produced in advance and is attached to the fabric using heat and/or adhesive, and pressure. Thermoplastic films are bonded with a patterned, heated roller. In adhesive bonding, tiny adhesive droplets are applied to the fabric surface prior to pressing.

Laminated and coated fabrics share many applications, but laminated have higher potential as they can be attached to not a film only, but also a foam laminate, felt or another fabric, which can be bonded to create two or more layers, with no limit of number. This allows for high variety of products and more complicated structures, such as PU laminates, which can be double-sided lamination of a thin PU film with fabrics. The purpose of lamination is to impart certain properties to the fabric and enhance the properties of two combined materials compared to them used alone, which can be increased durability, stability, adaptivity, or widely varying functionality.



PICTURE. Laminated Fabric (Hatch, 1993).

Lamination: Possibilities in Circular Economy

- Laminating enables creation of fabric structures of improved properties, which, typically, extends the material's lifespan.
- Different components made of the same material increase the laminated textile's recyclability and decrease the final cost of the manufacturing process.
- If plastic film applied carries a chemical finishing, the same as for coatings, it is more long-lasting than the same finishing applied with other methods (except for fiber modification).
- Despite the energy consumption by heat, the performance benefits preponderate them, but it's becoming a critical issue to develop technologies utilizing less energy.
- Use of hot-melt adhesives is an exemplar trend towards sustainability. It involves use of thermoplastics, which can be melted afterwards to separate the joined layers. Theoretically, any thermoplastic can be used for this purpose, but their variety should be minimized or indicated well to facilitate sorting and recyclability.

Lamination: Limitations in Circular Economy

- Typically, makes the bonded materials inseparable and, thus, non-recyclable.
- All possible incompatibilities of the components used must be considered, especially, for mechanically recycled ones. It can be natural incompatibility, which is quite easy to control (more difficult with blends, though), or incompatibility of chemicals used in production or finishing. Those chemicals may be hazardous to workers of garment manufacturing factories, users or the environment , or cause unwanted reactions when attached to each other. This also restricts the textile's recyclability.
- Differences between different components, and their possible recycling methods particularly, must be considered, as they affect the recyclability, and differences in their production increase the final cost.
- Hot-melt adhesives involve use of stabilizers, tackifiers, waxes and various fillers. Doesn't only this abundance affect recyclability of the adhesive, but a possibility of some of the chemicals used to be hazardous. Also, service temperatures of such adhesives are relatively low due to their low melting temperatures. In a long term, these materials tend to flow, with a few exceptions, so they are recommended to use primarily for hold-in-place operations with negligible load requirements. Also, depending on a thermoplastic and layers, the removal of the adhesive may be problematic. (Ebnesajjad, 2009.)
- The process is energy-intensive, as it utilizes high temperatures to melt adhesives (e.g., hot-melt) or activate bonding layers, generates significant continuous pressure, tension and rotation of rollers or presses, involves drying (or cooling down), requires constant ventilation, and multi-layer structures may require repetitive machine passage.

Lamination: Effect on Recyclability of the Material

- Typically, difficult to recycle because the different materials combined are hard to separate. Compared to solid laminated materials, may be somewhat easier to separate, as if a laminated fabric is in a roll, it can be handled with a smaller machine which splits it into two or more layers, each of which is rolled onto its own roller. Solid laminates (and other composites), which cannot be rolled, require more space to be disassembled.
- Multilayer structures or filmed textiles are unidentifiable (if mono-material, could work) (by digital identification and sorting technologies), and the more there are layers, and the thinner they are, the less recyclable the textile is. Also, blends complicate identification and not just recycling processes. Manual identification is the most suitable option for such textiles nowadays, and digital technologies, probably, involving AI, are hoped for, but their development cost and price on the market will be very high.

Lamination: Effect on Recyclability of the Material

- Although laminated fabrics are generally considered inrecyclable (especially, with liquid coating polymers), for example, if an adhesive is used to combine the layers, it could be somehow modified to allow quick disassembly in recycling facilities, meanwhile not sticking of any of the components or being recyclable with them simultaneously. But this idea is mostly for innovative laminates, as old laminates need to be identified and, originally, their adhesives are not designed for being broken down.
- Hot-melt adhesive are one of the examples of a developing innovative subfield, but application of those substances is not always a good idea. However, recyclability of laminates is case-specific because of wide variety of fabrics and other layers (films, foams, membrane structures etc.) (structures, materials, finishings, blends, etc.), and thus, their combinations, which also complicates the sorting and recycling processes a lot. The recycling processes should be compatible for all the other layers (at least, inflict no damage). Although various composite materials are impossible to recycle mechanically or chemically, they are suitable for thermal conversion, so the easiest way currently is to put laminated fabric to the mixed waste stream.
- Pyrolysis by the action of high temperature produces syngas and oil (and smaller fractions of liquid, solid carbon residues and ashes). Oil obtained can theoretically be further refined into polymer starting materials. Without proper treatment, the process can be hazardous to the environment. The process is suitable for many end-of-life textile fractions impossible to be recycled mechanically or chemically, such as various alloy materials and dirty fractions. Sorting is not required, and natural and synthetic fibers can be pyrolyzed together, which eliminates the cost of identification and sorting. But better accuracy provides better controllability of the process and properties of the end products, and it impacts the process's yield and ratio. Another option of thermal conversion is gasification, which is more suitable for certain alloys.

Lamination: Effect on Recyclability of the Material

- All chemicals used for components' production or finishing have their impact on the laminated textile's recyclability, which is very case-specific. Generally, the impacts can be described as hazards to human health and environment in different stages of the textile life (which restrict recyclability) and unwanted reactions in recycling processes. The same thing goes for the components' physical properties, for example, tendency of some materials to clog the mechanism of the mechanical opener, preventing mechanical recycling (such as elastane or various plastics (e.g., films)). Even when there would be a method to separate layers, the total recyclability of a material is still majorly based on recyclability of all the layers individually.
- Except for the abovementioned wide diversity of possible layers and their combinations, especially considering the possibility of multiple layers, a variety of adhesives complicates sorting and recycling processes even more, making it impossible for the nearest years' technologies to handle. Commonly used adhesives include PVA, PVC, PU, HMPUR, HMMC, PA hot melt adhesives acrylic, and rubber, and as mentioned before, any thermoplastic (other than already mentioned) can theoretically be used for this application. (Prostech, n.d..)
- As mentioned before, the more diverse the components are chemically, the less recyclable they are. Oppositely, monomaterial textiles are more recyclable. Some of the examples are rainwear (or some other outwear) items produced by Helly Hansen and Reima, which also utilize recycled materials (e.g., PET bottles). Reima also say that their outwear is 100% recyclable. (Helly Hansen, n.d.; Reima, n.d..)

Lamination: Utilization of the Recycled Material

- Fabrics used, thermoplastic films and foams and paper substrates etc. can be made from recycled material. Reasoned by enhanced properties of laminated fabrics, recycled materials can be more likely integrated, replacing virgin options, as their poorer general performance would be not as significantly impactful. As an example, PET bottles could be utilized there, as they do it in Vilikkala to produce felt for further lamination (they also utilize discarded textiles) (Vilikkala, n.d.). However, it would be more favorable to use textile waste more, as, currently, 93 % of all recycled textiles comes from plastic bottles, which increases involvement of fossil fuels into the textile industry and doesn't enable a closed-loop circular economy, which is questionable and discussed within the EU. Thus, the main concern in this situation is to develop technologies enabling effective fiber-to-fiber recycling. (Euractiv, 2024.)

Lamination: Utilization of the Recycled Material

- As was mentioned for limitations, previous chemical finishings of recycled materials must be considered to avoid chemical incompatibilities of different components.
- Use of blends of unknown and/or inconsistent compositions can cause performance fluctuations.
- Also, it's very important to avoid use of textiles containing substances hazardous to human health and/or environment. These reasons necessitate analysis of recycled textiles, particularly possible chemical residues (and their removal, if needed).

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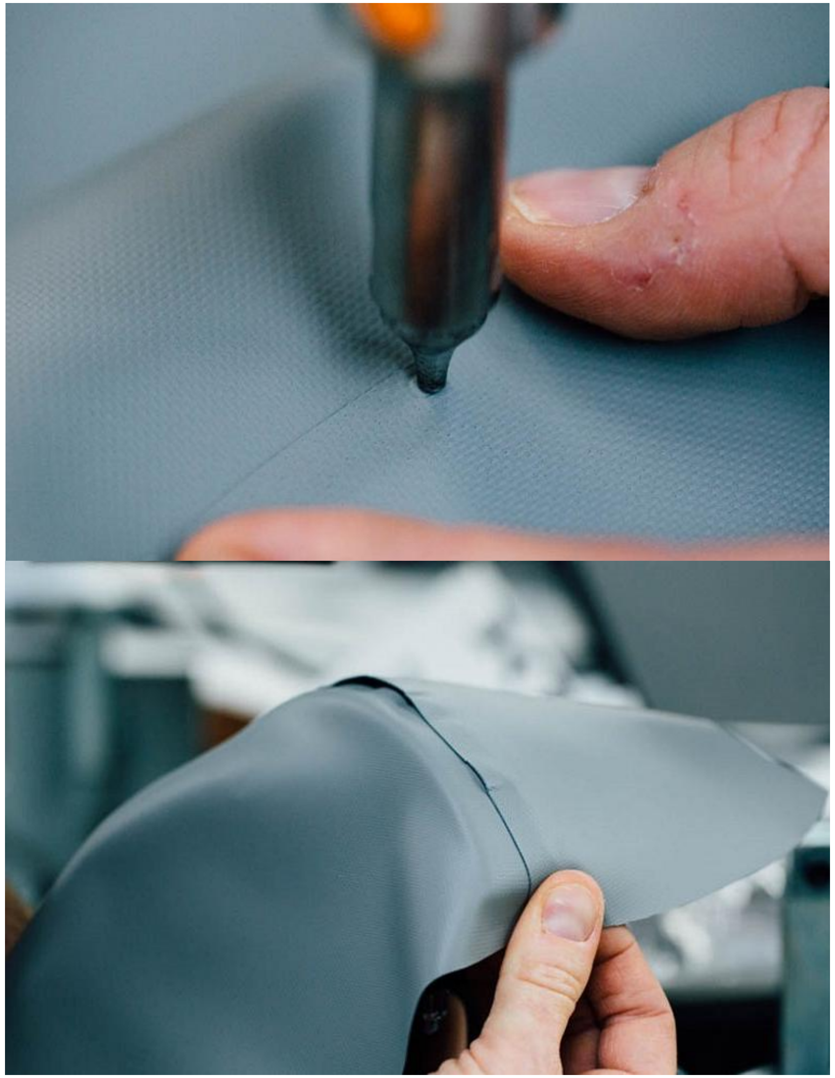
Textile Welding

Textile Welding: Definition

A process of joining fabrics by application of heat, rotational friction, pressure, and, sometimes, laser, ultrasonic vibrations or electromagnetic energy, or combinations of these factors. Heat-based welding methods are known for their efficiency and strong seamless bonds they produce, which makes them the most used in the industry, but in more specific, intricate uses, solvent or ionic liquid/MOF welding (experimental) can be used. Less commonly, threads can be welded too, when uniformity of yarns to work with is important (e.g., no knots), e.g., in woven technical textiles. Ultrasonic or laser welding technologies can also be used to cut, sealing the edges, emboss, laminate, or perforate fabrics.



PICTURE. Textile welding and a weld (CARRY HQ, 2016).

Textile Welding: Possibilities in Circular Economy

- Allows for keeping treated materials more integral, leaving no needle holes. This is typically important in coated rainwear and technical textiles but is also beneficial in, e.g., medical, extreme and aerospace applications as well as ones for various extreme conditions, to ensure good isolation. Strong bonds extend the textile's lifespan, compared to sewn seams, as they are stronger, distribute the load better, and traditionally used threads can rip relatively easily.
- Very thin and delicate materials can be welded, for example, by ultrasonic welding, which expands the range of application and provides a good advantage to the category as there is no seam and additional materials needed.
- The process is more versatile and flexible than traditional metal welding, and it allows working with all thermoplastic materials.

Textile Welding: Possibilities in Circular Economy

- The ultrasonic method is exceptionally efficient and provides superior weld strength and aesthetics. Also, welding in general produces strong bonds of materials at the molecular level.
- Radio Frequency welding can produce strong, uniform bonds across large areas, making it suitable for high-volume production
- There's no need for bonding material, such as an adhesive or threads for seams, which, except for zero material consumption, increases the technology's flexibility, as different materials (suitable) can be practically welded in any order without a need to fill the machine up with a required material, which would lead to some waste generation, and longer downtime. Also, if adhesive was needed, it would require more research and calculations on compatibility and performance (than needed now).
- Advanced welding technologies offer methods to reduce energy consumption, such as impulse welding.
- Can be used for production of composite multilayer textiles (laminated but in a limited way), which provide certain benefits for circular economy.
- Laser welding offers minimal thermal degradation of the material.
- Allows for more aesthetic repair of damaged clothes, prolonging their use.

Textile Welding: Limitations in Circular Economy

- Some techniques are limited to small welding areas (and limited lamination) and lap joint, also depending on the material.
- The lifespan of some equipment (e.g., ultrasonic welding technique) is short due to fatigue loading, and its initial investment and repair cost are high. Also, the workers need to be trained.
- Application range of welding technology is limited to thermoplastics only, which is still quite wide, but excludes all natural materials and thermosets, which are many plastics. Besides this, not every technique is suitable for every material, final product application, production scale (including the required working time), and, sometimes, desired bond strength which restricts the welding performance.
- Multilayer structures typically cannot be welded at one time, which requires continuous parallel mounted welders. This limits lamination realization and lowers productivity for this application and/or increases the initial investment.

Textile Welding: Effect on Recyclability of the Material

- There are practically no effects of welding on the recyclability of a treated textile, as the technology is based on melting thermoplastic materials and fusing them with pressure. However, in a long term, after multiple welding cycles (number depends on the chosen technique), the polymers will start to thermally degrade.
- If the textiles involved are mono-material, the recyclability depends directly on the material in question. There can be some negative effects, however, if two different materials are welded together, forming a plastic alloy on the seam, which is, typically, more difficult to recycle. Thermal recovery opportunity is probably not affected in this case, though it is not typically considered a recycling option in the EU and Finland specifically.
- Laminated multi-material textiles produced with welding still have some restrictions, but, typically, much less, since no adhesive is used.
- If the welding technique is not based on heat, but some solvent or ionic liquid, not only the recyclability may reduce, but the environmental impact worsen, especially speaking of wastewater treatment and chemical recovery. This is case specific and is not as significant, as the methods are not used much.

Textile Welding: Utilization of the Recycled Material

- Advanced welding technologies offer methods to incorporate recycled materials.
- The main problem that can be expected from recycled materials is their possible degradation, which might weaken the welded bond. Also, added to the thermal degradation occurring after a certain number of welding cycles, will reduce the lifespan of the weld in a long-term, following the lower strength.
- If the recycled material is a blend, there may occur several problems:
  - Thermoplastic + thermoplastic: may not form strong molecular bonds with each other, forming weaker weld.
  - Thermoplastic + thermoset: have the same problem as above, but more likely. Also, at the temperatures needed to work with thermoplastics, the thermoset may degrade or even ignite.
  - Thermoplastic + natural fiber: depending on the exact fiber, the natural fiber may degrade or ignite, both of which disable proper bonding.

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