Regenerated Cellulosic Fibers and Their Implications on Sustainability

Sohel Rana, Subramani Pichandi, Shama Parveen and Raul Fangueiro

Abstract This chapter discusses the present scenario and market trend of regenerated cellulosic fibers, and the properties of principal fibers existing in the market as well as some new fibers recently developed and yet to be explored. Production technologies of these fibers are discussed and their potential applications are presented. Various sustainability issues related to the production of regenerated cellulosic fibers are dealt within this chapter. The last section discusses the results of research studies conducted to assess the environmental impacts and sustainability aspects of regenerated cellulose fibers.

Keywords Regenerated cellulosic fibers · Production · Processing · Applications · Lifecycle assessment · Sustainability

1 Introduction

1.1 Present Scenario and Market Trend

Among the various regenerated cellulosic fibers, viscose rayon is mostly used in the textile industry and accounts for roughly 90 % of total regenerated cellulosic fibers

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produced. Natural materials such as wood, bamboo, and cotton linters are the raw materials for this fiber. Viscose rayon is used as continuous filament and staple fibers, among which 90 % of viscose rayon is produced as staple fibers [1]. Since the twenty-first century, the production of viscose rayon has shifted from Europe, the United States, and other developed countries to the Asia–Pacific regions due to high labor costs and stringent environmental regulations. The developing countries in the Asia–Pacific regions are now producing about 80 % of the global viscose production with China being the world's largest viscose fiber producer accounting for about 62 % of the global total in 2012. The production of viscose fiber in China rose very quickly from 2006–2012 at an average compound annual growth rate of 12.1 %, leading to production of 2.588 million tons in 2012 [1]. Viscose fibers produced in China are mainly distributed in East, North, and Northwest China. However, China needs to import other types of high-end regenerated cellulosic fibers such as Lyocell and modal fiber. In 2012, the world's largest manufacturer of viscose fiber was Aditya Birla Group with production capacity of 800,000 tons and plants in countries including India, Thailand, Indonesia, and China. The second largest manufacturer was Austrian Lenzing, producing 770,000 tons (2011) in the plants located in Austria, Indonesia, China, the United Kingdom, and the United States. Besides holding the second rank in viscose fiber production, this company occupies a monopolistic position in Lyocell and modal fiber production. Other large viscose fiber producers are mainly from China. In 2012, 77.3 % of total viscose fiber in China was produced by the top 10 viscose fiber producers. Fulida Group and Xinxiang Chemical Fiber and Grace Group are the largest staple and filament fiber manufacturers in China, respectively. Jilin Chemical Fiber is the largest bamboo fiber company in China, producing 48,000 tons/year and 7,000 tons/year of staple and filament fibers in 2012, respectively [1]. This company is trying to maintain their dominant position in the bamboo fiber market through expansion of bamboo pulp and bamboo staple fiber production capacity [1].

2 Properties of Regenerated Cellulosic Fibers

2.1 Viscose Rayon Fiber

In 1891, English scientists Cross and Bevan discovered viscose rayon fiber. Viscose fiber was previously called artificial silk, wood-silk, or viscose silk and officially named viscose rayon by the National Retail Dry Goods Association in 1924. Longitudinal and cross-sectional views of viscose fiber are shown in Fig. 1.

Viscose fiber possesses excellent aesthetic properties like silk fiber, good feel, and drape characteristics. Viscose shows similar properties to those of cotton or other cellulosic fibers due to the presence of cellulose backbone in their structure. However, viscose possesses higher moisture absorbency as compared to cotton. Breathability, softness, comfort, and ease in dyeing with glowing colors are the other favorable properties of viscose fibers [4–7].

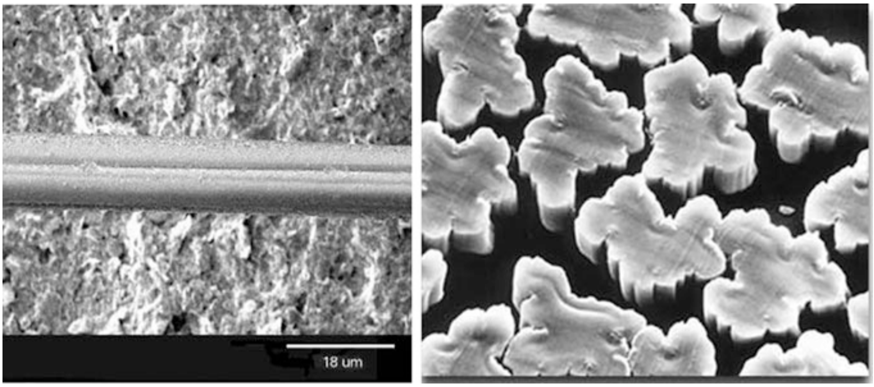


Fig. 1 Longitudinal and cross-sectional view of viscose fiber [2, 3]

Viscose rayon has good dry strength and abrasion resistance. However, it has poor resiliency and therefore, wrinkle formation is a problem. Its heat resistance is slightly less than that of cotton. To decrease cost or improve properties such as luster, softness, absorbency, and comfort, viscose is often used to blend with many other fibers.

The resistance of viscose rayon towards acids and alkalis is moderate and shows good resistance against bleaching agents and organic solvents. The burning characteristic of viscose fiber is similar to other cellulosic fibers [2, 5, 7, 8]. Physical properties of viscose fiber are listed in Table 1 and its chemical resistance is provided in Table 2.

2.2 Bamboo Viscose Fiber

Bamboo viscose fiber is produced from the cellulose obtained from the pulp of bamboo trees. Hebei Jiago Chemical Fiber Company in China grows most of the bamboo trees for production of bamboo viscose fiber. The Organic Crop Improvement Association (OCIA) has certified bamboo viscose fibers as organic fibers. Bamboo viscose is a 100 % cellulosic fiber obtained from natural resources and can degrade completely in soil through the action of microorganisms and sunshine, without causing any harmful effects to the environment. Figure 2 shows the cross-sectional and longitudinal views of the bamboo viscose fiber [9–14].

Bamboo viscose fiber possesses high breathability and coolness owing to the presence of numerous microlevel gaps and holes in its cross-section. This fiber presents good moisture absorption and ventilation properties [9, 11, 13]. The physical properties of bamboo viscose fiber are given in Table 3.

Table 1 Physical properties of viscose rayon [3]

Properties	Values
Tenacity (gram per denier)	
Dry	2.5–3.0
Wet	1.4–2.0
Breaking elongation (%)	
Dry	16–24
Wet	21–29
Recovery from stretch (2 %)	85 %, poor
Cross section	Serrated
Moisture regain (%)	11–14
Density (g/cc)	1.50

Table 2 Chemical properties of viscose rayon [3]

Chemical agents	Resistance
Acids	Damaged by strong acids and moderate effect with weak acids
Alkalis	Good resistance against weak alkalis but strong alkali is harmful
Bleaching agents	Strong oxidizing agents damage viscose rayon fiber
Organic solvents	Good
Mildew	Not good
Insects	Not good

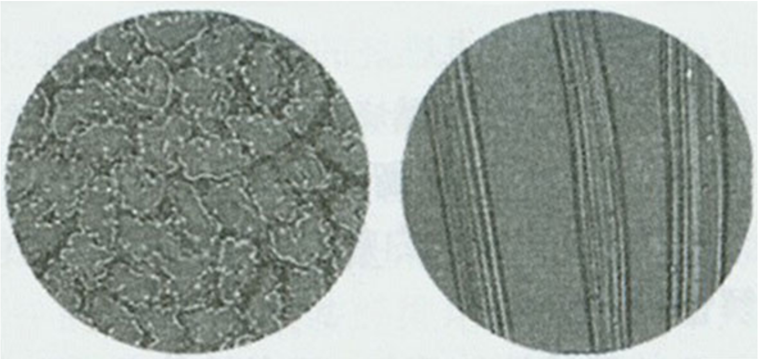


Fig. 2 Cross-sectional and longitudinal views of bamboo viscose fiber [13]

Table 3 Physical properties of bamboo viscose fiber [13]

Properties	Values
Tenacity (cN/tex)	
Dry	2.2–2.5
Wet	1.3–1.7
Dry breaking elongation (%)	14–18
Cross section	Serrated with microgaps and holes
Moisture absorbency rate %	90–120
Moisture regain (%)	13
Density (g/cc)	1.32

2.3 Cellulose Acetate Fiber

Cellulose acetate is one of oldest regenerated fibers produced from the cellulose derived from wood sources. Camille and Henry Dreyfus first developed the commercial process to produce cellulose acetate fiber in 1905 and the spinning of cellulose acetate fibers was commercialized in 1924 in the United States [15–17]. Over the other textile fibers, cellulose acetate presents some uncommon characteristics. This fiber possesses good luster and is softer than viscose and other textile fibers. Cellulose acetate has very good handle (soft, smooth, dry, crisp, and resilient) and comfort properties (breathes, wicks, dries quickly, and no static cling). Fabrics made from cellulose acetate also give very good handle characteristics and are easily dyeable to brilliant, soft, and attractive shades [15, 17, 19]. Figure 3 shows the longitudinal and cross-sectional views of cellulose acetate fiber and its physical properties are listed in Table 4. Table 5 presents the chemical properties of cellulose acetate fiber.

2.4 Cuprammonium Rayon Fiber

Cupromonium rayon is produced through regeneration of wood cellulose dissolved in a cuprammonium solution. To produce this fiber, cellulose is made soluble by combining it with copper and ammonia [20, 21]. The longitudinal and cross-sectional views of this fiber are shown in Fig. 4.

2.4.1 Properties of Cuprammonium Rayon

Cuprammonium fiber can be produced in extremely fine deniers (1.33 denier is produced regularly, whereas the common denier for viscose rayon is around 2.5) to obtain softness and handle characteristics similar to silk. The burning characteristics of this fiber are similar to viscose rayon; it burns rapidly and chars at 180 °C.

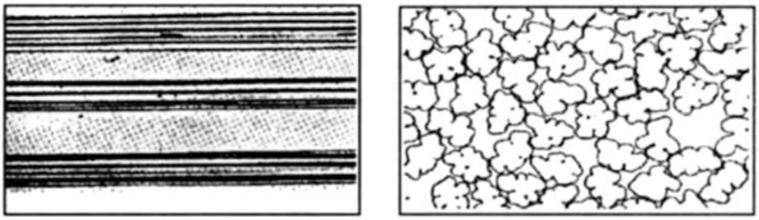


Fig. 3 Longitudinal and cross-sectional views of cellulose acetate fiber [18]

Table 4 Physical properties of cellulose acetate fiber [15]

Physical properties	Cellulose acetate
Tenacity (g/d))	0.9–1.4
Density (g/cc)	1.32
Elongation at break (%)	Very good
Elasticity	Not so good
Moisture regain (%)	6
Resiliency	Not good
Melting point	230 °C
Abrasion resistance	Moderate
Luster	Light to bright

Table 5 Chemical properties of cellulose acetate fiber [15]

Chemical/biological agents	Resistance
Acids	Soluble
Alkalis	Strong alkali damages and weak alkali also damages slightly
Bleaching agents	Strong oxidized agents will damage but it has strong resistance against weak oxidizing and reducing agents
Organic solvents	Soluble in acetone. Dry cleaning agents do not affect cellulose acetate
Mildew	Good
Insects	Good

Ashes produced from this fiber after ignition contain copper. Degradation and weakening occur due to exposure to sunlight in the presence of oxygen and moisture. Tensile strength of the fiber is in the range of 1.7–2.3 g/d in the dry state and 0.9–2.5 g/d in the wet state. The elongation at break in the dry state is 10–17 % and moisture regain at 70 °F and at 65 % RH is 11 %. The fiber has a round and smooth cross-section or occasionally slightly oval [23].

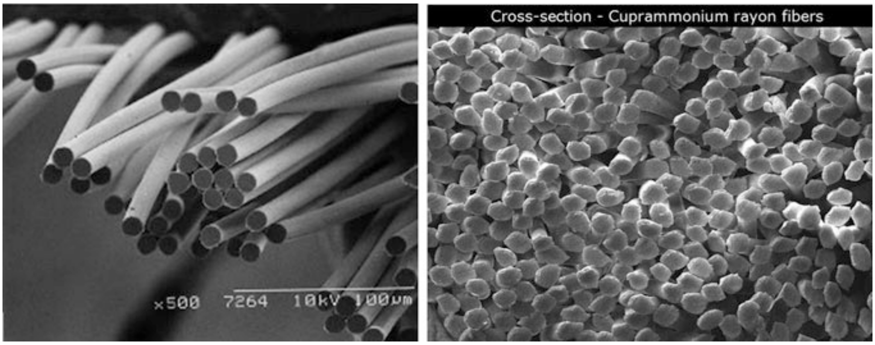


Fig. 4 Longitudinal and cross-section views of cuprammonium rayon fiber [22]

2.5 Lyocell Fiber

Lyocell (trade name, Tencel®) is the first new-generation cellulosic fiber spun using solvent spinning technology. The demand for an environmentally favorable process of producing fibers from renewable raw materials led to the development of Lyocell technology. This fiber was produced first in 1984 and on a commercial scale in 1988 [24–30].

Lyocell fiber is completely biodegradable. It possesses good moisture absorbency. Unlike viscose, Lyocell fiber presents high strength in both wet and dry conditions. This fiber can be easily blended with other fibers such as linen, wool, and cotton. Fibrillation of Lyocell fiber occurs when it is abraded in the wet state leading to formation of surface fibrils. These surface fibrils remain attached to the fibers, but peel away from the fiber surface producing an eye-catching aesthetic appearance. The longitudinal and cross-sectional views of Lyocell fiber are shown in Fig. 5.

The advantageous features of fabrics made from Lyocell fiber are wrinkle resistance (due to high modulus), good stability to washing, dyeability to vibrant colors with a variety of effects and textures, and good drapeability [24, 26]. The basic physical properties of Lyocell fibers are listed in Table 6 and compared with other textile fibers.

2.6 SeaCell Fiber

SeaCell fiber (see Fig. 6) is a third-generation regenerated cellulosic fiber. This fiber is produced using an innovative Lyocell technique, in which seaweed containing vitamins, minerals, and trace elements are added to the cellulose pulp before the spinning process. As a result, the produced fiber provides health-promoting and skincare effects. Commonly, SeaCell fibers are produced from cellulose either adding only seaweed (SeaCell® pure) or adding both seaweed and silver (SeaCell® active) [31, 32].

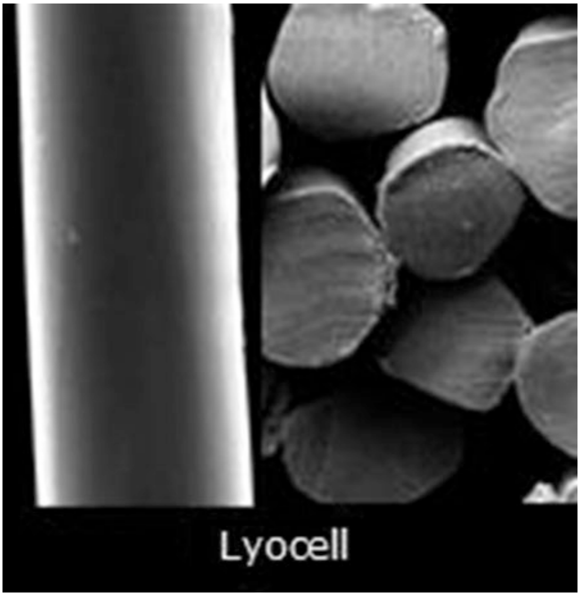


Fig. 5 Longitudinal and cross-sectional views of Lyocell fiber

Table 6 Physical properties of Lyocell fiber [24]

Property	Tencel	Viscose	Cotton	Polyester
Fiber fineness (dtex)	1.7	1.7	–	1.7
Dry tenacity (cN/tex)	38–42	22–26	20–24	55–60
Dry elongation (%)	14–16	20–25	7–9	25–30
Wet tenacity (cN/tex)	34–38	10–15	26–30	54–58
Wet elongation (%)	16–18	25–30	12–14	25–30

Fig. 6 Roving of Seacell fiber [33]

Seacell fiber possesses softness and breathability, providing a pleasant feeling of well-being. SeaCell® active is suitable for medical textiles due to its antibacterial and fungicidal properties. SeaCell fiber can be easily blended with synthetic and natural fibers and it is most suited for application in underwear and childcare textiles [31]. The physical properties of Seacell fiber are provided in Table 7.

2.7 Modal Fiber

Modal fiber is produced through regeneration of cellulose obtained from the pure wood pulp of beech trees. Unlike viscose rayon, which can be produced from the wood pulp of different trees, the wood pulp obtained from beech wood is the only source of cellulose for the production of modal fiber. Therefore, modal is a type of viscose rayon fiber. This fiber possesses high tenacity and high wet modulus [34, 35]. Figure 7 shows the longitudinal and cross-section views of modal fiber. Modal fiber has a higher wet modulus and lower elongation compared to viscose rayon due to its higher degree of polymerization. This fiber possesses a silk-like texture (luster, shine, and gloss) and smoother surface than mercerized cotton [37–39]. Physical properties of modal fiber are provided in Table 8 and compared with viscose rayon fiber.

3 Production Process of Regenerated Cellulosic Fibers

3.1 Production Process of Viscose Rayon

Cellulose extracted from some varieties of trees such as spruce, pine, and hemlock is the raw material for producing viscose rayon fiber. The manufacturing steps of viscose rayon fiber are as follows [5–8].

3.1.1 Cellulose Purification

First, cellulose extracted from trees is purified. For this purpose, the bark of spruce or other trees is removed and after cutting into small pieces treated with a solution of calcium bi-sulphite in steam under pressure for about 14 h. This treatment removes the lignin present in the wood by converting it into water-soluble sulphonated compounds, without affecting the cellulosic part of the wood. Purified cellulose is then obtained after washing with water and subsequently, purified cellulose is bleached using sodium hypochlorite. It is then converted into paper boards or sheets, known as wood pulp, which is usually purchased by the manufacturers for producing viscose rayon.

Table 7 Physical properties of Seacell fiber [31]

Properties	SeaCell fiber
Fiber fineness (dtex)	1.7
Strength (cN/tex)	≥35
Wet strength (cN/tex)	≥30
Elongation (%)	13
Dry elongation (%)	17
Wet modulus (cN/tex)	≥180

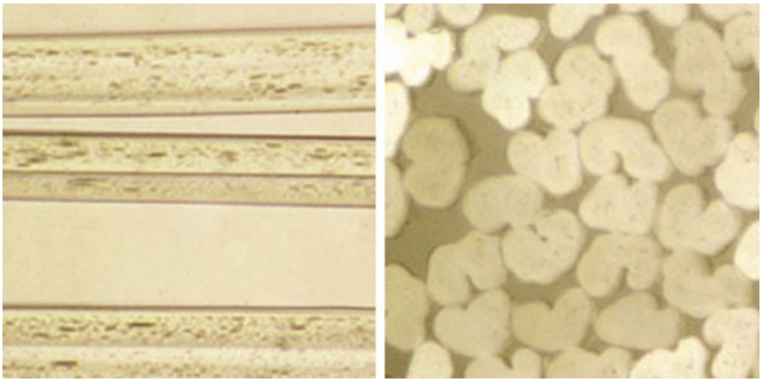


Fig. 7 Longitudinal and cross-section of modal fiber (1.3dtex) [36]

Table 8 Comparison of physical properties of modal and viscose rayon fiber [38]

Properties	Modal fiber	Viscose rayon
Fiber density (g/cm^3)	1.53	1.51
Tenacity (g/d)		
Dry	2.2–4.0	1.2–3.0
Wet	3.8–5.0	0.5–0.8
Breaking elongation (%)		
Dry	7.0	15–30
Wet	8.5	30
Moisture regain (%)	11.8	12.5

3.1.2 Conditioning of Wood Pulp

After purification, the desired moisture is added to the wood pulp by keeping it in a conditioning room with good air circulation and temperature maintained at 30 °C.

3.1.3 Steeping Process

The conditioned wood pulp is next subjected to the steeping process, that is, treated with 17.5 % caustic soda solution to convert cellulose into soda cellulose. The wood pulp sheets are allowed to soak for about 1–14 h until the color turns dark brown. The sheets are then pressed to remove excess NaOH solution. 310 kg of soda cellulose is obtained from 100 kg of sulphated pulp.

3.1.4 Cutting or Shredding Process

A shredding machine is then used to cut the wet and soft sheets of soda cellulose into small bits and subsequently break into fine crumbs during a time period of around 2–3 h.

3.1.5 Ageing Process

Soda cellulose is then subjected to the ageing process which decreases the degree of polymerization of soda cellulose from 1,000 to 300. This is done by storing the soda cellulose in small galvanized drums for about 48 h at 28 °C. The degree of polymerization decreases due to the oxygen present in the air contained in the drum.

3.1.6 Xanthation or Churning Process

Sodium cellulose xanthate is then formed by treating the soda cellulose crumbs with carbon disulphide (10 % by weight of the crumbs) in air-tight hexagonal mixers rotating at a speed of 2 rpm for 3 h. After this process, the colors of the product turn from white to reddish orange.

3.1.7 Mixing or Dissolving Process

Sodium cellulose xanthate is then mixed with caustic soda and stirred for 4–5 h in a dissolver. Cooling of the dissolver is also carried out. A clear brown thick liquor like honey is formed after dissolution of soda cellulose xanthate. This liquor, called viscose, contains about 6.5 % caustic soda and 7.5 % cellulose.

3.1.8 Ripening Process

In the ripening process, the viscose solution is stored for 4–5 days at 10–18 °C and this results in an initial decrease in viscosity and subsequent rise to the original value. The ripened viscose solution is then filtered carefully before spinning the filaments.

3.1.9 Spinning Process

The viscose solution is forced through the fine holes (diameter around 0.05–0.1 mm) of a spinneret immersed in a solution containing the following chemicals.

Sulfuric acid	10 %
Sodium sulphate	18 %
Zinc sulphate	1 %
Glucose	2 %
Water	69 %

The spinning solution temperature is maintained at 40–45 °C. The dissolved sodium cellulose xanthate precipitates out due to the presence of sodium sulphate in the coagulation bath and sulfuric acid converts the xanthate into cellulose, carbon disulphide, and sodium sulphate. The function of glucose present in the coagulation bath is to provide softness and pliability to the filaments whereas zinc sulphate is responsible for giving added strength. The manufacturing process of viscose rayon is presented in Fig. 8.

3.2 Production Process of Acetate Rayon

In the production of cellulose acetate [15, 17, 41], cellulose is treated with acetic acid to convert the free hydroxyl groups of cellulose into ester groups. This is then dissolved in acetone or chloroform and spun into fibers through evaporation of the solvent. Therefore, cellulose acetate is a regenerated as well as a modified cellulosic fiber unlike viscose and cuprammonium rayon which are pure regenerated cellulosic fibers.

3.2.1 Acetylation Process

Acetylation of purified cellulose pulp is carried out in a metal tank (acetylator) by treating it with a mixture of glacial acetic acid, acetic anhydride, and a small amount of concentrated sulfuric acid. 100 kg of cotton linters is treated with 300 kg of glacial acetic acid, 500 kg of acetic anhydride and 8–10 kg of concentrated sulfuric acid at 25–30 °C for 7–8 h by mixing thoroughly with the help of a stirrer with rotating blades. As the acetylation reaction is an exothermic reaction, it is favored by removing heat through circulation of cold water through a jacket surrounding the acetylator (see Fig. 9). The acetylation process leads to the formation of triacetate in the form of a suspension and is called the acid dope.

The acid dope is then stored in jars containing sulfuric acid, acetic acid, and water for 10–20 h to carry out the ripening process. This process partially converts the

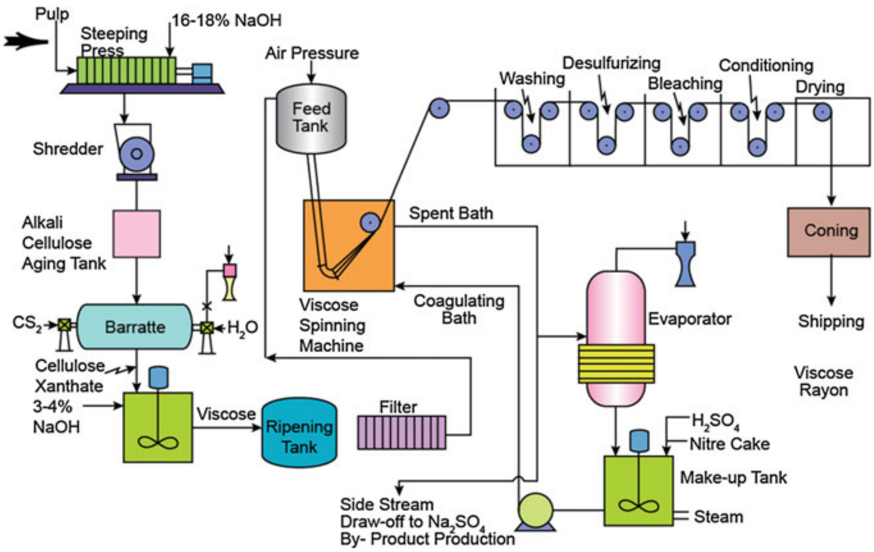


Fig. 8 Schematic diagram of the manufacturing process of viscose rayon fiber [40]

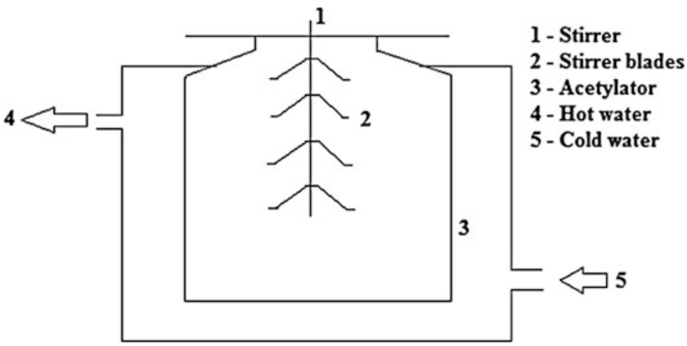


Fig. 9 Schematic diagram of acetylator [17]

acetate groups of cellulose acetate into hydroxyl groups. White flakes of cellulose acetate are then precipitated out as a result of water addition and continuous stirring. The cellulose acetate flakes are then dried after centrifuging the excess water.

3.2.2 Preparation of Spinning Solution

The dried acetate flakes are then slowly dissolved into acetone (ratio of cellulose acetate to acetone is 1:3) in enclosed tanks with the help of an intensive stirring process for 24 h. A thick clear dope is obtained and this is next filtered and deaerated.

3.2.3 Spinning Process

A dry spinning process is used to spin acetate rayon filaments. After the spinneret, the filaments are formed due to evaporation of solvents. The filaments travel a distance of 2–5 m vertically downwards to a feed roller and then pass over a guide roller to the bobbin at much higher speed than the spinning speed, in order to draw the filaments to some extent. The manufacturing process of cellulose acetate fiber is shown in Fig. 10.

3.3 Production Process of Cuprammonium Rayon

Similar to other cellulosic fibers, cotton linters are also the raw material for cuprammonium rayon [43]. Cotton linters are first purified using the following treatments: (a) mechanical treatment and (b) chemical treatment.

3.3.1 Mechanical Treatment of Cotton Linters

Mechanical treatment of cotton linters is carried out to open and remove the mechanically attached and loosely bound impurities such as dust, sand, seed residues, and so on.

3.3.2 Chemical Treatment of Cotton Linters

In the chemical treatment, Na_2CO_3 (soda ash) solution (2 %) and a small amount of dilute caustic soda are added to cotton linters and boiled under pressure for several hours. The fatty acids present in the cotton linters are converted to soluble substances due to reaction with soda ash and are removed.

3.3.3 Dissolution of Cellulose

In this process, 300–400 L of water is mixed with a solution of hydrated copper sulphate, a small amount of sugar, and caustic soda solution in a vessel at room temperature with stirring. Copper hydroxide is formed due to the reaction of copper sulphate and caustic soda. Copper cellulose is then formed through addition of ground cotton linters to the above mixture and filtered to remove the liquid. Copper cellulose is then dissolved in a solution of ammonia in water.

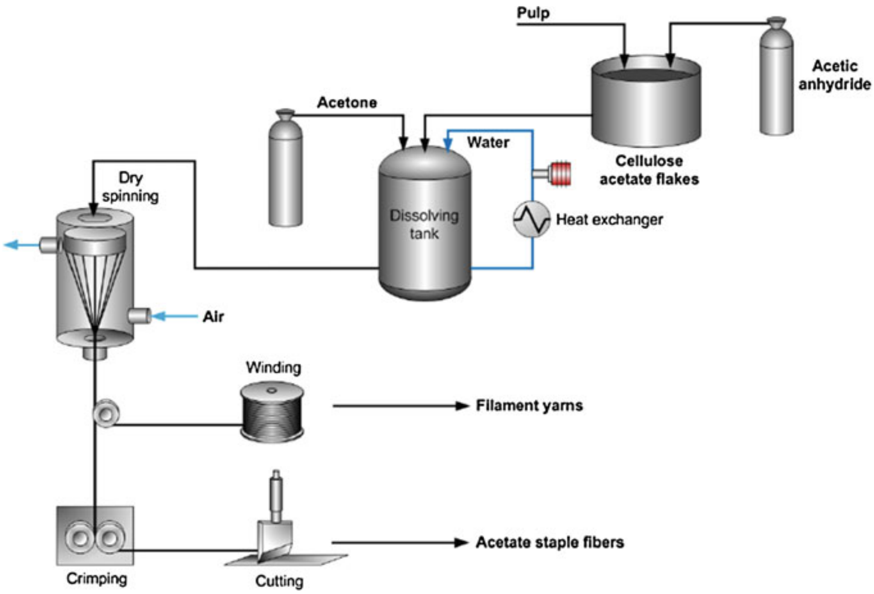


Fig. 10 Schematic diagram of acetate rayon manufacturing process [42]

3.3.4 Spinning Solution

To prepare a dope suitable for the spinning process, a few compounds are added to the cuprammonium solution such as glycerin, glucose, tartaric acid, citric acid, oxalic acid, cane sugar, and so on.

3.3.5 Wet Spinning

The spinning dope is discharged through the spinneret holes into the coagulation bath containing H_2SO_4 and this leads to formation of relatively thick filaments, which are subsequently stretched to reduce the fineness. Figure 11 shows the flowchart of the manufacturing process of cuprammonium rayon.

3.4 Production Process of Lyocell Fiber

In the Lyocell process, cellulose is dissolved in hot aqueous NMMO (N-Methylmorpholine-N-Oxide) solution due to the formation of hydrogen bonds between cellulose and polar NMMO. Subsequent addition of NMMO and removal of water results in a maximum cellulose concentration of about 23 %. The resulting solution is highly viscous, similar to lye (a liquid from wood ashes), and therefore this process and fibers produced are called Lyocell (i.e., lye of cellulose).

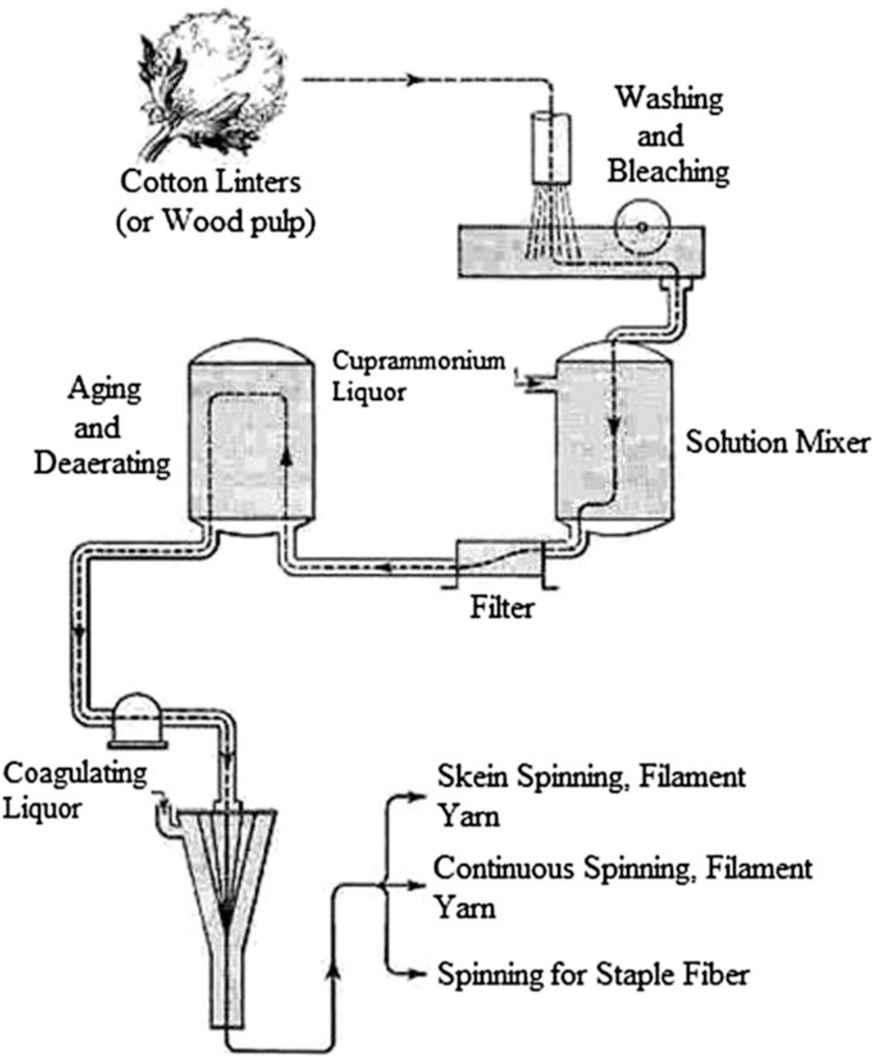


Fig. 11 Schematic diagram of manufacturing process of cuprammonium rayon fiber [44]

The spinning dope is extruded through a spinneret at high temperature which helps in easy extrusion through the decrease in viscosity of the spinning dope. Coagulation of extruded filaments is carried out in water. The produced fibers are then washed thoroughly to remove NMMO and dried. NMMO can be recovered up to 99.6 % after the spinning process. The Lyocell process allows the highest solvent recovery among all cellulosic fiber spinning processes [24–26]. The flowchart of Lyocell spinning process is provided in Fig. 12.

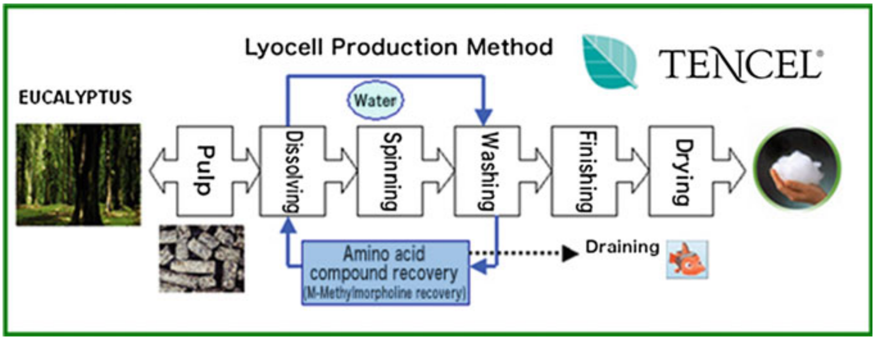


Fig. 12 Schematic diagram of the manufacturing process of Lyocell fiber [45]

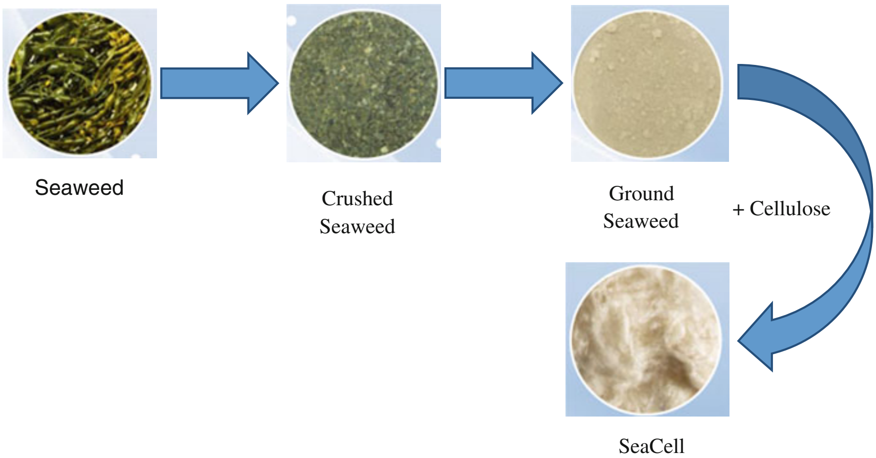


Fig. 13 Flowchart of seaweed extraction process for SeaCell fiber production [31]

3.5 Production Process of SeaCell Fiber

In the production of SeaCell fiber, cellulose pulp and seaweed are mixed together and spun into SeaCell fibers using the Lyocell production process [31]. Seaweed is extracted from the seaweed sources as follows (Fig. 13).

3.6 Production Process of Modal Fiber

Wet spinning is used to produce modal fibers. Due to the use of many chemicals in the spinning of modal fibers, this fiber can be called a biobased fiber instead of a natural fiber. Except for a few steps, the production process is similar to that of viscose rayon fiber [46].

3.6.1 Steeping and Pressing

In the steeping process, cellulose is converted to its alkoxide derivative (known as alkcell). For this purpose, cellulose pulp is treated with an aqueous solution of 17 % sodium hydroxide and this treatment results in the swelling of cellulose and conversion into sodium cellulosate. Then extra caustic soda is removed from the alkcell slurry by pressing.

3.6.2 Shredding

Alkcell contains 30–36 % cellulose and 13–17 % soda. Alkcell slurry is then opened through a shredding process, in order to facilitate the penetration of oxygen and CS_2 in the subsequent mercerizing and xanthation reactions.

3.6.3 Mercerizing or Ageing

After the shredding process, oxidative or irradiative depolymerization of cellulose is carried out in order to decrease the degree of polymerization.

3.6.4 Xanthation

The reaction of mercerized alkcell and CS_2 vapor is carried out under vacuum in order to form sodium cellulose xanthate. Sodium cellulose xanthate is then dissolved in a dilute NaOH solution to obtain the spinning dope.

3.6.5 Filtration and Deaeration

Before spinning, impurities present in the spinning solution are removed in order to prevent the choking of spinneret holes. The use of automatic mechanical filters of sintered metal screens with automatic backflush is a commonly used method. Subsequently, vacuum is applied to remove any dispersed air forming bubbles.

3.6.6 Spinning

In the modal fiber spinning, zinc is not used in the spinning bath as used in viscose rayon and coagulation is carried out in a cold low-acid–low-salt bath for only a short period. The process steps for wet spinning of modal fibers are shown in Fig. 14.

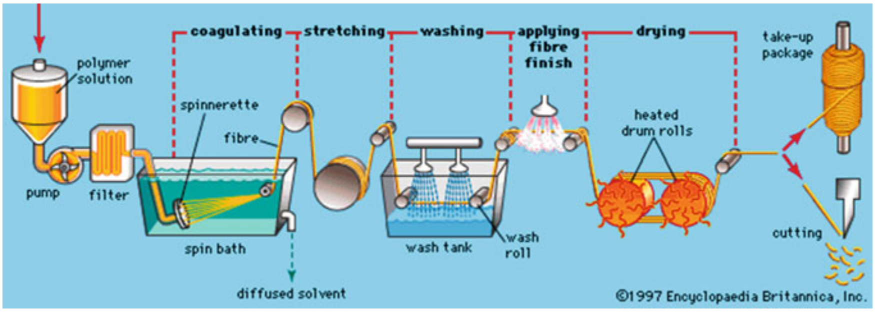


Fig. 14 Process steps for wet spinning process of modal fiber [47]

3.6.7 Coagulation

In the modal process, coagulation and stretching are done simultaneously before regeneration and this results in the formation of very high wet modulus fibers. Before regeneration, the filaments are drawn three times of their spun length leading to formation of a fibrillar fiber structure. The very high dry and wet modulus of modal fiber result from this stretching process which orients the cellulose molecules to a very high degree.

4 Impact of Production Process on Sustainability of Regenerated Cellulosic Fibers

4.1 Viscose Fiber

Viscose fiber is the first fiber developed in the family of regenerated cellulosic fiber. The important sustainability aspects of viscose fiber are as follows [48].

- The trees (such as pine, beech, etc.) from which the raw materials of viscose fiber are collected are replenishable. These trees usually grow using rainwater and therefore do not need any other type of water supply. Land used for these forests is specific and their use does not cause any environmental impact [48].
- Spinning of viscose fibers from wood pulp uses many chemicals, such as caustic soda, carbon disulphide (CS_2), sulfuric acid, sodium sulphate, and zinc sulphate. A high amount of caustic soda is used in the processing of viscose fiber and sodium sulphate is produced as a by-product. Nowadays, it possible to recycle and reuse up to 70 % of CS_2 and the remaining 30 % is converted into sulfuric acid which is also recycled by the process [48]. The main sustainability concern in the fiber production stage is the consumption of energy and the use of fossil fuel in fiber production as well as in the production of various chemicals including caustic soda, sulphur, and NaOCl. The lifecycle of viscose

Fig. 15 Lifecycle for viscose fiber [49]

fiber is shown in Fig. 15. The factors influencing the sustainability of cellulose acetate, cupramonium rayon, and modal fiber are more or less similar.

4.2 Bamboo Viscose Fiber

Bamboo viscose is regenerated fiber produced from the cellulose of bamboo trees through the viscose production process. The production of bamboo viscose is considered to be sustainable [50] because:

- No pesticides or chemical fertilizers are required for the growth of bamboo trees.
- Bamboo trees grow using rainwater and irrigation is not necessary.
- Replanting of bamboo trees is seldom required.
- The growth of bamboo trees is fast and harvesting can be done in 3–5 years.
- Oxygen production in the case of bamboo trees is 35 % more as compared to an equivalent stand of trees.

- Bamboo trees are therefore very important in terms of balancing oxygen and carbon dioxide in the atmosphere.
- Bamboo trees can provide very good protection against soil erosion.

The production of bamboo viscose is mostly a closed-loop system, in which NaOH used in the spinning process is recycled completely and also 74 % of CS_2 is recovered and recycled for further use. The use of caustic soda is approved for use in textiles under the GOTS as this chemical does not cause any harm if used and disposed of properly.

4.3 Lyocell Fiber

Significant environmental benefits and sustainability are the important advantages of Lyocell fibers [24]. The reasons behind the sustainability of Lyocell fiber are:

- Lyocell fiber is produced using raw material which is renewable. The trees from which the cellulose pulp is extracted are always replenished.
- Complete recycling of solvents (with very little loss) used in the production process of Lyocell fiber.
- Lyocell fiber is biodegradable.

The simplified lifecycle of Lyocell fibers, from the raw material to product disposal stage is shown in Fig. 16.

- Raw material for fiber production is wood pulp, extracted from trees grown in managed forests; that is, a reforestation process will be carried out after the deforestation.
- A very simple production step in which wood pulp is dissolved directly in a solvent (NMMO) and formed into fibers. Solvent is recovered almost completely (99.96 %.) and there are no chemical by-products.
- Lyocell fibers find widespread textile and industrial applications with significant environmental benefits during product manufacturing and use.
- At the end of the lifecycle, Lyocell fiber products are biodegradable and the biodegradation process contributes to photosynthesis and hence to the growth of new trees for future Lyocell production [24].

4.4 SeaCell Fiber

Some important sustainability aspects of Seacell fiber are:

- The raw material is wood pulp that comes from recycled or waste wood, and seaweed extracted from marine environments causing no harmful effects to the wildlife.

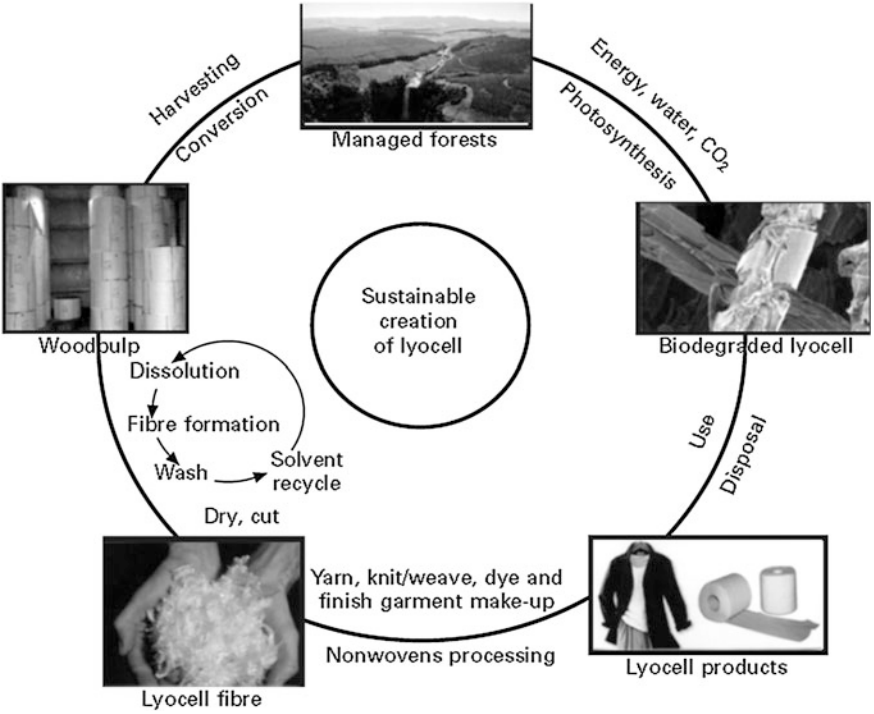


Fig. 16 Lyocell sustainability [24]

- It is biodegradable fiber.
- This fiber has good prospects for application in underwear or gym clothes due to its breathability and capability to pass nutrients into the skin [51].

5 Applications of Regenerated Cellulosic Fibers

5.1 Applications of Viscose Fiber

Apparel: Accessories, blouses, dresses, jackets, lingerie, linings, millinery, slacks, sport shirts, sportswear, suits, ties, work clothes [5–8].

Home Furnishings: Bedspreads, blankets, curtains, draperies, sheets, slipcovers, tablecloths, upholstery.

Industrial Uses: Industrial products, medical surgical products, nonwoven products, tire cord.

Other Uses: Feminine hygiene products.

5.2 Application of Bamboo Viscose

Bamboo intimate apparel: Used in sweaters, bathing suits, mats, blankets, and towels due to comfortable hand, special luster, bright colors, and good water absorbance. Due to antibacterial activities, it is used in underwear, tights, T-shirts, and socks. Owing to its antiultraviolet nature, it is used in summer clothing, especially for the protection of pregnant ladies and young children from the damages of ultraviolet radiation [11, 13].

Bamboo nonwoven fabric: It is used in the field of hygiene materials such as sanitary napkins, masks, mattresses, and food packing bags due to its antibacterial nature.

Bamboo sanitary materials: Used in sanitary materials such as sanitary towels, gauze masks, absorbent pads, bandages, surgical clothes, nurse's wear, and so on, due to its natural effect of sterilization and bacteria stasis.

Bamboo bathroom series: Due to good moisture absorption, soft feel, splendid colors as well as antibacterial characteristics, it is used in towels and bathrobes.

Bamboo decorating series: Used in wallpapers and curtains that can absorb ultraviolet radiation in various wavelengths, resulting in less harm to the human body. Also used in television covers, sofa slipcovers, and so on.

5.3 Applications of Acetate Fiber

- Used to produce different types of clothing such as women's night wear and formal wear, coats, accessories for Japanese dresses, blouses, sweaters, scarves, and so on [15, 17].
- Used to produce home furnishing and bedding products such as blankets, bed clothes, fabrics for curtains, and so on.
- Used for making umbrella fabrics and cigarette filters.

5.4 Applications of Cuprammonium Rayon Fiber

- For clothing [37].
  A variety of fabrics for women's wear, blouses, underwear, Japanese dresses, linings, accessories for Japanese dresses, scarves, and so on.
- For home furnishings and bedding.
  Curtain, bedclothes, cover cloths for mats, and so on.
- For other uses.
  Square cloth for wrapping things, umbrellas, and so on.

5.5 Applications of Lyocell Fiber

- Used to produce home textile products. The fiber is used in sleeping products such as mattresses, mattress pads, bed covers, and linens. It is also used to make botanic beds [24–26].
- Staple fibers are used to produce a variety of apparel such as denim, chino, underwear, casual wear, and towels.
- Filament fibers are used in items with silk-like appearance such as women's clothing and men's dress shirts.
- Used in conveyor belts, specialty papers, and medical dressings.

5.6 Applications of Seacell Fiber

- In blends with other fibers, Seacell fiber is used as knitted, woven, or nonwoven fabrics with excellent softness and breathability in sportswear and yoga attire as well as in sheets, towels, blankets, and baby clothing [31].
- Used by various activewear manufactures such as Lululemon, Orca triathlete outfitters, Adea yoga clothing and sleepwear, and Falke socks and hosiery.

5.7 Applications of Modal Fiber

Modal fiber is widely used in clothing as a replacement for cotton and may also be used in blends with cotton, wool, and other synthetic fibers such as spandex, and the like [52].

- Used for both clothing and household textiles.
- Used for tablecloths and bedding, bathrobes, upholstery, and in home furnishings. Also used in outerwear, sportswear, and leisurewear.
- Applications in undergarments and toweling purposes.
- Lenzing modal is used exclusively for soft flowing tops and lingerie; exclusively in knitwear markets having high-end apparel/nonapparel products.
- For socks and stockings, as well as in technical applications, such as tire cord, abrasive ground fabric, rubber cloths, and other coat supports.

6 Sustainability Studies on Regenerated Cellulosic Fibers: Environmental Impact Assessment

A few studies have been conducted to investigate the impacts of regenerated cellulosic fibers on sustainability. The environmental impact of these fibers has been assessed using the lifecycle assessment (LCA) tool. In one of these important studies, regenerated cellulosic fibers produced from Lenzing AG, which accounts for 1/5th of world's total regenerated cellulosic fiber production, were studied using LCA, and the environmental impact of these fibers has been compared with those of commonly used natural and synthetic fibers [53, 54]. All steps starting from the extraction of raw materials and fuels, followed by all conversion steps until the delivery of the staple fiber to the factory gate were considered. The details of fiber used for this LCA study are provided in Table 9.

6.1 Sustainability Parameters

The various sustainability factors considered were the use of energy, land, and water and CML impact factors such as global warming potential, abiotic depletion, ozone layer depletion, human toxicity, freshwater aquatic ecotoxicity and terrestrial ecotoxicity, acidification, photochemical oxidant formation, and eutrophication. To assess energy use, cumulative energy demand (CED), nonrenewable energy use (NREU), and renewable energy use (REU) were considered. CED is the cradle-to-factory gate primary energy, that is, energy found in its original or natural form, and is the sum of NREU (total of fossil fuel such as oil/gas/coal and nuclear energy from uranium) and REU (biomass, solar, hydro, and wind energy). In land use, only biomass production (agricultural and forest) was considered and other forms of land use such as for infrastructure (for fiber plant or a spinning factory) and transportation were not considered [56–58].

In the case of water use, the sum of original natural freshwater consumption in the form of process water, cooling water, and irrigation water was considered. These three types of water can have different energy requirements and environmental impacts. In the environmental impact categories, global warming potential (GWP), abiotic depletion, ozone layer depletion, human toxicity, freshwater aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidant formation, acidification, and eutrophication were studied. The results obtained from this study were also normalized to determine the relative contribution of the impact of the selected product systems to the total environmental loads of that region in a one-year time period [59–62].

Table 9 Types and geographic scope of regenerated cellulose, cotton, PET, and PP fibers used in the LCA study [55]

Regenerated Cellulose Fiber					
Fibers used	Trade Name (Fiber type)	Wood	Pulp	Fiber plant	Process energy
Viscose (Asia)	Lenzing viscose	Eucalyptus	Market pulp	Asia	Local electricity, coal, gas, oil
Viscose (Austria)	Lenzing viscose	European Beech	Integrated pulp and fiber production in Austria		Biomass, recovered energy from MSWI
Modal	Modal (modal)				
Tencel	Tencel (Lyocell)	Eucalyptus and Beech	Mixed Lenzing pulp and market pulp	Austria	70 % gas, 30 % biomass
Tencel (2012)	Tencel (Lyocell)				100 % recovered energy from MSWI

Commodity Fibers			
Fibers used	Type	Geographic scope	Data source
Cotton	Natural fiber	US and CN	Literature data
PET	Polyester	Western Europe	
PP	Polyolefin	Western Europe	

6.1.1 Energy, Water, and Land Use

Energy requirements of the studied fibers are presented in Fig. 17. It can be noticed that NREU of all cellulose-based fibers is lower than PET and PP fibers. The lowest NREU can be observed in the case of viscose (Austria), whereas PET presented the highest NREU. Among the cellulosic fibers, viscose (Asia) showed 70 % more energy requirement than cotton, and Tencel also had a slightly higher NREU. On the contrary, modal, Tencel (2012), and viscose (Austria) required 30, 40, and 50 % less energy as compared to cotton, respectively.

Viscose (Asia) required relatively higher NREU as compared to cotton and regenerated cellulosic fibers due to the use of relatively inefficient coal-based heat and power production (Fig. 18). Fossil fuel use in fiber production was the most important factor influencing the energy requirements of various fibers. However, energy use in the production of chemicals used in the manufacturing process of regenerated cellulosic fibers was also an important factor. In the case of viscose (Austria) and modal, the process energy from fossil fuels did not have such a significant influence unlike the energy required for caustic soda production which accounted for more than half of the NREU (Fig. 18). Production of other chemicals such as sulphur, CS_2, and NaOCl (sodium hypochlorite) also had a significant contribution to energy use. The Lyocell process, however, involves a much lower use of chemicals as compared to viscose rayon. The use of natural gas contributed

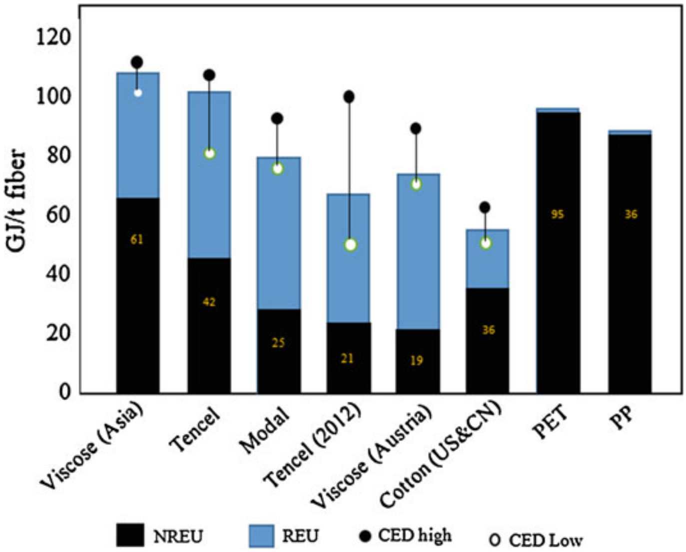


Fig. 17 Cradle-to-factory gate primary energy requirements (NREU, REU, and CED) of one tonne of staple fiber (default allocation method for by-products) [55]

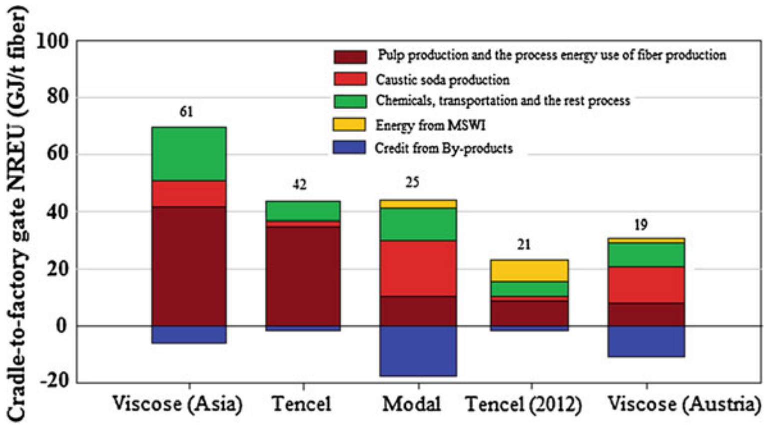


Fig. 18 Breakdown of cradle-to-factory gate NREU of regenerated cellulosic fibers (default allocation methods for by-products) [55]

more than 70 % of the total NREU of current Tencel fiber. However, the NREU of Tencel (2012) decreased by half (from 42 to 21 GJ/t) because the energy recovered from external municipal solid waste incineration (MSWI) was used to supply the process energy (Fig. 18). It can also be noticed that the REU for the regenerated cellulosic fibers was significantly higher than that of cotton, PET, and PP owing to the use of renewable feedstock and also due to the use of a large amount of biomass energy in the production.

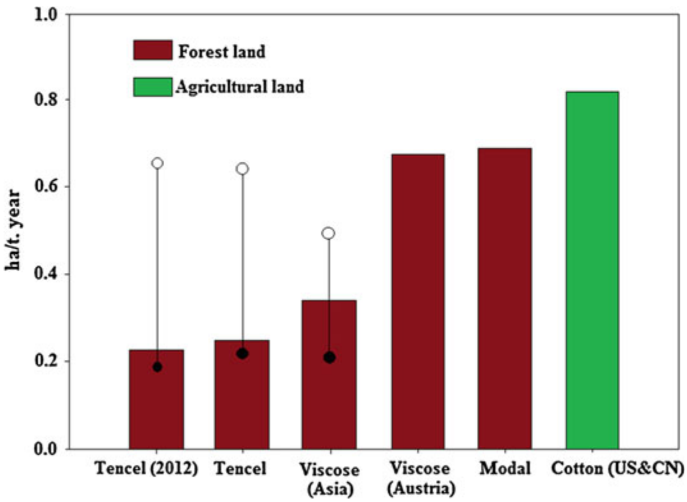


Fig. 19 Land use for biomass production for one tonne of staple fiber (economic allocation for by-products) [55]

Table 10 Water use for one tonne of staple fiber, based on natural water origin (m^3 per tonne of fiber, default allocation method for by-products) [55]

Type	Fiber	Process water	Cooling water	Irrigation water
Petrochemical fiber	PP (W. Europe)	<2	74	–
	PET (W. Europe)	<5	125	–
Regenerated cellulosic fiber	Viscose (Asia)	11	308	–
	Tencel (2012)	20	243	–
	Tencel	20	243	–
	Viscose (Austria)	42	403	–
	Modal	43	429	–
Cotton	Cotton (US and CN)	<5	37	5690 (4300–6860)[a]

[a] The lower range represents average US cotton; the higher range represents average Chinese cotton

It can be observed from Fig. 19 that the land requirement for cellulose fibers produced based on European wood was higher than those produced based on eucalyptus wood grown in warmer regions. This was because the forestry biomass yields in Europe are much lower than those of warmer regions. As MSWI was used as the source of process heat in the case of Tencel (2012) instead of biomass, the land use for this fiber was lower than Tencel fiber. However, among the studied fibers, cotton showed the maximum land use, mainly agricultural land.

It is clear from Table 10 that 90–90 % of the total water used in the case of cellulosic fibers is the cooling water. Processed water which includes softened water, deionized water, decarbonized water, and tapwater accounts for the rest, 5–10 %. It is interesting to note that water use in the case of cotton is significantly higher than that of regenerated cellulosic fibers; excluding cooling water, 100–500 times more water is consumed in the case of cotton and including cooling water, the consumption is about 10–20 times higher. Water is used mainly for the irrigation of cotton and for the average Chinese and US cotton, groundwater supplies about 70 % of the irrigation water and the rest (30 %) is supplied by surface water. Among the different forms of water use, irrigation water has strong environmental impacts as it may lead to freshwater resource depletion, soil salination, and water shortage downstream of the river.

6.1.2 Global Warming Potential

It can be seen from Fig. 20 that all regenerated cellulosic fibers have lower global warming potential as compared to polyester fibers. Except for viscose (Asia), other regenerated cellulosic fibers have very low GWP, nearly zero for modal and Tencel (2012), and negative for viscose (Austria). The negative GWP in case of viscose (Austria) indicates that it takes more carbon dioxide from the environment than it emits. The contribution of the process to the GWP for one tonne of regenerated cellulosic fibers is shown in Fig. 21.

For viscose (Asia), the factors responsible for its total carbon emissions are the market pulp, process heat, and power used in fiber production and also production of caustic soda and other chemicals, whereas for viscose (Austria) and modal, production of caustic soda is the most important factor and is responsible for more than 50 % of the total fossil carbon emissions. The avoided fossil carbon emissions from the by-products (especially Na_2SO_4 and acetic acid) are the primary reason for low GWP in the case of modal fiber. In the case of Tencel, combustion of natural gas for process heat accounts for more than 50 % of fossil carbon emissions. The use of an alternative energy source in the case of Tencel (2012) results in 90 % lower GWP as compared to Tencel which uses natural gas.

6.1.3 Abiotic Depletion

According to Table 11, among the regenerated cellulosic fibers, the highest impact on abiotic depletion is shown by viscose (Asia), whereas Tencel (2012) shows the lowest impact. The impact of the synthetic fibers, PET and PP, are higher than cotton and regenerated cellulosic fibers. Coal, market pulp, and caustic soda account for nearly 60 % of the abiotic depletion impact. More generally, for the fibers produced with the viscose process, caustic soda, CS_2, and sulphur production are the most important factors next to process energy use. For fibers based on the Lyocell process (i.e., Tencel), the process energy and market pulp are the most important factors, whereas the material consumption plays a less key role.

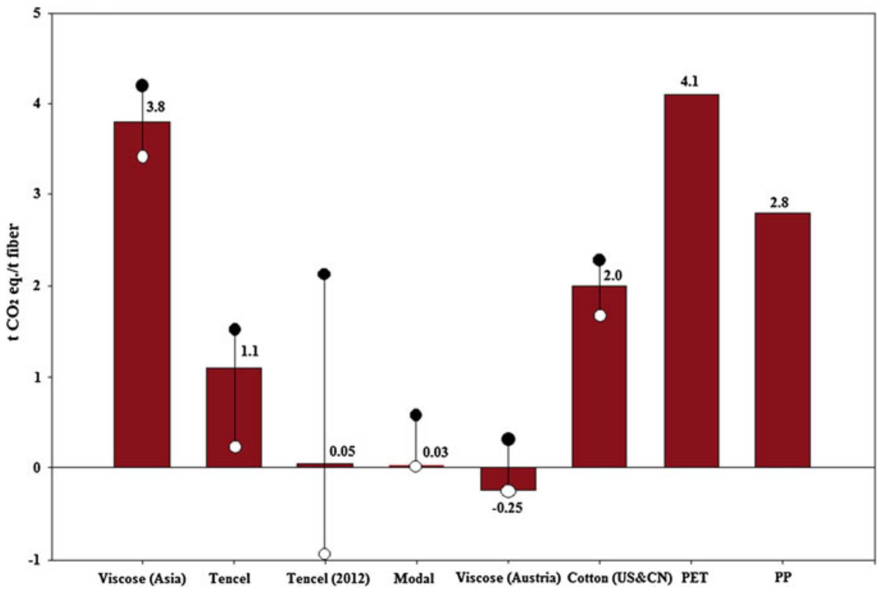


Fig. 20 Cradle-to-factory gate GWP for one tonne of staple fiber [55]

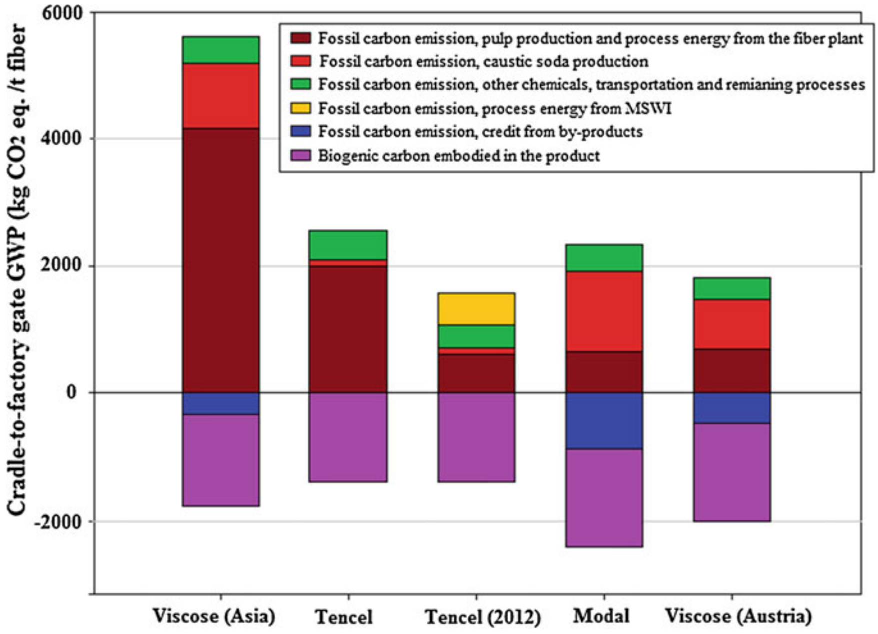


Fig. 21 Process contribution to cradle-to-factory gate GWP for one tonne of manmade cellulose fibers [55]

Table 11 Cradle-to-Factory Gate Environment Impact Assessment of One Tonne of Staple Fiber [55]

	Cotton	PET	PP	Viscose (Asia)	Viscose (Austria)	Modal	Tencel	Tencel (2012)
Abiotic depletion (kg Sb eq./t)	17	45	42	40	14	18	20	7
Ozone layer depletion ($\times 10^{-4}$ kg CFC11 eq.t)	2.0	0.7	0.7	2.8	0.3	0.4	1.1	0.7
Human toxicity (kg 1,4 DB eq./t)	1,700	4,393	369	1,490	630	765	470	660
Freshwater aquatic ecotoxicity (kg 1,4 DB eq./t)	17,310	58	53	160	74	93	85	75
Terrestrial ecotoxicity (kg 1,4 DB eq./t)	1,568	12	12	16	11	16	5.0	5.0
Photochemical oxidant formation (kg C_2H_4 eq./t)	0.7	1.0	0.6	1.8	0.5	0.5	0.6	0.4
Acidification (kg SO_2 eq./t)	41	21	11	45	14	15	17	13
Eutrophication (kg PO_4^{3-} eq./t)	22	1.2	1.0	2.3	1.2	1.3	1.8	1.9

6.1.4 Ozone Layer Depletion

Processes that require oil as input show a relatively high ozone layer depletion impact because of Halon emissions from crude oil production. Halon is used in fire extinguishing systems, especially in the Middle East, Russia, and Africa. Viscose (Asia) has the highest impact on ozone layer depletion of all fibers studied. Approximately 95 % of the impact of viscose (Asia) is related to oil consumption for transportation, process fuels, and the production of grid electricity [63].

6.1.5 Human Toxicity, Freshwater Aquatic Ecotoxicity, and Terrestrial Ecotoxicity

For the human toxicity of viscose fibers, the most important processes are the production of caustic soda, market pulp, and external electricity use. These three factors account for more than 70 % of the total human toxicity impact of viscose (Asia). These factors cause little or no impact for the Tencel fibers. Tencel (2012) has a slightly higher human toxicity than Tencel because of emissions from the waste incineration plant. For cellulose fibers, pulp and caustic soda production are the most important factors for freshwater ecotoxicity and terrestrial ecotoxicity. For all cellulose fibers studied, the credits related to by-products, especially Na_2SO_4 and acetic acid, significantly contribute to lower human toxicity impacts and freshwater aquatic ecotoxicity. Terrestrial ecotoxicity is not particularly influenced by the credits of the by-products.

6.1.6 Photochemical Oxidant Formation

SO_2 emission is the main factor responsible for photochemical oxidant formation in the case of regenerated cellulosic fibers. The main causes of SO_2 emission is the use of SO_2 in the pulp production process and SO_2 emissions from energy production. The highest photochemical oxidant formation is observed in case of viscose (Asia) due to high SO_2 emissions during energy production in the fiber plant.

6.1.7 Acidification

Similar to photochemical oxidant formation, SO_2 emissions are mainly responsible for acidification. Among the regenerated cellulosic fibers, viscose (Asia) presents the highest emissions of SO_2 and impact on acidification, which is comparable to cotton fiber. The impacts of viscose (Austria), modal, Tencel, and Tencel (2012) on acidification are relatively lower and mainly caused due to the production of SO_2 in the pulp mill.

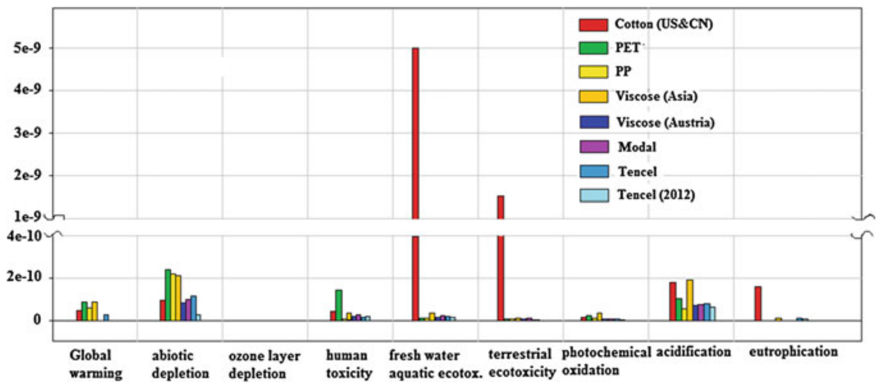


Fig. 22 Comparison of cradle-to-factory gate environmental impacts for one tonne of staple fiber normalized to World 2000 [55]

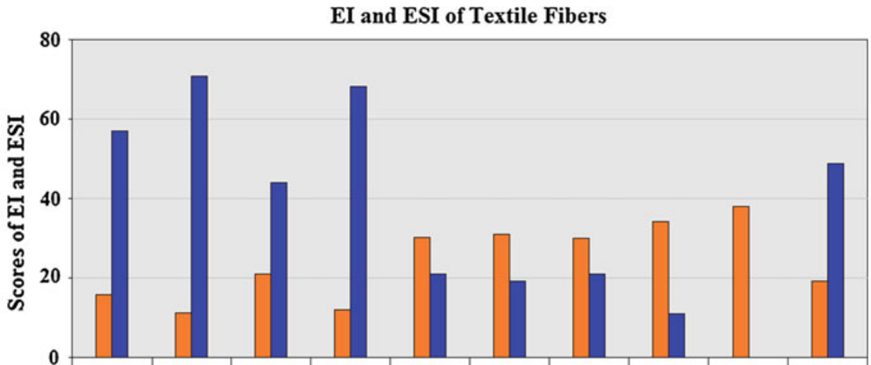
6.1.8 Eutrophication

Production of pulp and caustic soda are the important processes responsible for eutrophication in the case of regenerated cellulosic fibers, contributing about 50 % of the total impact for viscose (Asia). Another important factor contributing to eutrophication is the NOx emissions. Tencel (2012) has a significant contribution to eutrophication, resulting from the energy recovered from MSWI.

6.1.9 Normalized Environmental Impacts

The normalized environmental impacts of different fibers are represented in Fig. 22. It can be noticed that these fibers do not present visible effects on ozone layer depletion and photochemical oxidant formation. Also, the effects of regenerated cellulosic fibers on human toxicity, freshwater aquatic ecotoxicity, and eutrophication are not so significant. It is also evident that viscose (Austria) and Tencel (2012) do not make a significant contribution to the studied environmental impact categories. However, global warming, abiotic depletion, and acidification are the important environmental impact categories to be considered for viscose (Asia) fibers. In case of modal and Tencel, abiotic depletion and acidification can be considered as the relatively important environmental issues.

In a study conducted by Muthu et al. [64], sustainability of various textile fibers including viscose rayon was compared. In this study, the amount of energy and water consumed and greenhouse gases emitted were considered in a lifecycle inventory (LCI), and a lifecycle impact assessment (LCIA) was performed to evaluate the impact categories causing harmful effects to human health and related to ecosystem quality and resources. These factors which mainly influence the ecological sustainability were then used to establish a scoring system that was subsequently used to



	Cotton	Organic	Wool	Flax	Nylon 6	Nylon	Polyester	PP	Acrylic	Viscose
EI	16	11	21	12	30	31	30	34	38	19
ESI	57	71	44	68	21	19	21	11	0	49

Fig. 23 EI and ESI values of textile fibers

derive the environmental impact index (EI). Also, an ecological sustainability index (ESI) was determined from the EI values of different fibers.

The estimated EI and ESI values for different fibers are presented in Fig. 23. It can be observed that the EI of viscose fibers is lower than the petrochemical-based fibers such as nylon, polyester, PP, and acrylic and, consequently, ESI of viscose is better than these fibers. However, the environmental impact of viscose is higher than natural fibers such as cotton (both conventional and organic), wool, and flax fibers. Among these fibers, the highest impact is observed in the case of acrylic, whereas organic cotton fiber shows the lowest impact and highest ESI. Flax fiber needs the lowest amount of energy among all the studied fibers and consumes less water than cotton, leading to very low EI and high ESI values. In the case of organic cotton, no use of synthetic pesticides and fertilizers results in the lowest environmental impact and highest ecological sustainability. The reasons for the higher impact of viscose than other natural fibers, in spite of using less water than conventional cotton, are more damage to human health (due to the use of many chemicals in the viscose production process) and ecosystem quality, use of more resources during the production process, and lower capacity to absorb CO_2 than that of plants.

In another study, NREU and greenhouse gas (GHG) emissions of regenerated cellulosic fibers were compared with petrochemical PET, biobased PET, PLA, recycled PET, and recycled biobased PET [65]. As also observed in other studies, GHG emissions are highest for petrochemical PET. The lowest GHG emissions among all fibers studied were observed in the case of man-made cellulose fibers produced in integrated plants. Among the regenerated cellulosic fibers, modal and Tencel fibers show lower NREU and GHG emissions as compared to viscose fibers.

7 Conclusions

This chapter discusses various regenerated cellulosic fibers, mainly their production, properties, applications, and sustainability issues. Viscose rayon is one of the most widely used regenerated cellulosic fiber and very popular due to its aesthetic properties like silk fiber, and good feel and drape characteristics. Viscose fiber is extensively used in apparel, home furnishings, and industrial applications. Viscose fiber is produced from renewable resources (trees such as pine, beech, etc.), which grow using rainwater and, the land used for these forests is specific and therefore the growth of these trees does not cause any significant environmental effects. However, the one important sustainability factor for this fiber is the use of many chemicals, such as caustic soda, carbon disulphide (CS_2), sulfuric acid, sodium sulphate, and zinc sulphate during their spinning process. However, nowadays, this problem has been minimized through the recycling and reuse of up to 70 % of CS_2 and conversion of the remaining 30 % to sulfuric acid which is also recycled to the process. The main sustainability concern existing today for viscose rayon fiber is the consumption of energy and the use of fossil fuel in fiber production as well as in the production of various chemicals including caustic soda, sulphur, and NaOCl. Bamboo viscose fiber is a type of regenerated cellulosic fiber produced using the wood pulp of bamboo trees through the viscose rayon production process. Cultivation of bamboo trees are sustainable as bamboo is grown without pesticides or chemical fertilizers, requires no irrigation, rarely needs replanting, grows rapidly and can be harvested in 3–5 years, produces 35 % more oxygen than an equivalent stand of trees balancing oxygen and carbon dioxide in the atmosphere, and acts as an excellent soil erosion inhibitor. However, due to a similar production process to viscose rayon, the production of bamboo viscose also involves similar factors influencing its sustainability. Production of other regenerated fibers such as modal, cupramonium rayon, and cellulose acetate also involves many chemical reaction steps and the use of many chemicals, and the factors affecting their sustainability are also similar. Cellulose acetate is a regenerated as well as modified cellulosic fiber unlike viscose, modal, and cuprammonium rayons which are pure regenerated cellulosic fibers. Cellulose acetate fiber presents very good handle (soft, smooth, dry, crisp, and resilient) and comfort properties (breathes, wicks, dries quickly, and no static cling) and finds widespread applications in different types of clothes such as women's nightwear and formalwear, coats, accessories for Japanese dresses, blouses, sweaters, scarves, and the like, and also in home furnishings and bedding products such as blankets, bedclothes, fabrics for curtains, and so on. Cupramonium rayon fiber can be spun in extremely fine denier and possesses softness and handle characteristics similar to silk fiber. This fiber is used in similar applications to those of cellulose acetate fibers. Modal is produced through regeneration of cellulose obtained from the pure wood pulp of beech trees. 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. This fiber finds applications in clothing, home furnishings, undergarments, and socks and stockings, among others. Among the various regenerated cellulosic fibers, Lyocell fiber presents significant environmental benefits. In addition to being produced from renewable resources and completely biodegradable, Lyocell fiber is produced using a solvent that can be recovered almost completely. LCA studies carried out on these fibers showed that Lyocell fiber production (especially based on the use of MSWI as the source of process energy) is advantageous over the other regenerated cellulosic fibers due to lower requirements of energy, water, and land as well as lower impacts on global warming potential, abiotic depletion, ozone layer depletion, human toxicity, freshwater aquatic ecotoxicity and terrestrial ecotoxicity, acidification, photochemical oxidant formation, and eutrophication. Regenerated cellulosic fibers do not present significant effects on ozone layer depletion, photochemical oxidant formation, human toxicity, freshwater aquatic ecotoxicity and eutrophication when compared to cotton and petrochemical-based fibers. However, viscose fiber produced in Asia has a large contribution to global warming, abiotic depletion, and acidification. Although viscose fiber has higher sustainability as compared to petrochemical-based fibers, it shows higher environmental impacts and therefore is less sustainable than cotton fiber. SeaCell fiber is a third-generation regenerated cellulosic fiber produced using an innovative Lyocell technique, in which seaweed containing vitamins, minerals, and trace elements are added to the wood pulp before spinning. As a result, the produced fiber provides health-promoting and skincare effects. This fiber possesses softness and breathability, providing a pleasant feeling of well-being and is becoming very popular in sportswear and yoga attire as well as in sheets, towels, blankets, and baby clothing. This fiber has similar sustainability aspects to Lyocell fiber.

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