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A critical review of alternative raw materials that can be used in the production of lyocell to make it cost competitive

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ABSTRACT

The textile industry is one of the largest contributors to the looming climate crisis. Cotton, the most popular fabric, severely harms the environment because of its high water and carbon footprint. In current times, achieving sustainability is of utmost importance. Lyocell, a regenerated cellulosic fibre, is an eco-friendly alternative that offers similar benefits as cotton. However, due to the use of hardwood as a raw material in commercial production, it is twice as expensive and hence not widely adopted. This literature review evaluates the use of other raw materials that can be substituted into the conventional lyocell production process. The cost-effectiveness, time needed for implementation, and environmental impact of the method of generating the dissolving pulp and additional steps required for each alternative have been compared. After a critical evaluation, it was concluded that polycotton waste would be the most suitable alternative raw material as it will not harm the environment while also reducing pollution and offering a solution to recycle textiles and PET plastic, hence promoting sustainability and restoring the environment.

Keywords- *Production of Lyocell, Sustainability, Eco-friendly alternative to cotton, Recycling in the textile industry, Cost competitiveness, Raw materials for dissolving pulp*

1. INTRODUCTION

Today, floods, wildfires, and other natural disasters have become a frequent occurrence due to the adverse climate impact of the extreme pollution caused by human activities. The record level of atmospheric carbon dioxide has prompted mathematicians to go as far as to predict that the next mass extinction will begin by the end of this century. In times like these, achieving sustainability has become one of the foremost goals of innovation.

A huge contributor to climate change is the textile industry, which is known for its waste of resources. It is estimated that the textile industry generates around 8-10% of the world's carbon dioxide emissions and 20% of the industrial water pollution. To tackle this issue, numerous technological advancements have been made in the recent past to transform the linear textile production model into a circular model, one of them being the invention of lyocell fibres.

These fibres serve as a sustainable alternative to cotton, which has an enormous annual water-footprint of 250 billion tons and requires the use of chemicals more than any other crop. However, due to the high cost of raw materials and the machinery needed for processing, lyocell is expensive and not widely adopted. One of the possible methods to make lyocell more affordable is to use cheaper sources of pulp. Therefore, this paper will review the feasibility, advantages and disadvantages of using various raw materials and argue why one of them is the best alternative to reduce costs without compromising on the quality of the fibres.

The paper starts by introducing lyocell and giving a brief overview of the background and significance of this review through the following headings: 1. What is lyocell? 2. Production process of lyocell fibres 3. Lyocell as a sustainable fabric 4. Drawbacks of lyocell. Next, possible solutions to the problems discussed are presented, going into detail for each alternative raw material: 5. Hypothesized solution 6. Overview of possible alternative raw materials (6.1 Polycotton waste, 6.2 Sugarcane bagasse, 6.3 Waste paper, 6.4 Bamboo). Finally, these raw materials are evaluated and compared to conclude which one would be most effective in making lyocell a cost competitive alternative to cotton in order to make the textile industry more sustainable: 7. Comparative study of environmental impact of raw materials 8. Evaluation & Conclusion.

2. WHAT IS LYOCELL?

Lyocell is a type of regenerated cellulose fibre (man-made cellulosic fibre) made by dissolving the cellulose pulp directly in the N-methyl morpholine N-oxide (NMMO) solvent. It makes use of a closed-loop production process in which no harmful chemicals or by-products are released into the environment. Wood is the most commonly used raw material in this process.

2.1 Properties of Lyocell

- stronger than any other cellulosic fibres, especially when wet
- easy to process into yarns and fabrics alone or in blends
- easy to blend (unique fibre presentation)
- easy to spin to fine count yarns
- very stable in washing and drying
- thermally stable
- capable of taking the latest finishing techniques to give unique drape
- comfortable to wear (Borbély)

3. PRODUCTION PROCESS OF LYOCELL FIBRES

The production process mainly consists of 4 steps:

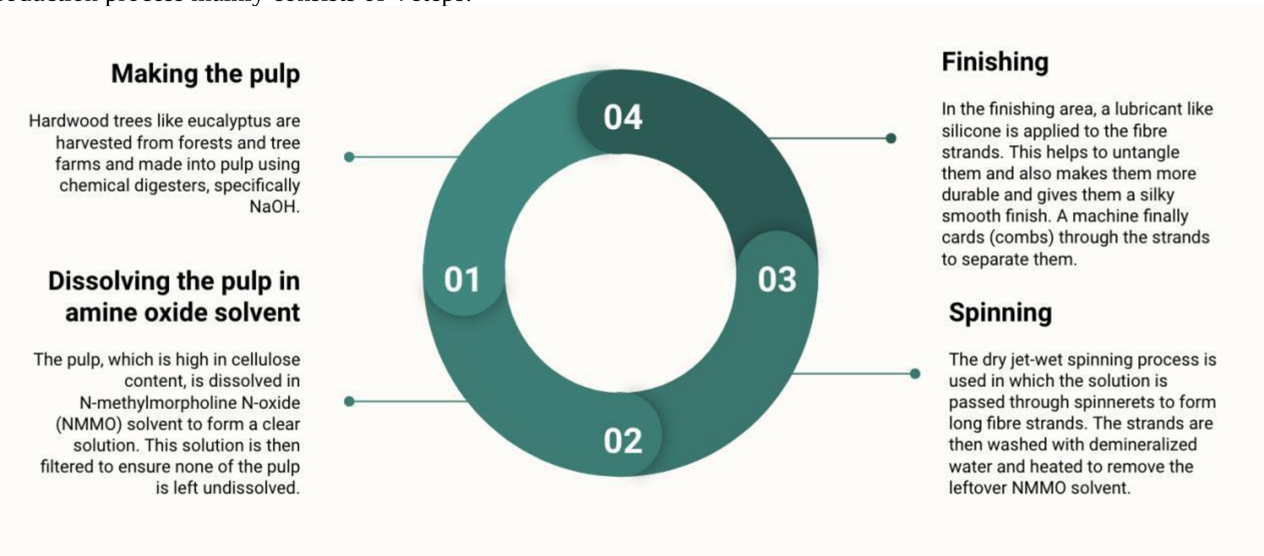

Figure 1: Steps of the lyocell production process (Made by author)

3.1 Making the pulp

The raw material is broken down into pulp using chemical digesters like strong alkaline sodium hydroxide solution.

In order to improve the efficiency of cellulose dissolution, decrease dissolution temperature and retention time, the pre-treatment technologies of dissolving pulp are necessary. Mixing technologies of high and low viscosity pulps, cellulose activation, pressing and smashing of pulp are employed. After that, the treated pulp is mixed with the NMMO aqueous solution, antioxidants and stabilizers to make a premix (Jiang *et al.*).

3.2 Pulp dissolution

The cellulose-rich pulp is dissolved in an aqueous solvent of N-methyl morpholine N-oxide (NMMO) to form a dope of high viscosity. The dissolution process take place in two stages – swelling of cellulose and its gradual dissolution.

The excellent dissolving capacity of NMMO on cellulose is due to its strong N-O dipoles and basicity, making NMMO an excellent hydrogen bond acceptor solvent. In the dissolution process, the N-O bond, which has a stronger basicity than hydroxyl group, will interact with the hydrogen atom on the hydroxyl group of cellulose and form new hydrogen bonds between NMMO and cellulose, replacing the intermolecular and intramolecular hydrogen bonds in cellulose.

During the cellulose pulp dissolution process, both swelling and dissolution occur (Rosenau *et al.*; Zhang and Tong; Ingildeev *et al.*). Its first step is to rewet cellulose fibres in a dilute NMMO aqueous solution under the typical conditions of: 50 to 60% NMMO, 20 to 30% water, and 10 to 15% pulp (Rosenau *et al.*), which will allow great cellulose swelling. Subsequently, an excess amount of water is removed by distilling, such that the desired ratio of cellulose/NMMO/water is obtained for cellulose dissolution Typical compositions are 76% NMMO, 10 % water, and 14% cellulose (Rosenau *et al.*). Under the above conditions, cellulose is dissolved, and a brown, transparent cellulose solution is obtained (Haule *et al.*). Generally, the ternary solutions are prepared at elevated temperatures from 90 to 120 ºC. It is desirable to for more water to be removed to reach the desired ratio of cellulose/NMMO/water to dissolve cellulose to form cellulose dope. However, a high temperature (*e.g.*, higher than 120 ºC), will cause undesirable loss of NMMO due to degradation (Ingildeev *et al.*). Therefore, a suitable temperature is desirable. To minimize the NMMO degradation, some stabilizers, for example, a combination of alkaline and antioxidant (NaOH, isopropyl gallate) can be added (Rosenau *et al*; Ingildeev *et al.*), and antioxidants also can be added to the dissolving tank (Zhang *et al.*).

3.3 Spinning

The lyocell process uses the dry jet-wet spinning process to produce fibres from the dope using the following sub-steps:
a. the dopes in the NMMO/water system are extruded out from the spinning nozzle, then into an air gap
b. the formed filament then immediately enters a coagulation bath to continue its formation (Rosenau *et al.*)

In the dry jet-wet spinning process, the spinning process ability depends highly on the process parameters, particularly the dope viscosity, air gap, spinning temperature, and spinning speed. The lyocell dope has a higher viscosity (DP of 500 to 600, based on the Staudinger method) than the viscose dope (DP of 250 to 350, based on the Staudinger method); such a difference is partially responsible for the superior strength properties of the lyocell fibre. Furthermore, the high viscosity of the spinning solution of the lyocell process can allow it to maintain a very stable spinning of fibres through the air gap (Haule *et al.*).

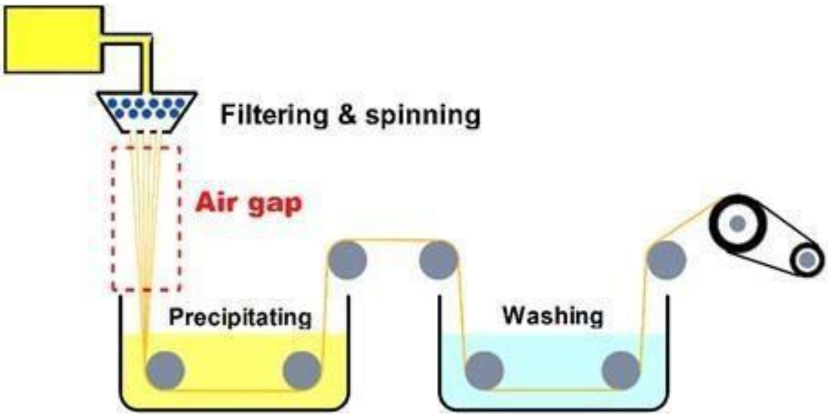

Figure 2: Dry jet-wet spinning in the lyocell process (Zhang *et al.*)

In fact, the air gap is a critical element of the operation, with significant changes in the solution, and the spinning ray stretched and oriented (Zhang *et al*.). A highly oriented structure is formed upon entering the aqueous precipitation bath. Air gap length influences the fibre strength (Zhang *et al*.). Reducing the air gap length, *e.g.*, from 250 to 20 mm, will reduce the fibre strength. A long air gap causes good orientation, increases in birefringence, and leads to high strength. However, if the air gap is too long, a reduction in orientation occurs, which is caused by relaxation effects before the fixation of the highly oriented solution in the bath. Therefore, an excessively long air gap should also be avoided.

The temperature of the coagulation and the wet spinning speed are also critical factors. When the temperature is fixed, the increase of speed (rise of draw ratio) leads to increase in fibre crystallinity, birefringence, and orientation, which contribute to the improvement in fibre strength (determined by orientation) and initial Young's modulus (determined by crystallinity). However, when the speed is fixed, with the increase of temperature, the fibre structure and properties show changes in the opposite direction.

With the air gap, in addition to the formation of lyocell fibre with highly oriented and crystalline structure, some weaker lateral links between the crystallites can lead to the so-called fibrillation, which is evident as some fibrous elements being exposed at the surface of the lyocell fibre under the condition of wet abrasion (Zhang *et al*.). Fibrillation can be reduced via changing the various spinning parameters such as air gap conditions and draw ratio. Usually, a low spinning speed means a long spinning ray in the air gap, which will result in a low fibrillation. On the other hand, with a short air gap, a high draw ratio will increase the fibrillation degree significantly, while a low draw ratio will lead to the production of fibres with good strength but a low fibrillation degree. For long air gaps and draw ratios of up to 10, fibres with very good mechanical properties and low fibrillation can be obtained (Zhang *et al*.)

3.4 Finishing

In the last step of production, a lubricant like silicone is applied to the fibre strands. This helps to disentangle the strands and also lends them durability and a silky-smooth feel. Thereafter, the strands are separated through combing them with the help of a machine.

4. LYOCELL AS A SUSTAINABLE FABRIC

Cotton is the most popular and widely-used fabric in the world, mainly because of the breathability, absorption and comfort it provides as well as its versatility. Half of all textiles are made of cotton, but cotton production is extremely harmful to the environment.

- It takes 2,700 litres of water to produce 1 cotton shirt. Global cotton production requires over 250 billion tons of water annually. Most of the water-footprint of cotton is in developing countries where people already don't have access to safe drinking water.
- Cotton is the crop most heavily sprayed with chemicals in the world. The hazardous pesticides pollute the soil and nearby water resources. In a Brazilian cotton region, acidic rain containing 12 cotton pesticides harmed the entire ecosystem there.
- 150 million trees are cut down for fabric production each year, many being cut to create cotton fields, leading to loss of habitat and reduction in CO_2 absorbed from the atmosphere. Cotton production also causes soil degradation and erosion.
- Cotton production is responsible for the emission of 220 million tons of CO_2 annually, which plays a significant role in climate change.

Lyocell, on the other hand, provides all the benefits of cotton while also being environmentally friendly.

- The pulp for lyocell is usually produced from hardwood trees that are sourced from tree farms, which do not use agrochemicals like cotton farming does.
- Lyocell uses a closed-loop production process and thus, no harmful by-products like carbon dioxide are produced.
- Less than half of the water and energy used in cotton production is used to produce lyocell.
- The NMMO solvent used to make dissolving pulp is non-toxic and 99.5% of it is re-used in the production process.

Based on the table below, it is clear that lyocell is as good a fabric as cotton and is also eco-friendly.

Table 1: Comparison of the characteristics of cotton and lyocell (Made by author)

	Characteristics	Lyocell	Cotton
1	Breathable	Yes	Yes
2	Absorbent	Yes	Yes
3	Durable	Yes	Yes
4	Versatile	Yes	Yes
5	Elastic	Yes	Yes
6	Soft texture	Yes	Yes
7	Anti-bacterial	Yes	No
8	Eco-friendly	Yes	No
9	Affinity for dyes	No	Yes

5. DRAWBACKS OF LYOCELL

Lyocell may be more sustainable than other fabrics, but one major hindrance to lyocell's wide adoption is that it is more costly. Pure lyocell clothing can sometimes be twice as expensive as pure cotton. This is because lyocell production involves the use of more advanced technology and requires an investment in the machinery.

Another reason for its high cost is that hardwood trees, like eucalyptus, are primarily used as the raw material. Hardwoods are specially used as they have high α-cellulose >90% (Uddin *et al.*) and low hemicellulose content, which is considered to be a necessity to attain a good yield of fibre. However, such trees require more water, maintenance and land, and are extremely valuable, making them more expensive to source.

Powerful machines are also needed to harvest and transport such large trees, unlike cotton, where labour is preferred to carefully pick the cotton bolls and clean the linters. Capital requires a higher investment than labour, once again adding to the cost of hardwood and thus increasing the cost of lyocell. The wood's hardness and durability also mean that a larger amount of chemical is needed to break it down into pulp and to pre-treat the fibres, increasing the cost of production.

6. HYPOTHESIZED SOLUTION

Recent investigations have reported that the yield of lyocell fibres produced from high and low hemicellulose content was approximately equal because most of the cellulose and hemicellulose can be converted into fibre in the lyocell production process. In fact, choosing cheaper source of pulps which have high hemicellulose content has been considered as an effective way to reduce the cost of lyocell fibres (Uddin *et al.*).

Usage of cheaper pulp to produce lyocell fibres can help reduce the cost of the lyocell fabric as:
a. it will reduce the cost of harvesting valuable hardwood trees
b. it will reduce the cost of pre-treatment of the fibres (Zhang and Tong)

Fibres that have high hemicellulose are also more resistant to fibrillation (Zhang and Tong) and thus more durable, increasing their cost-effectiveness. According to this speculation, waste products from the textile, agriculture and paper industry should work extremely well as the raw material as they have high hemicellulose content, helping to reduce the cost of production as well as provide a solution to the excessive waste collected on our planet and the textile recycling problem. Specific possible raw materials include cotton fabric, waste paper and paper-grade pulp (Shabbir and Mohammad), possibly made from agricultural produce.

7. OVERVIEW OF POSSIBLE ALTERNATIVE RAW MATERIALS

The conventional lyocell production process is followed from Steps 2 through 4 for each raw material. Only the method used in Step 1 to convert the source into pulp will differ for different materials. Some additional steps might also be required for each alternative.

7.1 Polycotton waste

Polyester, in particular polyethylene terephthalate (PET), and cotton are the most common synthetic and natural fibres, respectively, used in the world today. The differences in their strengths and weaknesses make the two a perfect combination. Cotton contributes with softness and high-water absorbency, and PET contributes with durability, strength, and a low price. This makes mixes of PET and cotton, in varying percentages, one of the most common textile materials, which are generally referred to as polycotton.

Polycotton is used in the main part of all service textiles, such as sheets, towels, and workwear. Recycling of service textiles could be an important step towards sustainability since the service sector uses large quantities of textiles with similar quality.

Additionally, the service sector has a large impact on their material providers. However, to recycle polycotton chemically and obtain cellulosic pulp, cotton and PET must be separated.

A straightforward process involving NaOH in water and temperature in the range between 70 and 90 °C for the alkaline hydrolysis of PET is used. In the process, the PET degrades to terephthalic acid (TPA) and ethylene glycol (EG) and a high yield of cotton cellulose, up to 97%, is obtained. The degradation that occurs from the use phase in this process helps to decrease the chain length (the degree pf polymerization, DP) and to get the cotton dissolving pulp into solution prior to regeneration into lyocell fibres using the conventional next steps (De La Motte and Palme).

7.2 Sugarcane bagasse

Bagasse is a fibrous residue that is left after the crushing of sugarcane stalks. Essentially, bagasse is a waste product, and so annual production of approximately 100 million tons requires additional disposal costs (Uddin *et al.*). Currently, some of the bagasse is burned in the furnaces of sugar cane mills to provide heat and to generate power or steam. These processes generate toxic dioxins. Bagasse pulp is also used to make several grades of paper: newspaper, writing paper, toilet tissue, paper towels, glassine, etc. Even so, an excess of bagasse exists, and this excess is deposited on empty fields, altering the landscape. Bagasse contains, on average, 49% moisture, 49% fibre and 2% soluble solids. The composition the fibrous part of bagasse is 50% cellulose, 30% hemicellulose, 18% lignin and some inorganic compounds (Uddin *et al.*).

To produce lyocell fibre, the bagasse is first treated in an alkali solution to extract impurities like lignin and inorganic compounds. It is then dissolved in the NMMO aqueous solvent with propyl gallate and sodium dodecyl sulphate. The conventional lyocell process is followed thereafter. Some amount of the NMMO solvent remains in the fibre matrix, which is removed by heating (Uddin *et al.*).

Sugarcane bagasse, which is generally considered as waste product, can thus produce regenerated cellulose fibres with mechanical properties comparable to those of commercial lyocell fibre.

7.3 Waste paper

Waste paper is mainly composed of cellulose fibres and can be used as a raw material to produce recycled paper and biomass materials. A global review of manufacturing sectors divulged that 17% of the total global waste comes from paper industries (Guo *et al.*). Pulp and paper mills make up roughly 26% of solid municipal waste in landfill sites, making this an ideally abundant raw material (Guo *et al.*).

To produce lyocell fibres, the waste paper first undergoes deinking, which aims to detach the printing ink from the paper fibres. The deinked paper is then soaked in water for 12 hours and ground in a hydra pulper machine (Guo *et al.*). After grinding, the pulp is rinsed with water, filtered using a vacuum pump and dried in the thermostatic oven. Next, alkali treatment with ultrasonic radiation is performed. The dry pulp is firstly soaked in NaOH solution, and then filtered with water to pH 7.0 and pre-treated with ultrasonic radiation. In the last step, the pulp is soaked in water and stirred in an electric mixer. 18% (in mass) kaolin and 0.5% (in mass) hexadecyl trimethyl-ammonium chloride are simultaneously added in this process (Guo *et al.*). After the pulp is filtered and dried, the conventional lyocell production process is used to generate fibres.

7.4 Bamboo

Bamboo is the common term for members of a particular taxonomic group of large woody grasses, commonly found in the tropical world. As an industrial raw material, bamboo has been used to produce both cellulosic fibres for paper and starch granules and in the production of ethanol. In general, the cellulose content in bamboo is 40 to 50%, which is comparable with the reported cellulose content of softwoods (40 to 52%) and hardwoods of (38 to 56%) (Sugesty *et al.*), and hence will produce pulp high in α-cellulose that can be used to produce lyocell fibres using the commercial production process without additional cost or chemicals needed. Bamboo is already being used in China to produce lyocell, and is thus its use in the near future is very promising.

8. COMPARATIVE STUDY OF ENVIRONMENTAL IMPACT OF RAW MATERIALS

Table 2: Environmental impact of possible raw materials (Made by author)

	Land space	Water	Soil Health	CO2 emissions	Rank
Wood Pulp (Eucalyptus)	Eucalyptus trees are grown in plantations, which requires large plots of land, usually coming at a cost of agricultural land. However, these trees can be grown on barren land and can be used for afforestation.	Eucalyptus trees require around 90 litres of water a day and is known for depleting the groundwater table. Plantations in Kolar, India have caused the mean depth of groundwater to increase from 177m to 260m (Reporter).	Eucalyptus consumes soil nutrients and inhibits the growth of neighbouring plants through allelopathic properties. No additional chemical inputsare needed.	Eucalyptus sequesters around 9 to 12 tonnes/hectare of CO2 (Behera *et al.*). These plantations are generally not located near the pulp-making factories so large vehicles are needed to transport the heavy wood logs, which emits high amounts of CO2.	**4**
Polycotton waste	Waste from the textile industry is used. Hence, no land	Using polycotton does not affect the amount of water used	Polycotton contains PET which can degrade the soil and groundwater.	Using waste to produce fibre ensures that it is not burned instead, hence reducing CO2	**1**

	is needed and the waste is recycled instead of being discarded in a landfill.	or cause excess water contamination.	Thus, by recycling it, this degradation is prevented.	emissions. This process also recycles the PET mixed in the textile into monomers that are used in the production of plastic.	
Sugarcane Bagasse	Bagasse is essentially waste from the agricultural sector. Hence, no land is needed and the excess waste is repurposed.	Using bagasse as the raw material does not affect the amount of water used or cause excess water contamination.	Using bagasse as the raw material does not affect the soil.	The fibres generated have NMMO trapped in the fibre matrix which must be removed by heating. Depending on the source of heat used, excess CO2 might be emitted. However, using waste to produce fibre ensures that it is not burned instead, hence reducing CO2 emissions.	**3**
Waste paper	No land is needed and the waste of the paper and pulp industry is recycled.	Additional amount of water is needed for the deinking process. Deinking also produces toxic black liquor, which contaminates the water. However, the black liquor can be used to produce high-performance carbon fibre and bioplastic.	The toxic black liquor produced causes soil pollution. The sludge by-product must beburied in landfills, causing degradation.	To extract cellulose pulp from waste paper, multiple machines must operate for long stretches of time, releasing CO2. However, using waste paper to produce fibre ensures that it is not burned instead, hence preventing CO2 emissions.	**5**
Bamboo	As it needs very little water, bamboo can grow almost anywhere and is commonly found as a grass, thus eliminating the need for special plantations. Replanting bamboo is seldom required, reducing land use.	Bamboo grows using rainwater and irrigation is not necessary.	Bamboo trees provide very good protection against soil erosion. No chemical inputs are needed.	Bamboo trees produce 35 % more oxygen as compared to an equivalent stand of trees. They also absorb more CO2 per acre than any other forest (12 to 17 tonnes/hectare). Bamboo trees are therefore very important in terms of balancing oxygen and carbon dioxide in the atmosphere.	**2**

9. EVALUATION AND CONCLUSION

Polycotton waste seems to be the most promising raw material for the production of lyocell compared to the other alternatives mentioned in this paper. Not only does it have no additional harmful effect on the environment but it also protects against soil, water and air pollution as seen in Table 4. Since both the textile and hotel industry, from which polycotton waste is sourced, are amongst the largest industries in the world, there will be sufficient waste generated to greatly increase the supply of lyocell, consequently making it cost competitive and increasing its demand as an alternative to cotton, thus promoting environmental sustainability.

The process to extract cellulose from the polycotton also produces terephthalic acid (TPA) and ethylene glycol (EG), which are monomers used in the manufacturing of PET plastic. Hence, using this alternative raw material will contribute to solving the textile industry's massive waste problem as well as produce recycled plastic that can be used to make bottles, bags and other commonly used products. As the demand and production of lyocell fibres increases over time, more and more recycled PET will be produced, soon causing the need to manufacture fresh plastic to reduce. This will in turn decrease the greenhouse gas emissions and the mining of fossil fuels associated with plastic factories, whose capital can then be repurposed for the manufacture of more sustainable technologies.

Using polycotton waste as a raw material will also improve the socio-economic standing of many third-world countries. As the landfills in these countries are often covertly used as dumping grounds for textile and other waste by many developed countries, factories producing cellulose pulp from polycotton can be established here. This will provide employment opportunities to the local citizens while improving the health and environmental conditions of the area by providing a clean method to dispose of the waste.

The biggest and best advantage of producing lyocell from polycotton is that most of the machines and chemicals used are the same as those currently used to produce commercial lyocell from wood. Hence, lyocell factories can easily shift to using this raw material without incurring heavy costs. There is also enough polycotton waste available at hand to initiate this shift immediately, making it a suitable solution to the impending climate crisis.

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