# Assessing Textile Raw Materials and Exploring Sustainable Sources for Future Renewable Textile Materials for IKEA of Sweden

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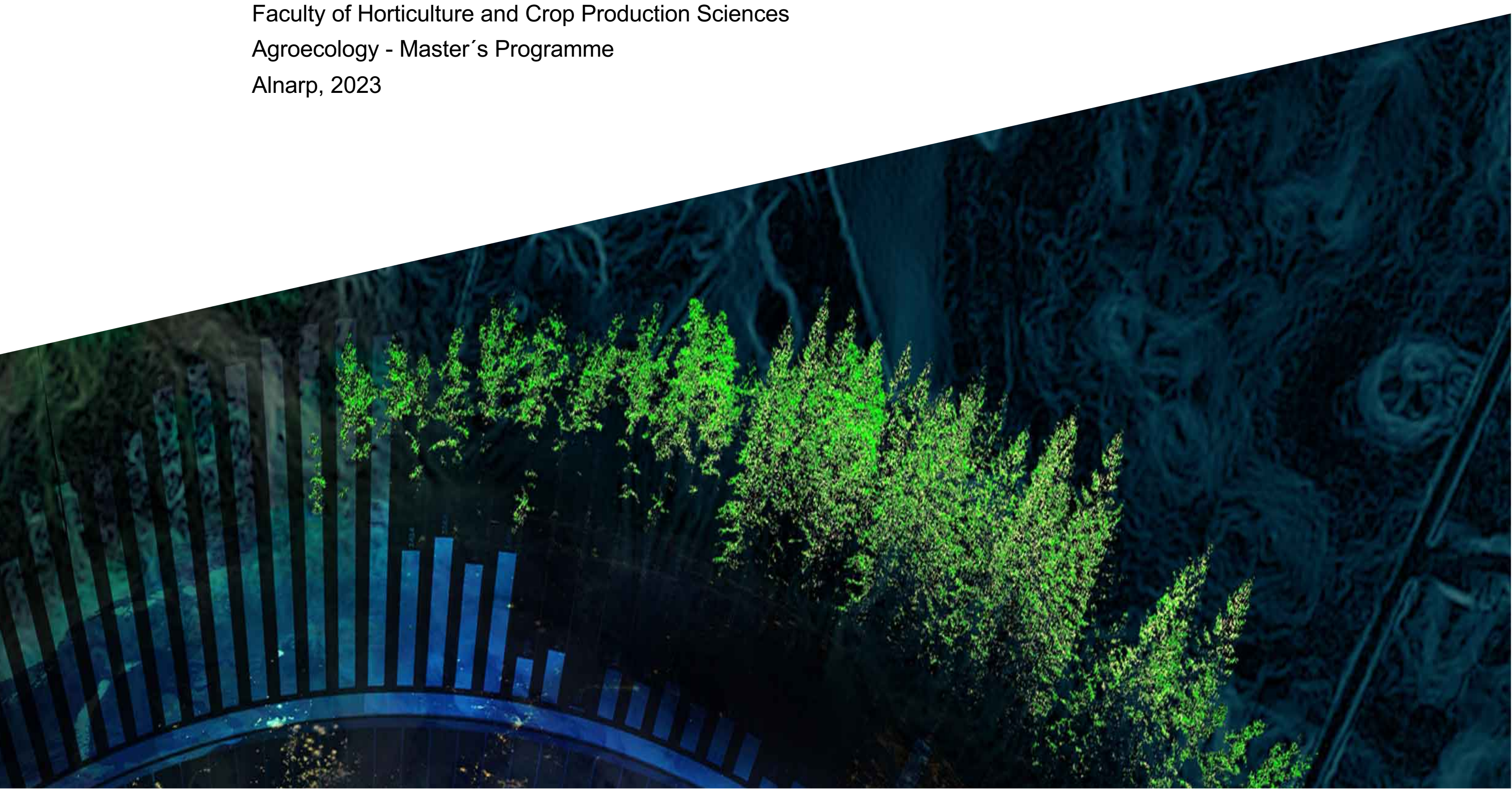
Degree project • 30 credits
Swedish University of Agricultural Sciences, SLU
Faculty of Horticulture and Crop Production Sciences
Agroecology - Master´s Programme
Alnarp, 2023



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|---|---|
| **Credits:** | 30 |
| **Level:** | A2E |
| **Course title:** | Independent Project in Agricultural Science |
| **Course code:** | EX0848 |
| **Programme/education:** | Agroecology Master's programme |
| **Course coordinating dept:** | Department of Biosystems and Technology |
| **Place of publication:** | Alnarp, Sweden |
| **Year of publication:** | 2023 |
| **Copyright:** | All featured images are used with permission from the copyright owner. |
| **Keywords:** | drought, water scarcity, land degradation, cotton (*Gossypium sp.),* synthetic textiles, viscose, lyocell, IKEA, agro-waste, poplar (*Populus sp.), bamboo ( Bambusoideae),*sustainability |

**Swedish University of Agricultural Sciences**
Faculty of Horticulture and Crop Production Sciences
Department of Biosystems and Technology

# Abstract

This degree project at the Swedish University of Agricultural Sciences has been conducted in collaboration with IKEA of Sweden.

The textile industry contributes to significant environmental challenges, including pollution and global water scarcity. Heatwaves and droughts are increasing in frequency and intensity, leading to reduced water availability, food insecurity, and land degradation. Water scarcity is a major concern in China and India, where large populations face high water stress and limited access to safe drinking water. Cotton production, the largest natural fiber globally, consumes extensive irrigation water, agrochemicals, and land, resulting in soil erosion, water pollution, and habitat destruction. Synthetic textiles and animal leather production further contribute to environmental contamination and $CO_2$ emissions. Conventional textile practices also result in large amounts of textile waste, with only a small fraction effectively recycled. The man-made cellulosic fiber (MMCF), viscose, has been associated with substantial environmental and social impacts. However, the adoption of sustainable practices, such as utilizing Forest Stewardship Council (FSC)-certified wood sources and employing closed-loop processes like lyocell production, has emerged as a viable strategy for mitigating the drawbacks associated with MMCFs. This thesis investigated sustainable sources for renewable textile materials, utilizing a literature review and analysis of diverse natural raw materials' production, land occupancy, and water footprint.

It is found that the utilization of recycled products, cotton (rCotton) and viscose, present opportunities for circular production, with potential benefits including reduced waste, carbon emissions, and water consumption, but challenges such as contamination from non-recyclable fibers and degradation of fiber properties need to be addressed. In prolonged drought and heat wave climates, hybrid poplar may be a better option than eucalyptus among fast-growing broadleaves for plantation, since eucalyptus have high flammability. Utilizing agro-waste for textile fibers offers efficient use of cropland. Commodity crop byproducts, corn and corn husks, abundant and affordable, can be used for corn-based polylactic acid (PLA) and corn husk fiber; banana pseudostem can be mechanically processed to fiber, and sugarcane bagasse can be used for producing viscose and lyocell and sugarcane-based foam, which offer eco-friendly alternatives for mattress filling. Coconut coir is well-suited for mattresses and brushes use, while buckwheat hulls as filling material for pillows and mattresses. Bamboo is an ideal choice for its rapid growth rate, capability for soil stabilization, efficacy in water purification, and extraordinary carbon sequestration and it can be utilized for rayon and mechanically produced fine fiber. The staple fiber produced by TreeToTextile is sourced from sustainably managed woods and processed via a closed-loop system with reduced chemical, energy, and water utilization. All these materials are considered feasible candidates for IKEA's future innovations in textile applications.

To enhance sustainability, IKEA could replace synthetic fibers with renewable raw materials and prioritize textile fibers from crops with high yield and woods with minimal environmental impacts. This approach contributes to circular production, creates more cropland availability for food cultivation or natural reserves of forests and wetlands, and preserves a healthy ecosphere, particularly in prolonged drought periods. The fibers derived from agriculture byproducts do not need to be strictly confined to the high-yield strategy, as the primary priority remains food production for human sustenance. Given the uncertain, future costs and availability of existing synthetic and natural fibers, IKEA can bolster abundance and price stability by increasing the diversity of textile raw materials it utilizes.

*Keywords:* drought, water scarcity, land degradation, cotton (*Gossypium sp.*), synthetic textiles, viscose, lyocell, IKEA, agro-waste, poplar (*Populus sp.), bamboo (Bambusoideae),* sustainability

# Forword

I chose the Agroecology program with the anticipation that the significance of agriculture would become increasingly prominent in the future, nurturing within me the aspiration of owning my own farm.

Through these courses, I have come to comprehend the essence of organic farming and have acquired fundamental techniques in cultivating crops, such as crop rotation, intercropping, fertilizer management, and irrigation. This learning has reinforced my understanding of the vital role sustainable agriculture plays in the ongoing development of both the agricultural realm and the world at large. Concurrently studying and actively applying these principles in my home garden and farmland, where I cultivate vegetables, fruits, and raise quails, has allowed me to merge theory with practice. This master program greatly contributes to my future aspirations of managing my own farm or engaging in agricultural value chains.

Throughout courses, I delved into research on Norwegian salmon farming and its supply chain, conducted visits and interviews at diverse farms in Sweden, gained insights into the forests of southern Sweden, and prepared to compile a research report on organic farming in Australia. The internship at IKEA's textile department has further enriched my knowledge and experiences. I have learned that the textile industry poses significant environmental challenges, including pollution and water scarcity. It is essential to conduct sustainable practices, such as utilizing recycled products like cotton and viscose, as well as exploring renewable raw materials like hybrid poplar, agro-waste, and bamboo, to reduce waste, carbon emissions, and water consumption in textile production. IKEA can enhance its sustainability efforts by replacing synthetic fibers with renewable alternatives, prioritizing high-yield crops and low-impact woods, thereby contributing to circular production and environmental preservation.

I am particularly excited about the prospect of interconnecting my background in medical science and microbiology with the agricultural domain, thus contributing to the positive development of humanity and our planet.

Whether it pertains to technological advancements or personal growth, sustainability stands as a cornerstone. In our current age, our planet bears the scars of myriad wounds, beset by recurring natural disasters. Post my engagement with this program, I find myself better equipped to steer towards the right direction in making a meaningful impact upon the world. Furthermore, I aspire to provide the right guidance and influence to those around me.

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# Abbreviations

| | |
|---|---|
| BCI | Better Cotton Initiative |
| CNCs | cellulose nanocrystals |
| EVA | ethylene vinyl acetate |
| FAO | Food and Agriculture Organization of the United Nations |
| FSC | Forest Stewardship Council |
| GHG | greenhouse gas |
| MMCF | the man-made cellulosic fiber |
| NMMO | N-methyl morpholine-N-oxide |
| PEFC | Programme for the Endorsement of Forest Certification |
| PET | polyester |
| PHA | Polyhydroxyalkanoates |
| PLA | polylactic acid |
| PP | polypropylene |
| PU | Polyurethane |
| SAC | Sustainable Apparel Coalition |
| SCB | Sugarcane bagasse |
| RCS | Recycled Claim Standard |
| rCotton | recycled cotton |
| rPET | recycled polyester |
| USDA | U.S. Department of Agriculture |
| VSF | Viscose staple fiber |
| WWF | World Wildlife Fund |

## Glossary of terms

Closed-loop production: during textile processing, chemicals and water used in production are recycled. Any post-consumer waste is recollected and reused to start the process all over again.

Lyocell: a relatively costly variant of rayon that utilizes N-methyl morpholine N-oxide (NMMO) solvent to dissolve cellulose. It is considered more eco-friendly than viscose as it employs a closed-loop solvent-spinning process without harmful emissions.

Rayon: a semi-synthetic fiber derived from regenerated cellulose obtained from wood and related agricultural products. It is made by dissolving cellulose and converting it into insoluble fibrous cellulose. Viscose and lyocell are two popular methods used to produce rayon.

Viscose: the most widely used variant of rayon that has been in production for over a century. The processing procedure involves the use of NaOH, $Na_2S$, and $CS_2$.

Tensile strength: the maximum amount of stretching force or load that the fabric can withstand before it starts to break under stretching conditions. It is typically measured in units such as Newtons, pounds, or kilogram-force.

# 1. Introduction

## 1.1 Climate change and some other worldwide challenges

### 1.1.1 Heatwaves

There has been a steady increase in global heat extremes in recent decades, and this trend is expected to continue due to global warming. The sequence of incredibly hot and arid summers in 2018, 2019, and 2020 confirms this trend (1). From June to August of 2022, heatwaves in Europe led to over 20,000 fatalities due to heat-related illnesses, with Portugal experiencing the highest recorded temperature of 47.0 °C (2). It is anticipated that European heatwaves will escalate faster in the upcoming years than the global average temperature (3).

### 1.1.2 Drought

Climate change makes droughts become more severe worldwide, with more drought areas globally and certain regions that are anticipated to encounter more frequent, intense, and prolonged droughts being especially vulnerable to its effects. Warmer temperatures cause increased evaporation and reduced surface water, soil moisture, vegetation, and precipitation to fall as snow. The decreased snowpack affects water management systems and ecosystems. Since snow acts as a reflective surface, decreasing snow area increases surface temperatures, further exacerbating global warming and drought (4).

Severe drought can result in limited access to water for household use. It affects livestock and crops, causing food price instability. If countries are already facing food insecurity, cost spikes can lead to social unrest, migration, and famine (4). It reduces flows in rivers and streams, resulting in concentrated pollutants, which threaten drinking water quality. It also influences transportation via e.g., lower river water levels, drought-fueled wildfires, and buckled roadways. The drought-fueled wildfires can exacerbate chronic respiratory illnesses among communities exposed to smoke and pollutants. Droughts also increase the concentration of carbon dioxide in the atmosphere and soil erosion and decrease land productivity, which can release carbon dioxide sequestered in trees and plants back into the atmosphere. Droughts affect electricity production by hydropower stations, coal, and nuclear power plants that require cooling water to maintain safe operations.

### 1.1.3 Water Challenges in China and India

Water does not have viable substitutes. In China, 65% of water usage is attributed to agriculture, 22% to power generation and manufacturing, and the majority of the remaining is consumed by households (5). The availability of water in China is limited. The water supply gap could reach 25% by 2030 (6). The groundwater resources reduce by approximately 60 billion cubic meters per year (7). Northern China's aquifers are among the most overdrawn in the world and the region north of the Yangtze River, the most populous portion of China, has experienced consistent decreases in water storage during the last 15 years (NASA GRACE) (8). The unsustainability of the water system in northern China threatens certain parts of southern China. As to surface water, about 19% was categorized as unsuitable for human consumption, and approximately 7% was deemed unsuitable for any purpose (9). China's farming practices currently use almost 2.5 times more fertilizer and four times as many pesticides as the U.S. (FAOSTAT, 10).

India, one of the most water-stressed nations globally, with 18% of the world's population, has access to only 4% of its water resources (11). Approximately 600 million people in India are facing high to extreme water stress, and 75% of households do not have access to drinking water on their premises (12). Groundwater is over-exploited and in some regions, more water has been extracted than its annual replenishment (13). The country's reliance on an unpredictable monsoon to meet its water needs increases this difficulty, which is expected to worsen due to climate change. Water scarcity raises questions about the future of food production. By 2030, 74% and 65% of the land utilized for growing wheat and rice will suffer significant water scarcity, respectively (NITI Aayog 2019) (14). In India, over 100 million people do not have safe water and the crisis is only going to get worse (15).

### 1.1.4 Land degradation

25% of the ice-free land area is subject to human-induced degradation (16). At least 4% of the world's agricultural land is seriously degraded (17). Land degradation affects 3.2 billion individuals worldwide, with a particular emphasis on rural communities, smallholder farmers, and those who are extremely impoverished (18). The degradation is mainly caused by extreme weather conditions, particularly drought, and human activities that pollute or degrade the quality of soils and land utility from *e.g.,* agriculture, livestock production, urbanization, deforestation, industry, and mining. Land degradation affects the productivity of croplands and rangelands, food security, food prices, biodiversity, environment, and ecosystem services and it is a major contributor to climate change as it leads to the release of soil carbon and nitrous oxide into the atmosphere (19). In turn, climate change exacerbates land degradation. Desertification is a form of land degradation by which previously fertile land loses its productivity and transforms into a desert-like environment. Recent warnings from scientists indicate that about 22 billion tonnes of fertile soil are lost annually, mainly due to unsustainable agricultural practices. If this trend persists, it could result in 95% of the Earth's land areas becoming degraded by 2050 (18).

## 1.1.5 Hunger

An estimated 702-828 million people in the world faced hunger in 2021 (Fig. 1) (20). FAO measures the percentage of a population that is encountering moderate to severe food insecurity. Moderately food-insecure individuals may have uncertain access to food and may take cheaper, less nutritious, highly processed foods that contribute to obesity and malnutrition. These foods, cheaper than fresh fruits and vegetables, may meet calorie requirements but lack essential nutrients for good health. Uncertain access to food and hunger can also contribute to overweight and obesity, with children being particularly vulnerable. In some countries, undernutrition and obesity coexist as consequences of food insecurity.

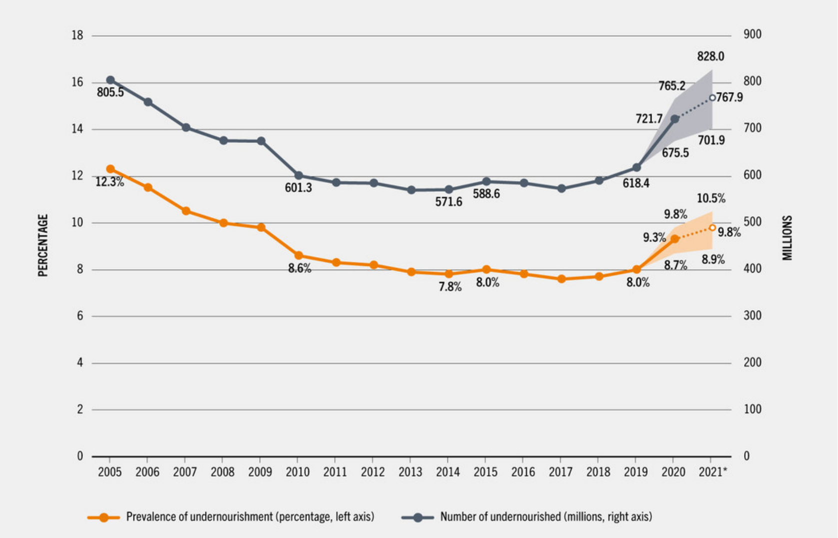

*Figure 1. Prevalence of undernourishment and number of undernourished population in the world (20) (Data are available on FAOSTAT).*

### 1.1.6 Arable land in Sweden

Agricultural land in Sweden covers 3 million hectares, consisting of nearly 2.6 million hectares of arable land and roughly 450,000 hectares of pasture land (21). Of the arable land, approximately 1 million hectares are used for growing grains, just over 1 million hectares for forage, and the remaining land is mainly dedicated to cultivating crops such as rape seed, potatoes, sugar beets, protein crops, and fallow areas. The cultivated area has been decreasing annually (Fig. 2), leading to a reduction in Sweden's self-sufficiency in food. In the past, Sweden utilized up to 50 percent more arable land than it does currently (21).

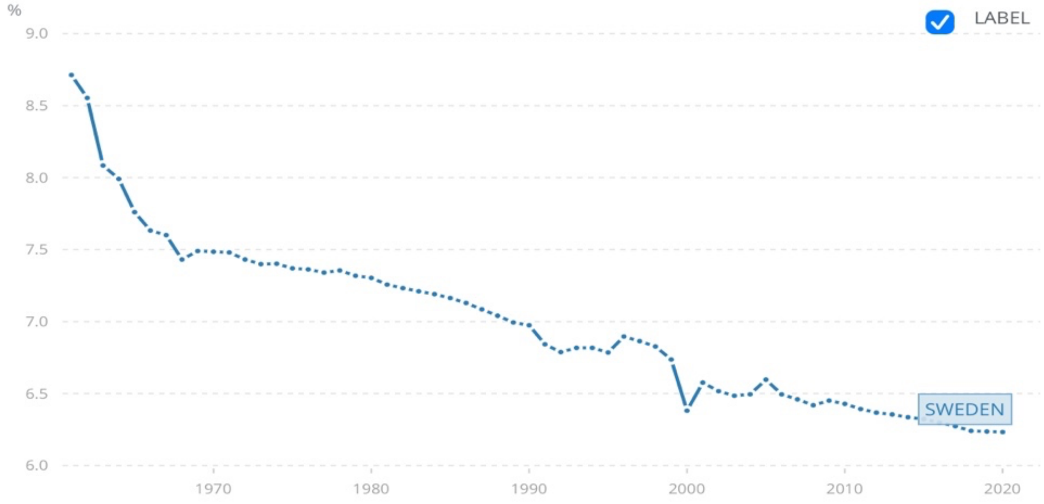

*Figure 2. Arable land (% of land area) in Sweden (22).*

### 1.1.7 The water footprint

The water footprint is composed of green, blue, and grey water types (23). Green water is the water transpired by plants and originates from rainwater that is stored in the soil. Blue water is the water found in surface and groundwater reservoirs, which is extracted for transpiration in irrigated agriculture. The efficient use of blue water is crucial for sustainable production. Soil is a storage reservoir for the green water that falls from the sky, or that which has been added through irrigation from blue-water reservoirs. Grey water, on the other hand, is water polluted during production, such as through the leaching of nutrients and pesticides in agriculture. The volume of grey water can be quantified by determining the amount of blue water required to dilute the receiving water body to an acceptable quality standard.

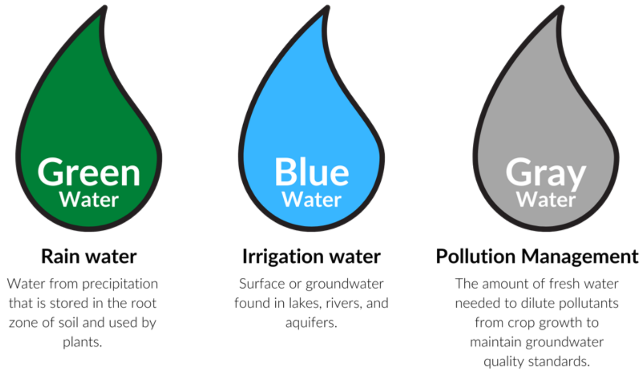

*Figure 3 Three colors of water that make up virtual water: green water is the evapotranspired rainwater from soil; blue water is used for irrigation purposes and grey water is contaminated by agrochemicals (24).*

## 1.2 Textile and its industry-induced environmental problems

Conventional textile production practices contribute to 10% of global greenhouse gas (GHG) emissions (25). Only 1% of textiles are effectively recycled after use worldwide (26). Out of the total textile waste generated by consumers in the EU, which amounts to 5.3 million tonnes annually, only a quarter of it is recycled or reused (27). In the U.S., this figure is 15% (28). The rest are either incinerated or dumped into landfills: non-degradable fabrics produce additional ecosystem pollution. Moreover, the production of synthetic textiles and animal leather induces tremendous contamination of the environment, including $CO_2$ emissions. The former utilizes nonrenewable fossil fuel resources and causes extra plastic waste, while the latter addresses animal welfare ethics. All these contaminations jeopardize the water cycle and soil and are detrimental to living organisms and negatively affect agriculture production. The global production of textile raw materials is shown in Fig. 4, which is estimated by Lenzing (29).

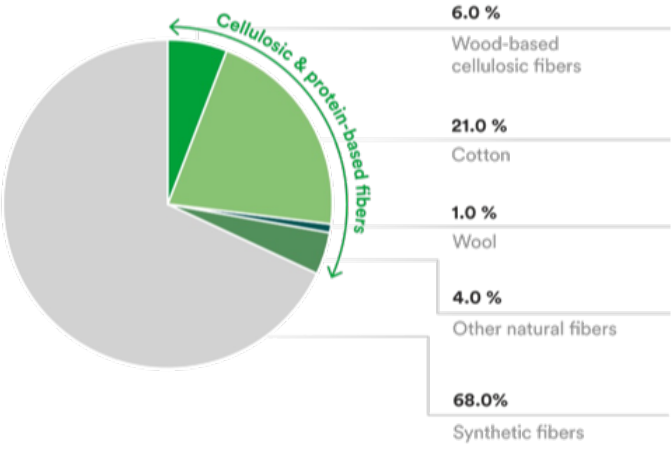

*Figure 4. Global textile fiber production 2021 by type of fiber in percent (basis = 105 million tonnes), Lenzing Annual Report 2021 (29).*

### 1.2.1 Cotton

Cotton (*Gossypium sp.*) is the largest natural fiber in the world: nearly 23 million tonnes of cotton is produced annually and its yearly economic influence is considerable, amounting to no less than 600 billion US dollars (30). Cotton is the most extensively grown non-food crop globally, known for its profitability. Its cultivation generates income for over 250 million individuals globally and employs nearly 7% of the workforce in developing nations (31). The top ten cotton-producing countries are India, China, the U.S., Pakistan, Brazil, Australia, Uzbekistan, Turkey, Turkmenistan, and Burkina Faso. Cotton cultivation occupies large areas of arable land (34.5 million hectares in 2021, FAOSTAT), consumes a huge amount of irrigation water (blue water 2955 liters/ton in 2021) (32, Tab. 1), and requires substantial agrochemicals (especially pesticides). This leads to soil erosion and degradation, water pollution, and damage to biodiversity and ecosystems.

While the global land area dedicated to cotton cultivation has remained steady for the last seven decades, the soil in numerous regions has been depleted and degraded due to cotton production. Despite cotton being predominantly grown on well-established fields, their exhaustion has necessitated expansion into new territories, leading to the destruction of habitats. The production of cotton in India has a significant land footprint. India has the largest land area dedicated to cotton cultivation, accounting for around 38% of the world's total cotton cultivation area in 2021 (29) and approximately 6% of India's total cropped area. India usually grows cotton on extensive monoculture farms, which worsens soil erosion and reduces fertility, leading to increased fertilization needs. Deforestation is a common practice to create space for cotton plantations in India (33).

Cotton is the most water-intensive crop (30). To irrigate cotton fields, both surface and groundwater are often redirected, resulting in a loss of freshwater due to evaporation and ineffective water management. Therefore, in many cotton-growing regions, water becomes a scarce resource, resulting from depleted local water supplies by irrigating cotton. In India, the severe water scarcity is exacerbated by the cotton industry. 24.8 thousand liters/tonne of total water is consumed by cotton in India (15), more than double the world's average water footprint (34). The cotton industry is one of the major contributors to water pollution: approximately 50% of all pesticides used in India are in cotton production (15). Water scarcity is a major issue for cotton farmers in China, too, as the overuse of water for cotton farming has led to a decline in groundwater levels, causing land subsidence and ecological problems, particularly in the northwest region where much of China's cotton is grown. In the U.S., rainfall was the only source of water for 64% of cotton produced, whereas a mere 5% was cultivated with full irrigation, however, presently, approximately 44.6%, of the U.S. is experiencing ‘moderate to exceptional’ drought (35).

*Table 1. The annual production, land occupation, and three major producers of seed cotton (Gossypium sp.) in the 2021 crop year, together with the annual production and yield of cotton lint in 2020 (FAOSTAT). The data for lint production in 2021 is not available in FAO. *The water footprint value of the cotton seed and lint is from Mekonnen and Hoekstra (32).*

| **Cotton** | |
|---|---|
| Global production (seed, 2021) | 90.0 million tonnes |
| Global production (lint, 2020) | 30.1 million tonnes |
| Land occupation (2021) | 35.6 million ha |
| Yield (lint, 2020) | 0.95 tonnes/ha |
| Water footprint (green, seed)* | 2516 liters/tonne |
| Water footprint (blue, seed)* | 1440 liters/tonne |
| Water footprint (grey, seed)* | 485 liters/tonne |
| Water footprint (green, lint)* | 5692 liters/tonne |
| Water footprint (blue, lint)* | 3257 liters/tonne |
| Water footprint (grey, lint)* | 1098 liters/tonne |
| Main producers of the lint (by shares, 2021) | India 20.4%<br>China 19.6%<br>The U.S. 10.6% |

Electricity is the primary input for the ginning process of the cotton industry, which involves separating seed cotton into lint cotton and seeds. The spinning process requires electricity, water, and chemicals like lubricants, emulsifiers, and coning oils. The wastewater produced during the spinning process is treated before disposal in countries with strict regulations or larger and more modern cotton spinning facilities. The results of characterizing conventional cotton cultivation in water consumption and water scarcity footprint are compared across five countries in Fig. 5 (36). The comparison involves scaling the results for each country in relation to China, which is taken as the baseline at 100%. Among the five countries, Pakistan and India have the highest water consumption, whereas Brazil has the lowest. However, Pakistan has the highest water scarcity footprint, which is significantly greater than that of India. The majority of water consumption is from seed cotton cultivation, with irrigation water (blue water) being the main contributor to this consumption.

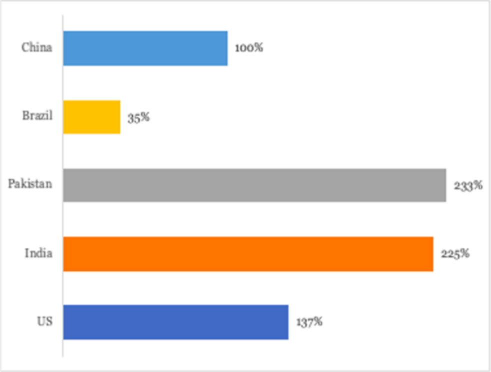

*Figure 5 Comparison of water consumption of conventional virgin cotton yarns in China, Brazil, Pakistan, India and the U.S. (36).*

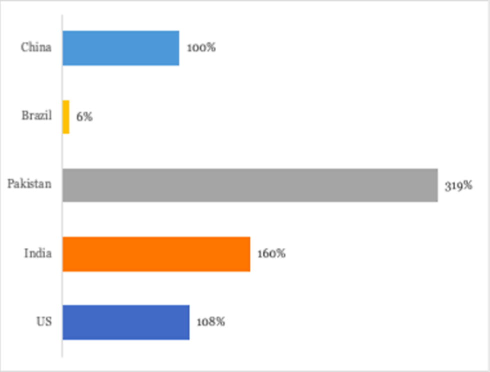

*Figure 6 Comparison of water scarcity footprint of conventional virgin cotton yarns in China, Brazil, Pakistan, India and the U.S. (36).*

Due to the many pests and weeds attracted to cotton, the sales of pesticides and insecticides for cotton farming make up 4.7% and 10% of the world's total sales, respectively (37). The overuse of pesticides can lead to the development of pesticide-resistant pests, disruption to populations of beneficial insects and secondary pest outbreaks, which makes it even harder to control them. India’s cotton production has the highest impact on freshwater eutrophication among several countries (China, Brazil, Pakistan, India, and the U.S.). India's impact is four-fold that of China, with Pakistan following as the second highest. Direct field emissions of phosphate and the production of coal-based electricity for irrigation, as well as the use of coal-based electricity within spinning, are the primary causes of freshwater eutrophication. Freshwater ecotoxicity mainly results from the use of electricity and fertilizers and India has the highest impact in this category, being twice that of China (36).

A pilot project was initiated by World Wildlife Fund (WWF) and IKEA to improve cotton-farming practices, which led to the establishment of the Better Cotton Initiative (BCI). BCI has emerged as the largest cotton sustainability program globally, aiming to promote sustainable practices that reduce environmental impact, enhance soil health, promote biodiversity, improve the livelihoods of cotton farmers, and enhance transparency in the cotton supply chain. The BCI accomplishes its objectives through a range of measures, including education, training, and partnerships with farmers, businesses, and other stakeholders such as textile mills, manufacturers, and retailers. These partnerships promote the adoption of sustainable cotton production practices and increase transparency and traceability in the cotton supply chain. Adopting the Better Cotton standards, over 75,000 Pakistani farmers have reduced their water use by 39%, and pesticide and chemical fertilizer use by 47% and 39%, respectively, while maintaining yields and increasing income by 11% (30). According to BCI's 2021 annual report, its program had reached 2.9 million farmers in 26 countries, and 4.7 million tonnes of Better Cotton had been produced, accounting for 20% of global cotton production 36. Additionally, BCI launched a new program in 2020 focusing on gender equality and women's empowerment in cotton farming communities (38). All of IKEA's cotton is sustainably cultivated through the BCI and the cotton takes up 20% of IKEA's total textiles and comfort materials by weight (39).

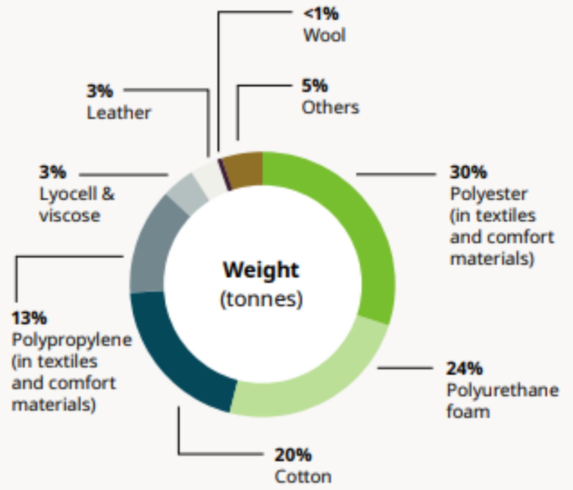

*Figure 7 Share of IKEA's textiles and comfort materials by weight (% tonnes) in 2022 (39).*

## 1.2.2 Synthetic textiles

Most synthetic fibers derived from petrochemicals, including commonly used types such as polyester, nylon, elastane, and acrylic, make up 62% of all fiber production. In 2020, the estimated global production of synthetic fibers reached approximately 62 million tonnes (40). China produced the most synthetic fibers in the world in 2021 at 73%, followed by India at 7%, and the U.S. at 3% (41). Synthetic fibers are characterized by their technical properties, affordability, and durability, while natural fibers require higher investments in land and water to grow. China is the primary producer of synthetic fibers. These materials tend to be resistant to biodegradation, leading to long-lasting pollution. The extraction and processing of these petrochemicals have significant environmental impacts, including air and water pollution, GHG emissions caused by a considerable amount of energy use, and wildlife habitat destruction. It demands a substantial quantity of water, especially during the dyeing and finishing processes, resulting in water scarcity in regions where water resources are already limited. In addition, washing synthetic textiles releases microplastics into the waterways, which are toxic to aquatic organisms, soil, terrestrial animals, and crops/plants and can ultimately end up in the food chain. The disposal of synthetic textiles through landfills releases GHG such as methane and carbon dioxide and chemicals that contaminate groundwater and surface water and harm aquatic ecosystems. It pollutes soil as well and inhibits plant growth.

Sustainable synthetic fibers can be obtained in two ways: either from recycled petrochemical feedstocks, such as plastic recycling, or from a natural source such as fungi or sugar (42), known as "bio-based synthetics". **Polyester (PET)** is an easily recyclable material, unlike nylon, and its recycling helps in reducing the waste that accumulates in landfills. PET constitutes around 55% of the global fiber production volume, with an annual production of 52 million tonnes. PET is characterized by its low cost, range of properties, durability, good strength, and resistance to fading, shrinking, wrinkling, moisture, abrasion, and chemicals. Currently, textiles contain an average of 15% recycled polyester (rPET). Due to the growing demand for sustainable products from consumers, governments, and NGOs, the utilization of rPET in textiles is rapidly increasing. The primary source of rPET is post-consumer PET bottles that are melted down and re-spun into new polyester fibers. Recycling one ton of polyester conserves 11,100 kWh of energy, which is equivalent to the energy consumption of an average household for two years (41). Additionally, using mechanically recycled polyester results in a reduction of over 70% in GHG emissions compared to virgin polyester (43). IKEA has managed to attain an almost 90% rate across all polyester-based materials (textiles and filling fibers) and it has launched numerous new products that contain 100% recycled polyester (40). Polyester products make up 30% of total IKEA textiles and comfort materials (Fig. 7)

**Polyurethane (PU)** is petrochemical-based material. Global production is 25 million metric tonnes in 2019 (44). Asia Pacific accounts for nearly half of global polyurethane market production, with China being the top producer at 32% of global output in 2021 (45). Foams are the largest application accounting for 67% of all PU produced in 2016. PU is combustible and decomposition from the fire can release various hazardous substances, such as carbon monoxide, hydrogen cyanide, nitrogen oxides, isocyanates, and other toxic byproducts (46). Due to the flammability of the material, PU needs to be treated with flame retardants, particularly in the case of furniture. However, the majority of flame retardants are known to be harmful (47). However, non-burned PU is considered safe for human health. PU foam is affordable, durable, and comfortable. There are currently no widely available and cost-effective alternatives that can match the performance characteristics of PU foam in furniture. Sustainable alternatives, such as plant-based foams and natural latex, still have their own set of challenges, such as high cost, limited availability, or reduced durability. To address the environmental and health concerns associated with PU foam, IKEA has committed to phasing out the use of flame retardants in its products. PU can be recycled, but the process is often difficult and expensive, and the resulting recycled material may not have the same properties as the original PU.

The fiber of **polypropylene** (**PP**) produced worldwide was 3.03 million tonnes in 2021 (48). It has a high strength-to-weight ratio, which makes it strong and durable while also being lightweight. It is resistant to moisture, chemicals, UV radiation, mold, mildew, and other types of bacterial growth (49). Therefore, it is an excellent choice for fabrics used outdoors. It is easy to maintain, capable of being machine washed and dried without losing its shape or durability. It has been demonstrated that microbial colonies derived from soil samples containing starch are capable of degrading PP (50). While not highly flammable, PP-based textiles can liquefy under extreme heat, potentially causing severe burns to anyone wearing them in the event of a fire or explosion (51). While PP is recyclable, only around 1% of all PP in the U.S. is actually recycled (52). The dyeing process of PP is dope-dyeing, which does not require any water (53). Advocacy group Environmental Working Group makes PP categorized as a substance with a moderate level of risk in allergies and immunotoxicity (54).

While still a relatively small portion of the overall synthetic materials market, the production of bio-based synthetics is expected to continue to grow in the coming years as the technology and infrastructure for their production and processing become more advanced and cost-effective. Not all bio-based synthetic fibers are biodegradable. **Polylactic acid (PLA)** is derived from renewable resources such as cornstarch, sugarcane, or other plant-based materials and its reputation comes from its cost-effectiveness as well. As of 2021, it has the highest consumption volume among all bioplastics globally and it is the most commonly used plastic filament material in 3D printing (55). PLA is a type of compostable polyester that can be broken down naturally by certain bacteria under specific conditions, such as high temperatures and moisture. However, if these conditions are not present, for instance in a landfill and in the ocean, PLA can persist in the environment for a prolonged period, much like traditional synthetic fibers.

### 1.2.3 Man-made cellulosic fibers (MMCFs)

MMCFs are usually wood-based materials, such as viscose and lyocell, that are particularly promising alternatives to synthetics due to their natural, renewable, and biodegradable attributes. Bamboo (*Bambusoideae*) and cotton linters can also be used, depending on regional availability. **Viscose** comprises approximately 79% of the overall market share for manufactured cellulose fibers (56). Its production entails utilizing trees derived from both ancient and endangered forests, as well as plantations established as replacements for forests (57, 58). Pulp production plantations are present in countries with extensive forest coverage like Indonesia, India, Canada, the U.S., and Sweden. Indonesia, home to 23% of the world's carbon-rich tropical peatlands, experiences a climate impact when replanting occurs on peatlands due to the release of carbon into the atmosphere. Its manufacture processing involves the pre-treatment of wood pulp where chemicals like NaOH and $Na_2S$ are utilized to eliminate impurities and disintegrate the cellulose fibers and dissolution where the purified wood pulp is dissolved in a mixture of NaOH and $CS_2$, creating a thick and sticky solution (viscose). The viscous solution is then extruded through spinnerets, then washed, and stretched to improve the fiber's strength. The chemicals used can be toxic to workers and the environment if not managed properly. $CS_2$ is highly corrosive and in direct contact causes severe skin burns and damages eyes and it can cause neurological and cardiovascular diseases if exposed to high levels (59). The manufacturing process also demands substantial amounts of water and the resulting wastewater can be harmful to aquatic ecosystems and the hydrologic cycle if not adequately treated or disposed of. To mitigate these environmental impacts, some manufacturers are implementing sustainable practices such as using closed-loop production processes or seeking certification from organizations *e.g.,* the Forest Stewardship Council (FSC) and the Sustainable Apparel Coalition (SAC) to demonstrate their commitment to sustainable forestry: no trees harvested from old-growth forests or other types of protected forests. Viscose staple fiber (VSF) is a frequently produced type of viscose, and the Asia-Pacific region is predicted to dominate its market share due to surging demand for yarn production, with China serving as the foremost producer and consumer worldwide (58). VSF's advantages include its soft texture, high absorbency, moisture regulation, breathability, excellent drape properties, versatility, and ease of dyeing, while its limitations include unsuitable for the dryer, prone to knot weave, low tear strength, low wet strength, poor sunlight resistance, and a tendency to wrinkle.

**Lyocell** is also a regenerated cellulose fiber, but it is produced through an N-methyl morpholine-N-oxide (NMMO) solvent-spinning process (60). Wood pulp or other cellulose sources are dissolved in this non-toxic and biodegradable NMMO solvent to create a solution called "dope", which is then filtered to remove impurities before being extruded into a coagulating bath where solid fibers are formed. These fibers are washed and finished with various processes to enhance their properties. Lyocell is more environmentally friendly than viscose because it is produced using a closed-loop solvent-spinning process that allows for over 99.5% of the solvents to be reused and recycled, with the remaining 0.5% discharged as non-hazardous effluent (61). A lower amount of water is required in the processing compared with viscose (62), and lyocell takes up 50% of the water consumed by cotton production (63). This material is known for its soft and comfortable texture, high strength, and good moisture management, as well as its breathability and ability to regulate body temperature. Although lyocell production continues in countries such as Austria, the UK, and the U.S., the majority of this textile is currently manufactured in China (62). All of IKEA’s MMCFs are sourced from FSC wood. To expand its renewable textile options and reduce its climate footprint, IKEA is utilizing and plans to increase the use of more manufactured cellulose materials, including lyocell and viscose (39).

The objective of this thesis is to investigate current advancements in renewable fibers that exhibit greater sustainability compared to synthetic fibers and cotton in textile applications. Diverse natural raw materials were surveyed and chosen for analysis based on their productivity, ability to withstand prolonged periods of drought, and their potential to enhance food sufficiency. The annual production, yield, and water footprint of the selected plant raw materials were compared, while the environmental impact of both the cultivation and processing stages of various textile raw materials was evaluated. This thesis aims to facilitate the fashion and homeware industries, with a specific focus on IKEA, by examining these factors and aiding in the identification of sustainable sources for future renewable textile materials. This endeavor seeks to enable the introduction of novel material-based products or the expansion of existing product lines, while simultaneously promoting enhanced sustainability awareness among producers and customers.

# 2. Methods

Natural raw materials were identified through an extensive literature review, key words, such as textile innovations and name of each raw materials, were used for searching. Data pertaining to the annual production, land occupation, yield, and largest producers of the selected raw materials were obtained from the database of the Food and Agriculture Organization of the United Nations (FAO) https://www.fao.org/faostat/en/#data/QCL. Other data of production and yield that were marked with 'estimated' was calculated via the corresponding weight ratio. The data on water footprint was obtained from Mekonnen and Hoekstra, 2011 (32).

In the results section, only the most viable raw material candidates for IKEA textile applications were identified and subjected to analysis. Those textile raw materials, including flax that have been used in IKEA's textile production, were excluded from the candidate selection. However, flax was considered in the statistical comparison of production, land occupation, yield, and water footprint with other selected raw materials. The statistical test ANOVA (Analysis of Variance) two factors without replication (Microsoft Excel software) was used to compare the yield of four fiber raw materials from five countries (Fig. 31).

# 3. Results

## 3.1 Cotton

In the world, India uses the largest land area for cotton growth, with 38% of the world's total cotton cultivation area in 2021 (FAOSTAT, Fig. 8). However, it only contributes 19% to the global output due to the relatively low yield per acre. China is the biggest exporter of cotton (12.1 billion US dollars), but it is also the biggest importer (9.73 billion US dollars) in 2021 according to the value, and Vietnam and Pakistan have similar trade strategies (Fig. 9) (64). India and the U.S. did not export most of their cotton yield.

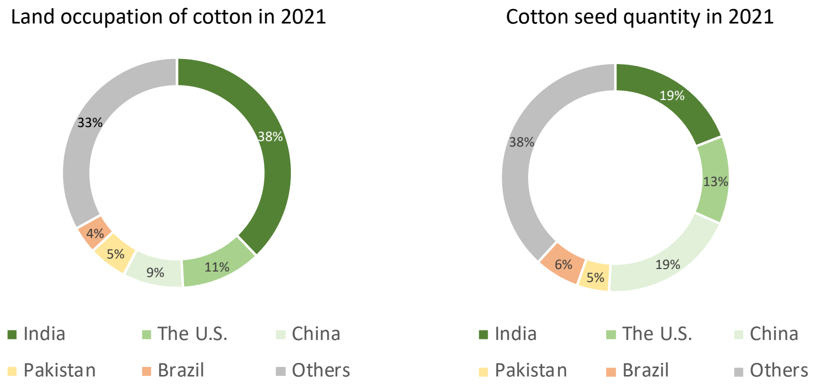

*Figure 8 The land use and quantity of cotton in India, the U.S., China, Pakistan, and Brazil in 2021 crop year. The data is originated from FAOSTAT.*

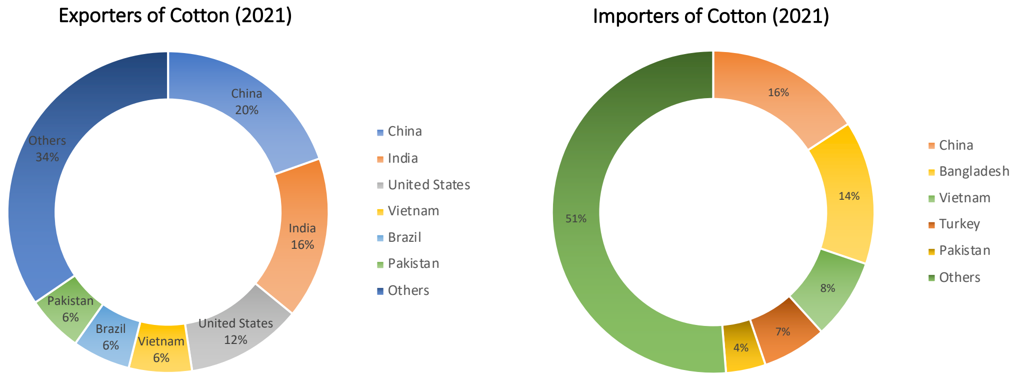

*Figure 9 Top exporters and importers of cotton by share in 2021 crop year. The data is from OEC (64).*

## 3.2 Viscose's raw materials and pollution status

Viscose is made of wood such as eucalyptus (*Eucalyptus sp.*), spruce (*Picea*), pine (*Pinus*), beech (*Fagus*), acacia (*Acacia*), bamboo (*Bambusoideae*), sugarcane (*Saccharum*), etc. (65, 66). Nevertheless, the environmental and social impacts of using specific tree species for producing wood pulp can vary, depending on factors such as the source of the wood, forest management practices, and production methods. Surprisingly, over 200 million trees are felled annually to manufacture cellulosic fabrics and approximately half of the 5.9 million tonnes of viscose pulp produced annually originates from ancient and endangered forests, such as the carbon-rich peatlands of Indonesia and old-growth boreal forests of Canada (67, 68). These vital forest ecosystems harboring a vast proportion of terrestrial life, exhibit exceptional carbon sequestration and storage abilities and are considered as a key component in mitigating both the climate crisis and biodiversity loss.

Cheap production, which is driven by the fast fashion industry, is proving to be a toxic mix. This is combined with lax enforcement of environmental regulations in China, India, and Indonesia, where most viscose manufacturers are clustered geographically. These viscose mills discharge untreated sewage and toxic fumes, polluting water bodies and air, impacting the health of residents, and potentially leading to increased cancer cases (69). Residents avoid drinking well water due to concerns about health impacts, and local fishermen's livelihoods are disproportionately impacted. Factory workers are observed washing viscose fiber intermediate products on riverbanks, exposing themselves to toxic chemicals. Yet it is possible to produce viscose sustainably, using closed-loop processes, where no chemicals enter the waste stream, and utilizing sustainable raw materials. Viscose produced under such circumstances can have a lower environmental impact than conventional cotton or oil-based synthetic fibers, such as polyester (67).

## 3.3 MMCFs innovations

TreeToTextile in Sweden sources wood pulp from sustainably managed forests, such as FSC or the Programme for the Endorsement of Forest Certification (PEFC) certified, and has implemented a closed-loop production system that minimizes chemical use via employing enzymes instead of harsh chemicals and utilizing efficient dyeing and finishing techniques, optimizes energy utilization, and recycles and reuses water and the chemicals used without sulfur emissions, allowing for a more sustainable and cost-efficient process compared to conventional technologies and fibers (70). The technology has reduced energy by 33%, chemical by 70%, and water usage by 80% compared to conventional viscose processes and has significantly lowered water consumption compared to average cotton and eliminates the need for pesticides, herbicides, and fertilizers. This regenerated cellulosic fiber has similar properties to both cotton and viscose. This innovation is currently in development to further refine its process. However, the technology is ready to scale up the production, with the aim of introducing the fiber to the market.

IKEA has sourced all of its MMCFs from FSC woods (39) and intends to exclusively source MMCFs from the "dark green shirts" designation by the end of 2025, as identified in Canopy's Hot Button Ranking and Report (71). This ranking is an essential tool for assessing primary fiber sourcing in the fashion industry, with a focus on forests, evaluating producers based on their risk of sourcing from endangered forests, leadership in conservation advocacy, and use of alternative feedstocks. The goal of the ranking is to eliminate the use of ancient and endangered forests in viscose and other cellulosic fabrics, while promoting textiles made from innovative fibers, with over 520 global brands seeking to source from "green shirt" producers and proactively engaging in greening their viscose supply chains. IKEA is the first major retailer focused on the home textile and furnishing space to join CanopyStyle.

**Recycled cotton (rCotton) and viscose** Given that the production of cotton and viscose textiles generates over 25 million tonnes of waste globally on an annual basis (72), the advent of technologies capable of generating nearly one tonne of MMCF from a single tonne of rCotton presents a unique opportunity for transitioning to circular production. Specifically, it is possible to produce all 6.5 million tonnes of viscose projected for this year using only 25% of the world's discarded cotton and viscose fabrics, thus resulting in a range of benefits, such as forest conservation, reduced municipal and industrial waste sent to landfills, as well as significantly lowering carbon emissions, energy, and water consumption compared to the process of growing, harvesting, and processing new raw materials. RCotton can be used to make textiles, including towels and stuffing (e.g. for stuffed animals and pillows).

However, cotton and other natural fibers cannot be continuously recycled. Pre-consumer cotton, the scraps of cotton fabric that have been left over from making textiles, is considered the most recyclable as it is easier to handle. Post-consumer cotton, the cotton textiles from consumers, is technically recyclable but is difficult to process due to the variety of colors, sizes, and textures, as well as the presence of blended non-recyclable fibers such as polyester or spandex, which increases the likelihood of contamination in the recycling stream (73). Recycling cotton fibers results in a reduction in their length, strength, durability, and consistency in structure, which can limit their use in certain applications, for example, less desirable for textile manufacturers who require uniformity in their raw materials. To maintain these properties in new textiles, rCotton might be blended with other materials. However, blending is often not feasible in recycling facilities, and the use of synthetic fibers in blends is not environmentally friendly. Cotton fibers share structural similarities with paper and wood, which constrains the number of times they can be recycled, contingent on the original product's size and strength. The cost of rCotton is frequently observed to exceed that of virgin cotton (73), but preliminary assessments from IKEA demonstrate that rCotton is approximately 30% less expensive than virgin cotton, while exhibiting an 80% lower climate footprint (39). The differences in price might result from the abundance of cotton-based waste fabrics and the thickness of rCotton yarn required. Taken together, the recycling of cotton is generally limited to textile manufacturers who generate substantial amounts of textile waste and possess the necessary resources to undertake recycling operations.

Infinna™, a cotton-like cellulose carbamate fiber, is produced from cotton-rich textile waste, used cardboard, paper, wheat, or rice straw (74). Blended post-consumer fabrics that contain materials like polyester and elastane can also be used as raw materials. Carbon disulfide ($CS_2$) is not used during processing. The technology has been proven and is available for licensing, and a commercial-scale factory will be established in Finland. In Sweden, Södra Mörrum's OnceMore produces rCotton dissolving pulp for textiles, utilizing fast-growing wood certified with both PEFC (Programme for the Endorsement of Forest Certification) and FSC and the Recycled Claim Standard (RCS)-certified post-consumer blended-fiber textile waste as raw materials (75). Currently, the waste that can be handled includes unbleached white cotton, cotton-polyester blends with at least 50% cotton content, and fibers such as viscose and lyocell in small quantities. This process involves the separation of cotton and polyester from polycotton blends, followed by the combination of cellulose from rCotton fibers (20%) with cellulose from wood (80%) (75). The resulting high-quality dissolving pulp is intended for use in the textile industry, akin to pulp commonly employed for viscose and lyocell production, and delivered to some of the world’s largest viscose manufacturers.

## 3.4 Diverse renewable raw materials can be used for textiles

### 3.4.1 Fast-growing trees

***Eucalypts*** (*Eucalyptus sp.*) have a global distribution and are currently found in more than 90 countries. The *Eucalyptus* forest type dominates the Australian landscape, covering a vast area of 101 million hectares (76), with a yield of 12.0 - 19.0 $m^3$/ha per year (77). Its plantation covers approximately 3, 1, and 0.6 million hectares in Brazil, India, and China, respectively, outside its natural range of Australia, Southeast Asia, and the Pacific (78, 79), with a yield of 16.0 - 25.0 $m^3$/ha per year in Brazil (77). *Eucalyptus* trees have a remarkable capacity to extract significant amounts of water from the soil, making them a popular choice for planting in regions with high groundwater levels to help regulate water levels (80). *Eucalyptus* has been cultivated in plantations worldwide due to its rapid growth and usefulness in producing valuable timber, pulpwood, honey, and essential oils, and among wood sources, *eucalypts* contribute significantly to the production of textile fibers. Brazil is a major country known for cultivating eucalyptus for textile fiber production. However, in some regions, they have been removed due to their high flammability, which poses a significant risk of forest fires. *Eucalyptus* oil is highly flammable and can cause trees to explode when ignited. Eucalyptus forests tend to promote fires due to the volatile and combustible oils produced by leaves, as well as the buildup of dry, combustible fuel from a litter containing high levels of phenolics that cannot be broken down by fungi (81). This can result in catastrophic firestorms, particularly in dense eucalypt plantings.

***Hybrid poplar*** (*Populus sp.*)The utilization of hybrid poplar trees as a source of fiber for the textile industry presents a dual advantage of conferring environmental benefits while fulfilling industry demands. These trees have high productivity during the initial years after establishment due to their life history strategy. Being pioneer species (as opposed to climax tree species), poplars are adapted to quickly colonize habitats without vegetation. They achieve maximum growth rate a few (5-15) years after establishment and are therefore cultivated in short rotations worldwide. Hybrid poplars can be cultivated on unutilized marginal lands in northern areas where traditional agricultural or forestry practices are not economically feasible. Europe has 43 million hectares of marginal land (82), which can potentially be used for cultivating hybrid poplar trees. A yield of 600-800$m^3$, which corresponds to a mean annual increment of 11 tons/ha or 31 $m^3$/ha of sustainable biomass, could be harvested each 20th-25th year from these stands grown on marginal lands in the Nordic region, which can be converted to 2.4 tonnes/ha of dissolving pulp for textile production using the lignin-first bio-refining technology (83). This sustainable fiber requires significantly less water than cotton, and no irrigation, resulting in a saving of 30 billion tonnes of blue water worldwide. Fertilization is also not necessary. Hybrid poplar trees can substitute cotton in textile production, freeing up agricultural land for food production. For example, the SnowTiger® clones of hybrid poplar trees can reach maturity in just 20 years (83), compared to the 50-100 years required for traditional secondary successional tree species such as spruce and pine, dominating Nordic forestry today. Hybrid poplar trees are also beneficial as riparian forest buffers in agricultural landscapes, as they can absorb high amounts of water and nutrients while reducing nutrient leaching and mitigating eutrophication in a changing climate (84). The adoption of hybrid poplar trees in textile production can significantly improve both economic and environmental sustainability.

*Table 2 The annual production estimation assumes that all marginal land in Europe is dedicated to the hybrid poplar cultivation. The yield of dissolving pulp was originated from Adler and et. al. 2022.*

| **Hybrid poplar** | |
|---|---|
| Global production (biomass, estimated) | 429 million tonnes |
| Land occupation (marginal land in Europe) | 43 million ha |
| Yield (dissolving pulp) | 2.4 tonnes/ha |

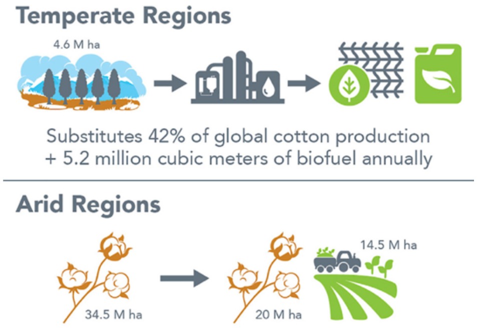

*Figure 10 2.9% of land in the Baltic Sea region (4.6 M ha) can be used for hybrid poplar plantation, which potentially frees up 14.5 M ha of fertile agricultural land currently used for cotton production (83).*

## 3.4.2 Agro-waste

Using agro-waste for textile fibers as well as food represents a more efficient use of cropland, which could be particularly beneficial in areas with limited agricultural land. The growing emphasis on agro-waste is also attributed to the sustainable management of agricultural residues and the desire to enhance the economic viability of the agriculture sector. In the textile industry, commodity crop byproducts, owing to their abundance, affordability, and renewability, are considered feasible resources for fiber production, with nearly 2000 million tonnes of such byproducts generated annually worldwide from major crops such as corn (*Zea mays L.*), wheat (*Triticum*), rice (*Oryza sativa*), soybean (*Glycine max*), *sorghum*, and sugarcane (*Saccharum*) (85). With the future cost and availability uncertainties of existing synthetic and natural fibers, utilizing agricultural byproducts as a source of natural cellulosic fibers has become increasingly interesting (86).

### 3.4.2.1 Corn and corn husk fiber

Corn (*Zea mays L.*) is by far the most widely grown cereal (1/10 of the world's crop area) (87) and the most important grain, based on a production amount of over 1.48 billion tonnes in 2021 (FAO). China's corn planting area covered one-third of the country's total arable land and produced over 272 million tonnes of corn, second only to the U.S. (384 million tonnes) (FAO). Corn has the second-highest yield among all crops due to its ability to be densely planted and grow upwards (88). Its growth duration is 4 months and it is more resistant to drought and high temperatures compared to wheat and rice since its leaves are less stretchable and have a protective cuticle. Corn can absorb carbon dioxide more efficiently than rice and wheat due to its unique type of C4 photosynthesis.

*Table 3 Annual production of corn (Zea mays L.), land occupation, yield, and three largest producers by weight production in the 2021 crop year (FAOSTAT). The global production of husk and yield of the husk was calculated based on the relative weight ratio of the corn husk compared with the corn (17.5:100) and the yield of husk fiber was estimated according to Mei Zheng et. al. 2022 (89). *The water footprint value of the corn is from Mekonnen and Hoekstra (32) and the consumption is only for corn cultivation.*

| **Corn** | **2021** |
|---|---|
| Global production (seed) | 1.48 billion tonnes |
| Global production (husk, estimated) | 0.26 billion tonnes |
| Land occupation | 249 million ha |
| Yield (corn) | 5.06 tonnes/ha |
| Yield (husk, estimated) | 1.04 tonnes/ha |
| Yield (husk fiber, estimated) | 0.76 tonnes/ha |
| Water footprint (green)* | 1044 liters/tonne |
| Water footprint (blue) * | 89 liters/tonne |
| Water footprint (grey) * | 214 liters/tonne |
| Main producers (by shares) | U.S. 25.9%<br>China 18.4%<br>Brazil 6.0% |

Approximately 5%-10% of corn is lost in the soil as waste at the end of each season (88). Corn fiber utilized for fabrics is extracted from PLA, derived from corn dextrose, following a chemical transformation during the fermentation process. It is considered a renewable sustainable textile, an eco-friendly alternative to synthetic fibers. Corn-based PLA can be extruded into both spun and thread forms, making it feasible for both fine light and stronger fabrics, as well as non-woven textiles (88). Thus far, the utilization of this fiber within the textile industry remains relatively novel. Corn fiber has a texture and appearance similar to cotton, but less dense. It is highly breathable, more resilient, durable, and springier but less prone to staining than cotton. Other characteristics include lightweight, wrinkle and sweat resistance, low odor retention, and having a fluid drape. The yarn has been used to make knitwear, sportswear, footwear, outer garments, undergarments, and home textiles. Corn fiber can be blended with cotton, wool, silk, viscose, and synthetic fibers, such as polyester. Two examples of corn textile products: corn-based PLA and corn fiber from Ingeo™, produced by NatureWorks LLC, require 50% less energy to produce and generate 50% fewer GHG emissions than polyester (90, 91). The Italian company Veja produced a leather alternative that is a semi-natural material comprising both corn waste and polyurethane and being coated onto a canvas substrate (92). This corn leather is more durable and resistant than conventional animal hide, while also remaining leather-like properties including elasticity and touch, and it is partially biodegradable.

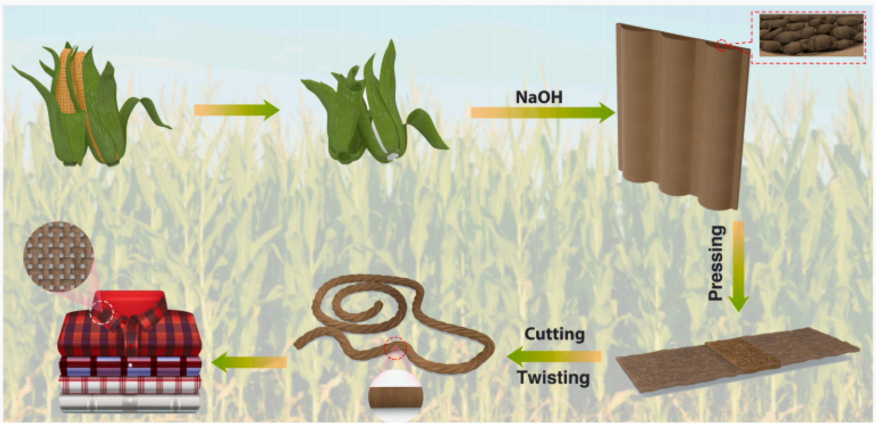

*Figure 11 Graphic illustrating the preparation of corn husk-based textile bio-fibers from natural corn husk via the alkali retting-splicing-twisting method (89).*

Corn husks, making up 7% of the plant's weight, contain approximately 46% cellulose. A room-temperature alkali retting-splicing-twisting method has been used to produce a high yield (73%) of husk-based textile fibers that feel like flax or jute (Fig. 11) (89). The resulting fibers have a higher tensile strength than wood-based fibers and the super-long fibers can be created without additional glue through overlapped edge-pressing of retted corn husks. The procedure only uses NaOH and has a low carbon footprint (estimated 0.74 kg $CO_2e$/kg), with no toxic gas emissions (89). Using this strategy, 13.2 million tonnes of husk fiber could be produced annually in China. To make finer cellulosic fibers, a tetramethylammonium hydroxide (TMAOH) post-treatment under controlled swelling is used after NaOH pre-treatment, resulting in cornhusk fibers with more oriented microstructures and increased cellulose content (84.47%) and that can be spun into textile yarns and woven into fabrics (93). These fibers show similar tenacity, longer elongation, and lower modulus compared to cotton and linen, which endowed them with durability and flexibility. It is estimated that a minimum of 1.8 million tonnes of these finer fibers, valued at around 2 billion US dollars, could be extracted from corn husks annually in the U.S. (93). Cornhusk fibers have the potential for applications beyond clothing, including the production of packing and wrapping materials, fiber composite materials, and industrial fabrics (94). Utilizing corn as a raw material for textile production has the advantage of requiring fewer chemical inputs for cultivation compared to cotton or linen plants.

#### 3.4.2.2 Banana pseudostem

Banana (*Musa nana Lour.*) trees are a sustainable crop that requires minimal water and pesticide usage for cultivation and has a low impact on soil health as they can re-grow in the same place and the roots are strong enough to prevent landslides. The fiber harvested from the pseudostems and leaves of banana trees has been used for textiles in Asia since at least the 13th century (95), with traditional textiles in Southeast Asia incorporating banana fiber for centuries. Currently, banana fiber textiles are gaining popularity in the fashion industry as a sustainable alternative to synthetic fabrics. India is the world's largest banana producer, accounting for 24.1% of global production in 2021, followed by China, Indonesia, Brazil, Ecuador, and the Philippines. The lifespan of a banana plant is approximately 10-15 years, and after producing fruit, the individual stem that carried the fruit will typically die back while new shoots emerge from the underground rhizome to produce new fruit-bearing stems. In the Philippines, approximately one billion tonnes of banana plant stems are wasted each year.

Producing one kilogram of the fiber requires around 37 kilograms of pseudostem (96). The process of extracting textile fiber involves scraping layers of the banana plant's pseudostem, known as the bark, and separating long fibers from shorter fibers. Subsequently, the fibers undergo boiling and pounding to soften and flatten them, after which they are woven or knitted into a textile. Manual spinning and weaving were previously employed, but the introduction of machines helped with large-scale production. The process of making banana fiber fabric is a low-energy, low-water consumption, and chemical-free practice. Since banana plants require relatively little water to grow, the overall water footprint of banana fiber production is relatively low. While the leaves of the banana plant can also be used to extract fibers, the fiber yield from the leaves is lower and finer than that of the stem, making it suitable for more delicate fabrics. Commercially, the primary source of fiber for textiles is the stem or pseudostem of the banana plant. Banana fiber fabrics possess desirable properties such as low density, suitable stiffness, natural sorbent, and resistance to heat, fire, and water, as well as grease-proof characteristics (96). Both the outmost fiber from stems, which is coarse and ideal for making ropes, mats, and thick outerwear, and the innermost, which is as soft as silk, yet delicate and expensive to produce, offer great breathability and comfort, while also delivering robust and long-lasting performance (97). Additionally, banana fiber fabrics have a cooling effect, making them suitable for wear on hot days. Optimal care for banana fiber fabrics involves washing by hand or machine in cold water and steaming with a gentle iron to remove any creases or wrinkles.

*Table 4 Annual production of banana (Musa nana Lour.), land occupation, and three largest producers by weight production in the 2021 crop year (FAOSTAT). The global production of pseudostem and leaves were calculated based on the relative weight ratio of the pseudostem and leaves compared with the fruit banana (4:1 and 5:1, respectively). The yield of fiber was calculated based on the relative weight ratio of the pseudostem and its fiber (37:1). *The water footprint value of the banana is from Mekonnen and Hoekstra (32) and the consumption is only for banana*

| **Banana** | **2021** |
|---|---|
| Global production (fruit) | 137 million tonnes |
| Global production (pseudostem, estimated) | 548 million tonnes |
| Global production (leaves, estimated) | 685 billion tonnes |
| Land occupation | 5.7 million ha |
| Yield (pseudostem fiber, estimated) | 2.6 tonnes/ha |
| Water footprint (green) * | 728 liters/tonne |
| Water footprint (blue) * | 107 liters/tonne |
| Water footprint (grey) * | 36 liters/tonne |
| Main producers (by shares) | India 24.1%<br>China 8.6%<br>Indonesia 6.4% |

*Figure 12 Fiber and fabrics from the pseudostem of banana plants.*

### 3.4.2.3 Sugarcane bagasse

Sugarcane (*Saccharum*) is a high-yielding crop that exhibits superior water-use efficiency and tolerance to high-temperature climates. Sugarcane is primarily cultivated for its sugar-rich stalk, from which juice is extracted. While it is predominantly utilized in sugar mills and alcohol mills, these industries cannot consume the entirety of the plant, leaving approximately 30% of pulpy fibrous residue (bagasse) that is removed before the cane is crushed (98). A yield of 154 kg of sugar cane straw is obtained from one tonne of cultivated sugarcane (CENBIO, 2003). Sugarcane bagasse (SCB) has a high concentration of cellulose and it is a preferred material for producing high-quality green products due to its cost-effectiveness. It was commonly used in the paper industry, but due to the decline of the paper industry as a result of the increased popularity of e-books and online learning, SCB is abundant.

*Table 5 Annual production of sugarcane (Saccharum), land occupation, and three largest producers by weight production in the 2021 crop year (FAOSTAT). The global production and yield of bagasse and straw were calculated based on the weight ratio of both compared with the sugarcane plant (3:10 and 14:100, respectively). The yield of fiber and rayon fiber was calculated based on the relative weight ratio of bagasse and two fiber types (3:1 and 10:1, respectively). *The water footprint value of the sugarcane is from Mekonnen and Hoekstra (32) and the consumption is only for sugarcane cultivation.*

| **Sugarcane** | **2021** |
|---|---|
| Global production (plant) | 1.97 billion tonnes |
| Global production (bagasse, estimated) | 0.59 billion tonnes |
| Global production (straw, estimated) | 0.28 billion tonnes |
| Land occupation | 27.9 million ha |
| Yield (bagasse, estimated) | 23.3 tonnes/ha |
| Yield (straw, estimated) | 11.1 tonnes/ha |
| Yield (fiber, estimated) | 11.5 tonnes/ha |
| Yield (rayon fiber, estimated) | 3.44 tonnes/ha |
| Water footprint (green)* | 153 liters/tonne |
| Water footprint (blue)* | 63 liters/tonne |
| Water footprint (grey)* | 14 liters/tonne |
| Main producers (by shares) | Brazil 36.3%<br>India 20.6%<br>China 5.4% |

SCB can be processed to produce viscose, lyocell, and other rayon fibers via conventional manufacturing methods, the rayon of which is glossier and more silk-like than wood pulp rayon. The direct use of SCB fiber in textile applications necessitates compliance with fundamental requirements, including tenacity, length, and strength, to enable effective yarn formation and resilience to the stresses of spinning and weaving processes (99). Sugarcane composites composed of natural fibers are increasingly used in textiles due to their advantageous properties such as strength, lightweight, and eco-friendliness. Generally, these composites are formed by combining sugarcane bagasse fibers with other natural fibers, such as cotton or bamboo, via spinning, weaving, or mixing of dispersed particles by a bonding agent (99). The sugarcane straw can also be used to produce lyocell via fiber isolation and alkaline pulping processes (100). In Brazil, sugarcane is often burned before harvest to facilitate manual harvest and increase the sugar content by weight due to water evaporation or after harvest to generate local energy (100). The burning leads to severe environmental consequences and respiratory problems, prompting a sustainable way to handle sugarcane straws and bagasse (100).

The sugarcane fiber and sugarcane-based foam, ethylene vinyl acetate (EVA), can also be used as filling materials for mattresses, a sustainable alternative to petroleum-based foam in mattress production. EVA, a rubber-like elastomeric copolymer of ethylene and vinyl acetate, possesses a remarkable combination of softness, flexibility, lightness, and durability, making it a versatile material for various applications (101). Its shock and vibration absorption properties further enhance its utility. Sugarcane-based EVA is known to exhibit recyclability, reusability, and biodegradability under certain conditions, with its initial development credited to the Brazilian resin supplier, Braskem (102). Sugarcane, when processed, yields a liquid byproduct known as molasses. This molasses is subsequently fermented with the aid of yeast, leading to the production of ethanol. The ethanol is then dehydrated to produce ethylene, which serves as a precursor for EVA copolymer (103). This sugarcane-based ethanol used to produce ethylene is an alternative to the conventional petrochemical route. Additionally, sugarcane waste can also be converted to cellulose nanocrystals (CNCs) which can be used for recyclable waterproof coating. Such a biodegradable coating can be applied to mattress covers, offering excellent suitability for use in baby bed mattresses (104). Sugarcane-derived CNCs, possessing thermal and barrier properties, function as reinforcing agents in a biodegradable polymer matrix to form a network that provides strength, flexibility, and water resistance to the resulting coating (105).

*Figure 13 Images of a typical sugarcane plantation (a), stalks (b), straws (c), bagasse (d), and sugarcane rayon (e), modified from (106).*

*Figure 14 Natural dyes extracted from sugarcane in Okinawa (107, 108).*

Natural dyes can be extracted from sugarcane via fermenting or boiling dried or fresh sugarcane (107, 108). The color of the dyes varies with the seasons, with summer leaves producing chartreuse shades and winter leaves producing darker green to brownish-green shades. SCB, together with some other agricultural wastes (*e.g.* corncob), has the potential as a renewable biosorbent for industrial effluent treatment, especially in polluted textile effluents. The textile industry produces highly toxic organic compounds such as synthetic dyes (*e.g.* BR46, extensively used in the textile industry) that are difficult to degrade and pose a serious threat to aquatic ecosystems, causing acute and chronic toxicity in aquatic biota and being associated with serious health problems in humans due to their mutagenic and carcinogenic properties (109). The worldwide production of dyes (up to the present 10,000 dyes) is estimated to be around 700 thousand tonnes annually, with 5-10% released in the effluents (110). Adsorption offers benefits over other technologies for the sequestration of dye pollutants from wastewater because of its cost-effectiveness, efficiency, operational flexibility, easy regeneration, minimal land requirements, and sludge-free operation, and does not involve any toxic intermediate (111). The agro-industrial byproduct SCB and its derivative activated carbon represent a non-conventional adsorbent for the efficient removal of methylene blue (by 95%) and BR46, which generate carcinogenic aromatic amines (112, 113). SCB, especially its modified forms, are better absorbents for remediating wastewater, which contains, for example, dyes, heavy metals, and pesticides compared to biosorbents derived from other agricultural wastes (111).

### 3.4.2.4 Coconut coir

The adaptability and usefulness of the coconut palm (*Cocos nucifera)* have enabled it to grow in coastal and interior regions of almost all tropical countries. The coconut husk constitutes about 35% of the coconut's total weight, of which approximately 30% is coir (114). Coir is the fibrous material obtained from the husk after processing. In 2021, global coconut production was estimated at 64.1 million tonnes (FAOSTAT, Tab. 6), yielding about 22.4 million tonnes of husks and a potential of 6.7 million tonnes of coir. Despite this, only 1.29 million tonnes of coir were produced globally (FAOSTAT, Tab. 6), indicating that a small fraction of the available coir is processed in coir mills with significant amounts remaining underutilized. The husk waste is commonly seen as large heaps and landfills surrounding coconut processing facilities, and while some of it is utilized for burning or charcoal production, a considerable amount remains unused (114). It can take decades to decompose to be biodegraded due to the husks' high recalcitrance and it generates breeding sites for pests like rhinoceros beetles and mosquitoes, methane emissions, and destructs of natural environments. One solution is to collect and utilize coconut shells rather than allow them to decompose in landfills.

*Table 6 Annual production of coconut (Cocos nucifera) and coir, land occupation, the yield of coir and three largest producers by weight in the 2021 crop year (FAOSTAT). #The data on coir production and yield was only available from 8 countries while that of the coconut shell was collected from 38 countries (FAOSTAT). *The water footprint value of the processed coir fiber is from Mekonnen and Hoekstra (32).*

| **Coconut coir** | **2021** |
|---|---|
| Global production (shell) | 64.1 million tonnes |
| Global production (coir)# | 1.29 million tonnes |
| Land occupation | 11.3 million ha |
| Yield (coir)# | 0.13 tonnes/ha |
| Green water (processed coir)* | 2682 liters/tonne |
| Blue water (processed coir)* | 2.2 liters/tonne |
| Grey water (processed coir)* | 17 liters/tonne |
| Main producers of coir (by shares) | India 45.9%<br>Viet Nam 31.1%<br>Sri Lanka 12.5% |

*Figure 15 Exterior parts of coconut (a, 114), discarded waste coconut husks (b, 114), and binderless coir pallet (c, 114). Coir is the fibrous material obtained from the husk after processing.*

The coir is relatively waterproof, resists contraction and expansion in changing temperatures, and is highly abrasive, strong, and resilient. Coir is also naturally antimicrobial, and breathable, and provides excellent support, making it ideal for use in various applications, including mattresses and brushes. Brown coir, identified by its brown and abrasion-resistant properties, comes from mature coconuts and has a thicker and stronger fiber than white coir, which is obtained from immature nuts and is smoother, finer, and lower mechanical strength and is usually spun into yarn for mats, ropes, and rugs (115). A coconut palm tree can start producing coconuts after 6-10 years of planting and continues to produce for up to 80 years, with an annual production of 50–200 fruits per tree, depending on cultivar and climate, making the coir fiber industry particularly important in some developing countries (116). India produces 60% of the total supply of white coir fiber, while Sri Lanka produces 36% of the total brown fiber output (117). Although over 50% of the coir fiber produced annually throughout the world is consumed in the countries of origin, mainly India, coir has a global market and is highly valued for its unique properties. IKEA produces coir-filled mattresses (118). It is claimed to offer good ventilation and comfort for sleep due to the coir bottom layer that allows air circulation. The durable and hardwearing coconut fibers help the mattress maintain its pliability and firmness over time.

Coir, possessing desirable thermomechanical properties, can be used as a raw material to produce molded products and high-density binderless fiberboards, which are composed of biomass fibers without added adhesives, an eco-friendly alternative to traditional boards that emit formaldehyde (119, 120, 121). Cocopallet, a Dutch company, has developed a shipping pallet made from binderless coir, which can potentially save millions of trees and has economic benefits (122). Furthermore, coir can be used as a reinforcing filler in the production of composite materials, including both synthetic and natural polymer matrices, concrete, and gypsum. It has been combined with diverse polymers, such as polypropylene, polyethylene, epoxy, and PLA, to make composites (114). It is also suitable for producing lightweight and biodegradable acoustic panels that offer excellent noise-dampening properties over a wide frequency range (114). Additionally, coir fibers can be used for environmental remediation due to their excellent sorption capacity for various pollutants and colorants.

### 3.4.2.5 Buckwheat hull

Buckwheat (*Fagopyrum esculentum*) is a fast-growing, short-season (6-8 weeks) cover crop (123). Buckwheat prefers moderate moisture weather to grow. Despite not being particularly drought tolerant, its short growing season may allow it to avoid droughts. Owing to being a host of nitrogen-fixing bacteria, it has the ability to fix nitrogen from the air and thus, requires less fertilizer. Its residue decomposes rapidly, releasing nutrients to the next crop. Buckwheat can thrive in poor soils, acting as a phosphorus scavenger and soil conditioner (123). Around three tonnes of husk waste are generated per one tonne of buckwheat groats during the processing of buckwheat (124). Buckwheat hulls are soft but not fragile, highly elastic, and known for their strong and aromatic characteristics (125). They have been used as a filling material for pillows, mattresses, and cushions due to their exceptional breathability and temperature regulation properties, as well as health benefits such as promoting sleep, the improvement of the human body's microcirculation system, preventing cardiovascular and cerebrovascular diseases, and skin diseases (125). They provide a unique firmness and support, which can help to reduce pain and tension while sleeping (126). Buckwheat hulls can adjust to the shape of the body with ease, properly supporting the head and neck during sleep. Buckwheat hull products do not attract dust mites or other bugs (127). The cleaning process of buckwheat after harvest involves a special vacuum process, with no use of chemicals (126). Buckwheat hulls have a long lifespan and are naturally resistant to fire. Given their chemical composition, buckwheat hulls may serve as a promising raw material for producing PU foams with flame-retardant properties (124).

*Table 7 Annual production of buckwheat (Fagopyrum esculentum), land occupation, and three largest producers by weight in the 2021 crop year (FAOSTAT). The global production and yield of the hull were calculated based on the compared weight ratio to the grain (2:3). *The water footprint value of the buckwheat is from Mekonnen and Hoekstra (32) and the consumption is only for sugarcane cultivation.*

| **Buckwheat Hull** | **2021** |
|---|---|
| Global production (grain) | 2.38 million tonnes |
| Global production (hull, estimated) | 1.59 million tonnes |
| Land occupation | 2.44 million ha |
| Yield (hull, estimated) | 0.72 tonnes/ha |
| Water footprint (green)* | 3052 liters/tonne |
| Water footprint (blue)* | 159 liters/tonne |
| Water footprint (grey)* | 252 liters/tonne |
| Main producers (by shares) | Russia 38.7%<br>China 21.1%<br>Ukraine 4.4% |

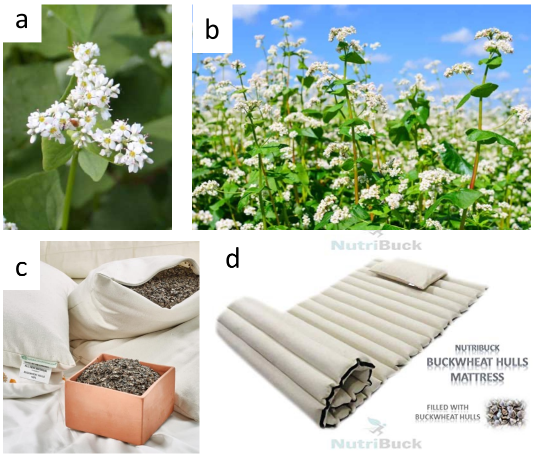

*Figure 16 Buckwheat's flowers (a), plants (b), buckwheat-filled pillows (c, 128), and mattresses (d, 129).*

### 3.4.2.6 Sorghum fiber

*Sorghum* is the fifth most significant cereal crop worldwide, following corn, rice, wheat, and barley (130). Sorghum is primarily grown in arid and semi-arid regions, particularly in developing countries. It has the advantage of being able to withstand a wide range of climatic conditions, particularly prolonged warm summers, and requires less water than other cereal crops. Hence, sorghum may represent a practical solution for farmers in the context of global temperature rise. On average, the weight ratio of sorghum grains to sorghum leaves and stems is roughly 1:1. Up to 6.3 million tonnes of cellulose fibers could be produced from sorghum leaves and stems annually. The fibers are characterized by remarkable strength, durability, and resistance to mold and mildew.

Sorghum byproducts are of limited use at present. However, a cost-effective and eco-friendly approach has been developed to extract fibers from sorghum stems and leaves using NaOH at 95°C followed by neutralization with $CH_3COOH$ (131). These fibers exhibit properties and structures similar to those of cotton fibers, rendering them suitable for textile applications. The resulting products made from sorghum fibers are comfortable to wear due to their softness and breathability. Ecomax, a company, has developed PET fabrics from sorghum distiller's grains (Fig. 24b), which are resistant to moisture, wind, and UV radiation, and possess deodorizing and regenerative heat preservation properties (132). Additionally, sorghum husk extracts are a promising natural functional dye and functional finishing agent for wool fabrics (133).

*Table 8 Sorghum's annual production, land occupation, yield and three largest producers by weight in the 2021 crop year (FAOSTAT). The global production and yield of leaves and stems and the yield of the fiber was calculated based on the compared weight ratio to the grain (1:1 and 6.3:100). *The water footprint value of the sorghum is from Mekonnen and Hoekstra (32).*

| Sorghum | 2021 |
|---|---|
| Global production (grain) | 64.37 million tonnes |
| Global production (leaves and stems, estimated) | 64.4 million tonnes |
| Land occupation | 41.6 million ha |
| Yield (grain) | 2.7 tonnes/ha |
| Yield (leaves and stems, estimated) | 2.7 tonnes/ha |
| Yield (fiber, estimated) | 0.17 tonnes/ha |
| Water footprint (green)* | 3149 liters/tonne |
| Water footprint (blue)* | 114 liters/tonne |
| Water footprint (grey)* | 96 liters/tonne |
| Main producers (by shares) | The U.S. 17.7%<br>Nigeria 10.4%<br>India 7.5% |

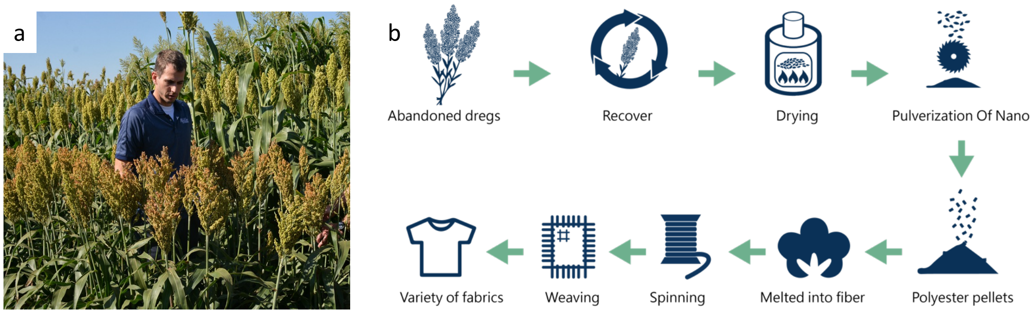

*Figure 17 Sorghum cultivation (a) and the manufacturing processes of sorghum distiller-based PET fabrics from Ecomax (b, 132)*

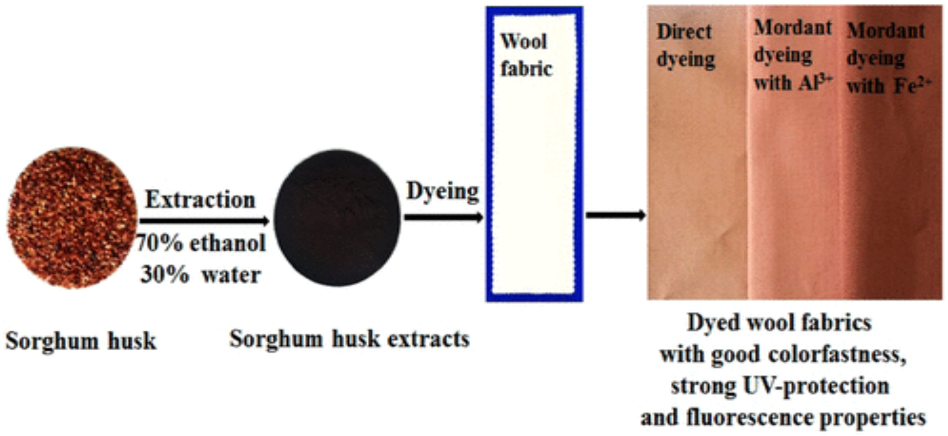

*Figure 18 The method to extract dyes from sorghum husk and the color and characteristics of wool fabrics obtained after being dyed directly or with $Al^{3+}$ and $Fe^{2+}$ mordant (133).*

### 3.4.2.7 Pineapple piña fiber

Pineapple (*Ananas comosus*) piña fiber, derived from the leaves of the pineapple plant, has been utilized for clothing production in the Philippines for centuries. North America and Europe are the two major consumers of piña fabrics (134). This tropical plant is perennial and it thrives in sandy, loamy soil that is not water-retentive (135). The weight ratio of pineapple leaves to the pineapple fruit in a mature plant of the most common species, *Ananas comosus*, is approximately 1:3. After pineapple plant leaves are harvested, the decortication process is used to scrape off the outer layer of the leaf and extract the fibers, followed by retting in water with added urea to separate the fibrous matter, which is then dried and used for spinning (135). The long leaves of the pineapple plant are the primary source of the silky piña fibers. The fiber boasts several desirable characteristics such as strength, flexibility, lightness, softness, breathability, and moisture-wicking capabilities, making it an ideal material for use in warm climates. Piña fiber can be spun into yarns and blended with other natural fibers such as cotton or silk. Additionally, it is a bast fiber, suitable for making strong and coarse string or twine, or fine enough for weaving into fabric. Only 52% of pineapple fruits are utilized for food and jam production and the remainder (discarded part) is rich in cellulose and lignin, which can be extracted and processed to produce silky, white viscose fiber (135).

*Table 9 Annual production of pineapple (Ananas comosus), yield and land occupation in the 2021 crop year (FAOSTAT). The global production and yield of the piña fiber and the production of leaves were calculated based on their compared weight ratio to the pineapple fruit (6.65:100 and 1:3, respectively). *The water footprint value of the pineapple fiber is from Mekonnen and Hoekstra (32).*

| Pineapple | 2021 |
|---|---|
| Global production (fruit) | 31.2 million tonnes |
| Global production (leaves, estimated) | 10.4 million tonnes |
| Global production (fiber, estimated) | 2.1 million tonnes |
| Land occupation | 1.28 million ha |
| Yield (fruit, estimated) | 21.36 tonnes/ha |
| Yield (fiber, estimated) | 1.42 tonnes/ha |
| Water footprint (green)* | 237 liters/tonne |
| Water footprint (blue)* | 10 liters/tonne |
| Water footprint (grey)* | 34 liters/tonne |
| Main producers | The Philippines<br>Thailand, China,<br>India, Brazil |

*Figure 19 Pineapple's cultivation, fibers in the leaf and fabrics made by 100% piña fiber (136, 137).*

### 3.4.2.8 Agave fiber

*Agave*, with an age span of seventy long years, is adapted to thrive in arid and hot environments and is useful in mitigating desertification and fixing sandy soils. The plant requires minimal water and external inputs to grow. Agave fibers are derived directly from agave leaves and the process involves crushing and cleaning the agave leaves to separate white fibers which are washed, brushed, and dyed as needed (138). Agave fibers are known for their high strength, durability, flexibility, elasticity, and absorption capacity, and are almost wrinkle-free (138). They have been used for the elaboration of extremely resistant textiles, such as rope, brushes, mats, rugs, and fillers. Twine blankets, cushions, and ornaments can also be made when they are blended with softer yarns. Sabra silk (also called Agave silk, cactus silk, and vegetable silk) is made in Morocco using vegetable dyes and the cacti hailed from the *Aloe Vera* species of the Agave family and are found in the desert of the Sahara (139). It has a silky texture (smooth and lustrous) and is used to make luxurious carpets, rugs, table napkins, cushions, and garments. The process of making Sabra silk is more intricate and labor-intensive than the production of agave fibers.

The Agave bagasse is from *Agave tequilana* and it is the agro-industrial waste from making Mexico's tequila and natural sweetener. In the production of tequila, around 1.4 kg of bagasse in wet weight is generated to produce 1 L of the beverage (140). The bagasse contains around 80% of cellulose and it can be used to make textile fibers and fillers in mattresses via MMCFs or cellulose nanocrystal processes.

*Table 10 Agave fiber's annual production, land occupation, yield, and three largest producers by weight in the 2021 crop year (FAOSTAT). #The global production of bagasse is from Íñiguez-Covarrubias and et. al. (141). *The water footprint value of the agave fiber is from Mekonnen and Hoekstra, 2011 (32)*

| **Agave fiber** | **2021** |
|---|---|
| Global production (fiber) | 40.7 thousand tonnes |
| Global production (bagasse)# | 0.81 million tonnes |
| Land occupation | 58.33 thousand ha |
| Yield (fiber) | 0.74 tonnes/ha |
| Water footprint (green)* | 7093 liters/tonne |
| Water footprint (blue)* | 10 liters/tonne |
| Water footprint (grey)* | 117 liters/tonne |
| Main producers of the fiber (by shares) | Colombia 37.2%<br>Mexico 15.4%<br>Nicaragua 13.7% |

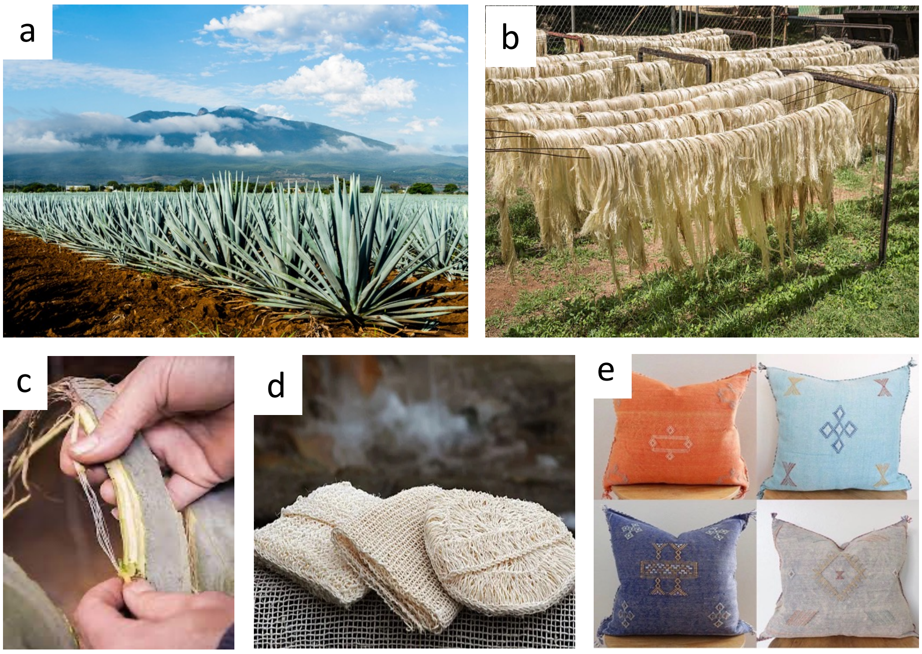

*Figure 20 A field of blue agave (a, 142), sun-dried agave cactus fiber (b, 143), fibers in the Agave leaves (c), Agave washcloths (d, 144) and Agave silk (e, 145)*

### 3.4.2.9 Loofah fiber

Loofah fiber (Loofah sponge from *Luffa sp.*)**,** obtained from matured dried fruits of luffa cylindrical, can either come from agricultural waste (unpicked loofahs get too old to eat) or are grown specifically for loofahs. Luffa cylindrica grows in Asia and Africa, and some sub-tropical areas, and it requires only minimal inputs such as water and fertilizer. The dried fiber obtained from a single mature loofah fruit can weigh up to 1 pound, while the projected yield for sponges is over 20,000 per acre (146). To extract loofah sponges, mature fruits must be harvested and dried in a well-ventilated area to prevent discoloration. Once dry, the skins can be easily removed from the sponges by soaking them in warm water, and a bleach solution can be used for a final rinse to lighten the sponges (146). Loofah fiber has high absorbency and abrasiveness and it serves as an exfoliant for shower towels. However, its abrasive nature can cause microtrauma to the skin, resulting in bacterial infections. It can be contaminated and colonized with human pathogens, including gram-negative Pseudomonas and gram-positive Enterobacteria, contributing to pathogen transmission (147, 148). Therefore, regular decontamination of the Loofah sponge is required. Loofah sponge is widely used to make household cleaning products for scrubbing dishes, pots, pans, barbecue grills, etc. Additionally, natural luffa sponge columns have the potential to be used as light mattress-filling materials and replace synthetic fibers in composite materials for vibration isolation, sound absorption, and packaging (149). Sponge cultivation may offer a substantial economic return (146). The value of Loofah's production, land occupation, and yield are not available from FAOSTAT.

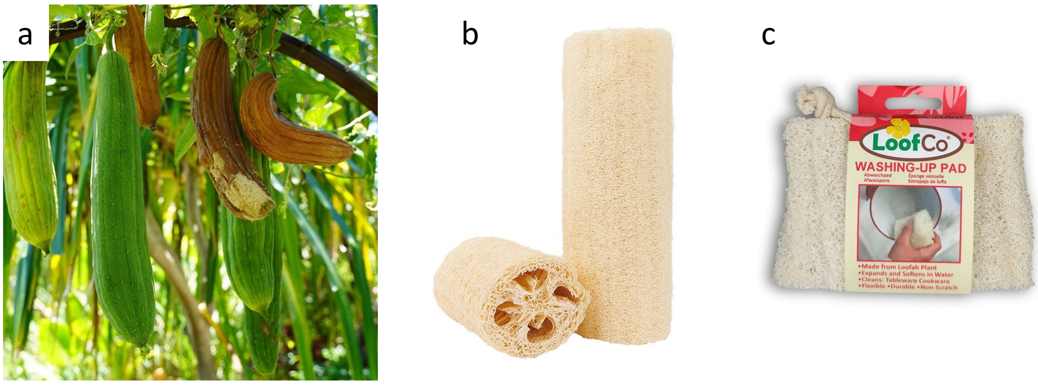

*Figure 21 Luffa fruits (a, 150), loofah sponge (b, 151), and one of its products (c, 151).*

### 3.4.3 Bamboo

Bamboo (*Bambusoideae*), spanning approximately 35 million hectares of land in Africa, Asia, and the Americas, has experienced a significant expansion, with a 50 percent increase in its area between 1990 and 2020, primarily driven by notable growth in China and India (152, 153). However, the reported 35 million hectares is an underestimation, as over 40 countries possessing abundant bamboo resources did not provide data for the Forest Resource Assessment (FRA) in 2020 (152). Consequently, accurately quantifying the global quantity of bamboo has proven challenging. With an extensive array of over 1600 recognized species, bamboo exhibits thousands of applications. Its economic significance is exemplified by the export of bamboo products reaching 3.054 billion US dollars in 2019 (152).

Bamboo is a self-regenerating plant and is considered one of the fastest-growing raw materials. It has an average yield of the most common bamboo crop in well-managed forests or plantations in China up to 25 tonnes per hectare (154). Its average wet yield is up to 60 tonnes/ha which greatly exceeds the average yields of most trees and cotton 20 tonnes/ha and 2 tonnes/ha, respectively (FAOSTAT) (155, 156). Its growth requires only 1/3 of the water needed for cotton to grow and its water-use efficiency (relative to growth) might be greater than many trees (155, 157). It needs little to no use of pesticides, herbicides, or fertilizers (157). Bamboo can grow on various soil types, including marginal land and poor-quality soils unsuitable for forestry and other crops, and grow in both high and low-rainfall regions. Bamboo cultivation, with its dense underground rhizome system and non-uprooting harvesting method, helps to stabilize soil, improve soil quality, and slow down soil erosion, for example, holding the soil together along river banks, in deforested areas, and in mudslide-prone regions (155). It can tolerate a range of temperatures, suitable for cultivation from tropical to cold areas. Due to its fast growth, it produces up to 35 percent more oxygen than similar stands of trees and sequesters 62 tonnes of carbon dioxide per hectare annually, which is four times more than a young forest (155). Bamboo extracts are believed to possess antibacterial properties attributed to bamboo-kun, a bio-agent that provides bamboo with a natural resistance against pests and fungal attacks. Bamboo exhibits a notable tolerance to greywater and high suitability for phytoremediation (158). Greywater encompasses wastewater that does not contain toxic chemicals or sewage, such as lightly used water from household origins like sinks, showers, and washing machines. Phytoremediation is the natural process by which plant tissue effectively absorbs greywater and eliminates, stabilizes, or degrades specific detrimental substances, thereby contributing to water purification and remediation processes (159). Bamboo is proven to act as a natural water filter for food industry effluent or runoff to remove sewage and toxic chemicals, and to have the capacity to remove heavy metals and nitrates from the soil (158, 160).

*Table 11 The land occupancy and main locations of bamboo (Bambusoideae) in 2020 are from FRA 2020 (FAO) (153). The dry yield is from NL Agency (154). The global production was estimated by the yield and land occupation from FAO. The yield of mechanically produced fine fiber and bamboo rayons was calculated according to the weight ratio of these two types of fiber to bamboo (1:10 and 1:8, respectively)*

| **Bamboo** | |
|---|---|
| Global production (estimated) | 875 million tonnes |
| Land occupation (2020) | 35.0 million ha |
| Yield | 25.0 tonnes/ha |
| Yield (mechanically produced fine fiber, estimated) | 2.5 tonnes/ha |
| Yield (bamboo rayons, estimated) | 3.1 tonnes/ha |
| Main producers in 2020 (by land use) | South and Southeast Asia 51.0%<br>East Asia 20.0%<br>South America 15.4% |

Bamboo has longer fibers, making it stronger and more flexible than most woods (155). Although it has been utilized for textile production for millennia in Asian cultures, predominantly China, where it grows in abundance, bamboo-based fabrics have become widely available in mainstream markets until the twentieth century (161). Bamboo usually grows as a cash crop by smallholder farmers in developing countries. Today China is the leading export of Bamboo, and India, Pakistan, Afghanistan, and Indonesia are notable producers and exporters. In China, Moso bamboo is the most prominent bamboo species and is present on approximately 3 million hectares (7.4 million acres), which accounts for roughly 2% of the country's forest area (155). Europe and the U.S. have started to cultivate significant quantities of bamboo for textiles, with the majority grown in the US for domestic purposes, resulting in minimal exportation.

Bamboo viscose is the most wildly used type of bamboo fiber used in textile production, but it is created via a complex chemical process that partially depletes the environmental benefits of using bamboo to make fabrics (162, 163). A closed-loop production process is a better option. Bamboo lyocell is more eco-conscious and is commonly used to make bamboo clothing. Bamboo rayons (viscose and lyocell) are highly absorbent and breathable, lightweight, consistently soft (feeling like cashmere), smooth, and silky with moisture-wicking, stretchy characteristics, resulting in their popularity for making bedding, sheets, curtains, carpets, and towels, other home decor items, and clothing. As for negative characteristics, the rayons have low warmth retention and are susceptible to wrinkling, shrinking, and pilling. The chemical-treated bamboo rayons are not allowed to produce in the US (161). Mechanically produced fine bamboo fiber, the third type of bamboo fabric, has longer fiber and is stronger, more durable, long-lasting high quality, and environment-friendly, but it is costly (normally more expensive than traditional cotton and bamboo rayons) to produce. The process involves mechanically breaking down the plant's stalk, followed by natural bamboo enzyme-retting, which further facilitates the extraction of individual fibers that can be subsequently spun into yarn after combing. In comparison to cotton, bamboo exhibits better shape retention despite being prone to shrinking, while also demonstrating consistent softness and comfort across products, with higher-quality bamboo featuring a greater thread count for increased softness. All bamboo fiber types are considered biodegradable. Organic certification by the U.S. Department of Agriculture (USDA) can be earned if the bamboo fabric has been produced using the mechanical process and it uses organic bamboo, or it is an organic cotton-bamboo blend. Bamboo fabrics can also be granted the Oeko-Tex Standard 100 certification, which requires meeting various requirements, such as the absence of allergens, testing for pesticides and heavy metals, and no biologically active finishes (161).

### 3.4.4 Abaca fiber

Abaca fiber (Manila hemp, *Musa textilis*), derived from the abaca plant (*Musa textilis*) thrives in well-drained loamy soil (164). Abaca plants have an extensive root system and its water-holding capacity plays a vital role in preventing soil erosion, landslides, and floods by stabilizing the soil, absorbing water, and regulating water flow. The plant takes 18 to 24 months to grow before reaching maturity for harvesting and subsequent utilization as raw material (164). The use of fertilizers and pesticides can benefit its growth. Processing can be carried out through manual or mechanized methods. It involves removing the plant's outer layer from its petiole, followed by the extraction of the fibrous strands by scraping the pulpy material. These strands are subsequently subjected to drying, either mechanically or through exposure to sunlight. Following this, the fibers are thoroughly cleaned and sorted in accordance with market requirements. The plant's outer covers yield the strongest fibers during this process. Abaca fiber, being recognized as the ‘strongest among all natural fibers in the world’, boasts exceptionally high tensile strength, retaining its strength even when immersed in water (165, 166). Additionally, it exhibits showcases resilience, durability, lightweight nature, and resistance to salt water. The fiber possesses versatility and can be easily molded into desired shapes. Abaca fiber, widely utilized for twines, ropes, rugs, and other floor coverings, is experiencing an increasing demand for clothing and home decor items. The Philippine Fiber Industry Development Authority (PhilFIDA) is in charge of developing the country's abaca industry through the production of high-yielding and disease-resistant crops, the improvement of fiber extraction automation, and the pursuit of international sustainability certification (164). The hybridization of abaca with banana has resulted in a more productive variant that is highly drought-tolerant and resistant to viruses, which is developed by the University of the Philippines Los Baños (167). The leading importers of abaca products are Europe, the US, and Japan.

*Table 12 Abaca fiber’s annual production (7 countries data collected), land occupation (5 countries data collected), yield (5 countries data collected), and two largest producers by weight in the 2021 crop year (FAOSTAT). *The water footprint value of the abaca fiber is from Mekonnen and Hoekstra, 2011 (32).*

| Abaca fiber | 2021 |
|---|---|
| Global production | 107.3 thousand tonnes |
| Land occupation | 174.1 thousand ha |
| Yield | 0.78 tonnes/ha |
| Water footprint (green)* | 21362 liters/tonne |
| Water footprint (blue)* | 271 liters/tonne |
| Water footprint (grey)* | 845 liters/tonne |
| Main producers | The Philippines 63.5%<br>Ecuador 34.&% |

*Figure 22 Abaca fiber harvest (168), drying (169), and fabrics (170).*

### 3.4.5 Kenaf (*Hibiscus cannabinus*) fiber

Kenaf is the second-largest cultivated plant for fiber production (171). It grows fast with a high yield production and matures progressively in hot, dry, shallow, sandy soils due to its deep root system enabling access to water even during drought periods. The growth cycle of kenaf ranges from 100 to 200 days, and its leaves have been utilized as a dietary component for both humans and animals for millennia in east-central Africa. Kenaf cultivation offers a range of advantageous applications, including soil remediation, toxic waste remediation, and the mitigation of oil spills on water surfaces (171). Its fiber exhibits exceptional strength, durability, and moisture absorption properties (172). The bast fiber, derived from the outer layer of the plant's stems, can be used for ropes, while the finer fiber found in the core is used for twine, coarse cloth, packing material, and environmental mats. Additionally, Kenaf stands out as one of the most investigated and industrially applied natural fibers for polymer composite reinforcement (172).

*Table 13 Kenaf fiber's annual production, land occupation, yield, and three largest producers by weight in the 2021 crop year (FAOSTAT).*

| **Kenaf fiber** | **2021** |
|---|---|
| Global production | 255 thousand tonnes |
| Land occupation | 157.6 thousand ha |
| Yield | 1.79 tonnes/ha |
| Main producers | India 39.9%<br>Russia 19.5%<br>China 10.1% |

*Figure 23 Kenaf's cultivation, flower and leaves and yarns.*

## 3.5 Comparison of plant-based raw materials in annual production, land occupation, yield, and water footprint

### 3.5.1 Potential of agro-wastes as raw material for textile fibers

A comparative analysis was conducted on the annual production of seeds, fruits, or grains from specific crop species that exhibit suitability for textile applications and possess available data from FAOSTAT (Fig. 24). The annual production of raw textile materials suitable for mechanical fiber processing is shown in Fig. 25 and for rayon production in Fig. 26. It indicates that the annual production of bamboo and commodity crop byproducts banana pseudostem and corn husk exceeds that of seed cotton, providing abundant and cost-effective raw materials for textile application with lower environmental impacts. The production of sugarcane bagasse which can be used for rayon production is ample as well. Estimated values have an inherent margin of error and it is worth noting that the reported data on bamboo is an underestimation.

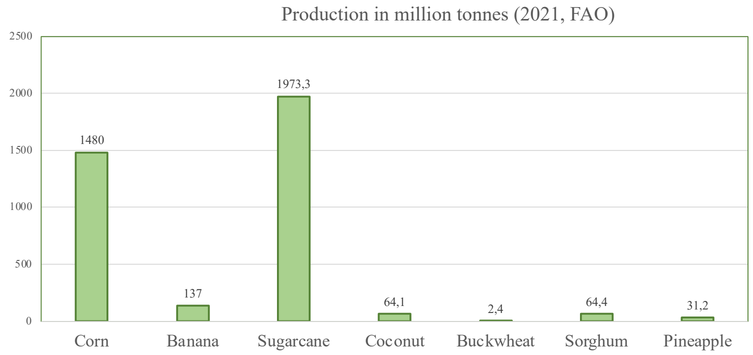

*Figure 24 Annual production of corn (seed), banana (finger), sugarcane (stem), coconut (seed), buckwheat (grain), sorghum (grain), and pineapple (fruit) in 2021 crop year. The data originated from FAOSTAT.*

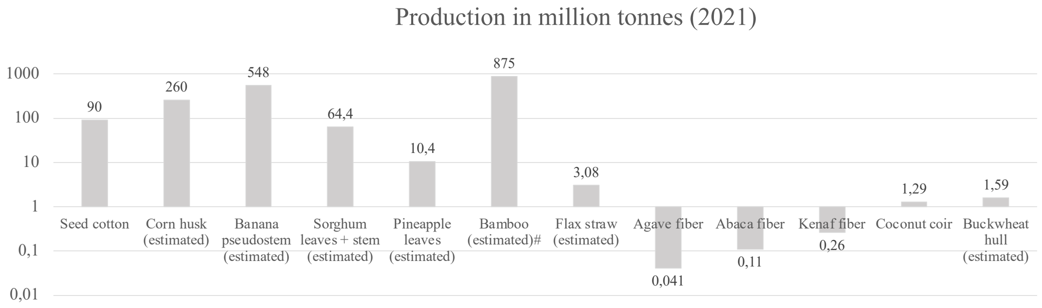

*Figure 25 Annual production of different natural raw materials suitable for mechanical fiber processing. The data of seed cotton, agave fiber, abaca fiber, kenaf fiber, and coconut coir in 2021 originated from FAOSTAT. Production of flax straw was calculated based on the approximate weight ratio of flax fiber processed and flax straw (3:10). The values of corn husk, banana pseudostem, pineapple leaves, sorghum, and buckwheat hull were estimated according to their relative weight ratio compared to the corresponding seed, fruits, or grain. The value of bamboo was calculated based on underestimated land occupancy and the yield from NL Agency (154). The fiber of agave, abaca, kenaf, and coconut coir are processed raw materials.*

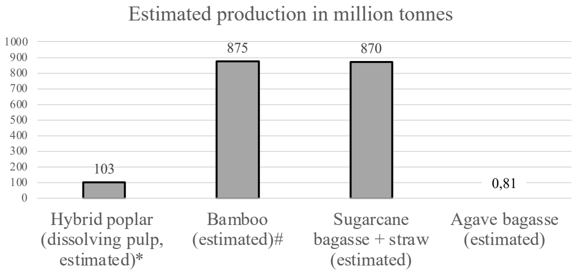

*Figure 26 Estimated production of the natural raw materials suitable for rayon fiber. *The cultivation of hybrid poplar on all available marginal land (43 Mha) across Europe (82) was taken into account for calculation purposes. The value of bamboo was calculated based on underestimated land occupancy and the yield from NL Agency (154). Sugarcane bagasse and straw were estimated according to their relative weight ratio compared to the corresponding sugarcane stem. The value of agave bagasse was from Íñiguez-Covarrubias and et. al (141).*

### 3.5.2 Comparison of land-use per produced tonne of textile fiber from different raw materials

The global land occupancy and fiber yield of selected raw materials during the 2021 crop year were assessed and presented in Fig. 27 and Fig. 28. The data analysis indicated that banana pseudostem, flax, sugarcane bagasse, hybrid poplar, eucalyptus, kenaf, and bamboo exhibit a greater capacity for fiber production per hectare in comparison to cotton. The fiber yield of bamboo, hybrid poplar, and banana pseudostem is similar (2.5, 2.4, and 2.6 tonnes/ha, respectively). From a sustainability perspective, it is advisable for IKEA to augment the utilization of textile fibers sourced from crops that exhibit a high yield per unit of land area. This approach would optimize land use efficiency in textile fiber production, freeing up additional cropland for food cultivation purposes. The fibers derived from agriculture byproducts are not limited to this approach.

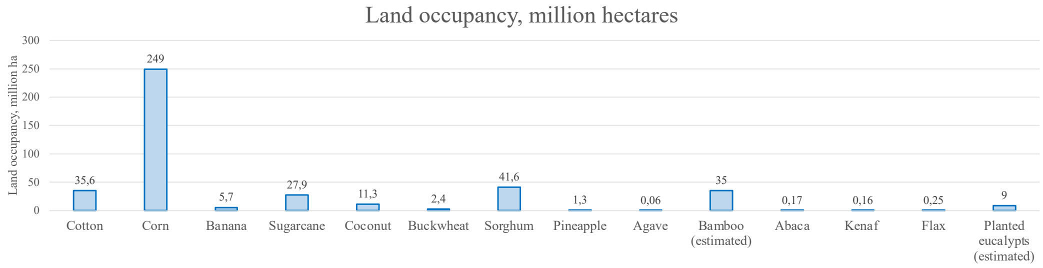

*Figure 27 The global land occupation of cotton, corn, banana, sugarcane, coconut, buckwheat, sorghum, pineapple, agave, bamboo, abaca, flax, and kenaf in the 2021 crop year (FAOSTAT). The value of bamboo is underestimated (152). The land occupation of planted eucalypts was an estimation for 2010 (173).*

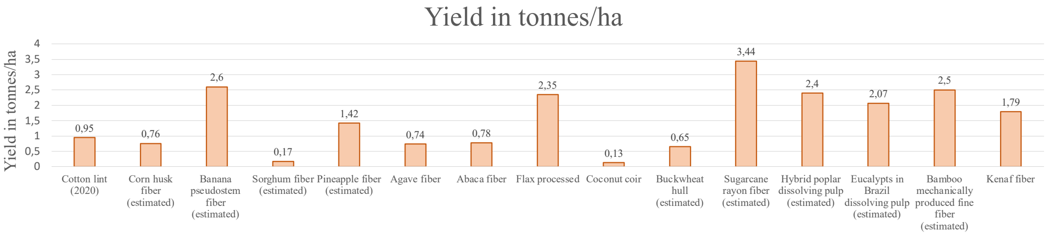

*Figure 28 The yield of natural raw materials for textiles. The value of cotton lint was from the 2020 crop year, FAOSTAT. The value of agave abaca, flax processed fibers, coconut coir, and kenaf fiber was from the 2021 crop year, FAOSTAT. Other data was estimated according to e.g. fruit/seed/grain production and weight conservation factors. Eucalyptus's yield (9.4 tonnes/ha) was calculated by an average yield of 20.5 $m^3$/ha/year (80) and an estimated density of 460 kg/$m^3$, and a conversion factor of 0.22 was used to estimate the dissolving pulp production. The yield of bamboo rayons is 3.1 tonnes/ha, which is not included in this figure.*

### 3.5.3 Comparison of water footprint per produced tonne of textile fiber from different raw materials

The water footprint of raw materials and/or their fiber is shown in Fig. 29 and 30, indicating that cotton cultivation exhibits the highest total water requirement, predominantly driven by a substantial need for blue water resource that is used for irrigation purposes. Based on the data, during the cultivation stage, sorghum and buckwheat demonstrate a higher requirement of rainfall or moisture climate compared to corn, banana, and sugarcane. However, both sorghum and buckwheat are considered more drought-tolerant crops, and sorghum cultivation is predominantly observed in arid and semi-arid regions, particularly in developing nations, and it exhibits a low demand for irrigation water. The water footprint of processed fiber of corn husk, banana pseudostem, sugarcane bagasse, sorghum stem, pineapple, and buckwheat hull depends on processing/extraction methods, and the data is not available in this thesis. Abaca fiber production entails a greater water demand throughout the entire fiber manufacturing process when compared to cotton, with a predominant reliance on green water. This observation suggests that abaca cultivation relies heavily on precipitation for growth and indicates a potential vulnerability to drought conditions, but is more resilient in flood.

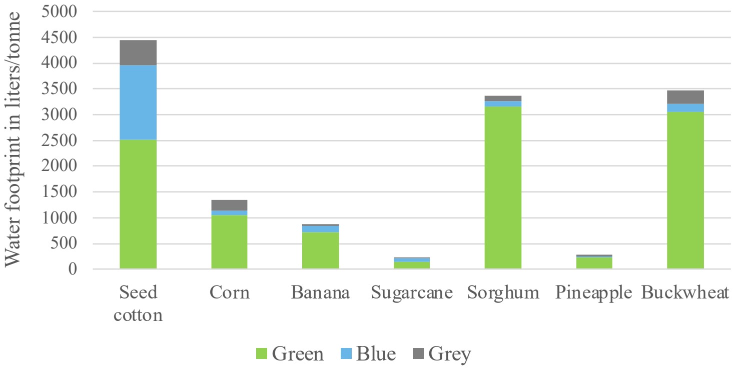

*Figure 29 Water footprint of different textile raw materials. The value originated from Mekonnen and Hoekstra, 2011 (32). Green water is the evapotranspired rainwater from soil; blue water is used for irrigation purposes and grey water is contaminated by agrochemicals (24).*

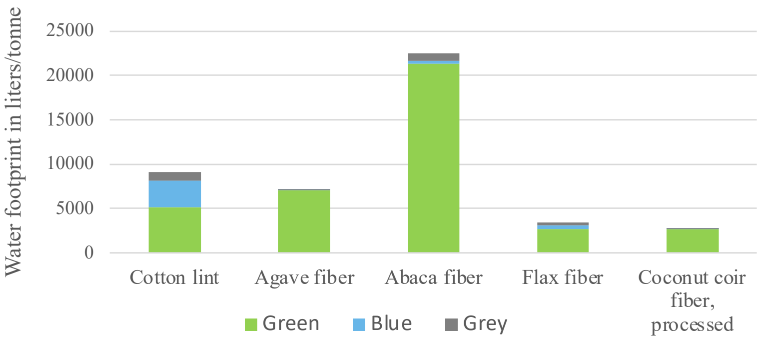

*Figure 30 Water footprint of five processed fibers. The value originated from Mekonnen and Hoekstra, 2011 (32). Green water is the evapotranspired rainwater from soil; blue water is used for irrigation purposes and grey water is contaminated by agrochemicals (24).*

### 3.5.4 The ANOVA test of raw materials

The yield of four fiber raw materials with abundant production from China, India, The U.S., Australia, and Brazil is compared in Fig. 31. These five countries are five of the main food producers in the world. It indicates that the yield of sugarcane bagasse and banana pseudostem from five countries is significantly higher than the yield of cotton lint, suggesting that these two crops possess the dual capability of serving as food sources while simultaneously supplying fibers suitable for textile production. Nevertheless, the precise fiber yield is contingent upon advancements in processing techniques and technology.

*Table 14 One-way ANOVA was applied to analyse the yield of four fiber raw materials by using yield of raw material as response variable and species as a factor. The yield of cotton lint was calculated by the production of cotton lint divided by the land occupation in 2020 (FAOSTAT) (The data of cotton lint in 2021 is not available). The yield of corn husk, sugarcane bagasse, and banana pseudostem in dry weight were estimated according to their relative weight ratio compared to the corresponding cobs, stems, or fruits in 2021 from FAOSTAT (corn:husk=100:17.5; fresh sugarcane stem:dry sugarcane bagasse=10:3; fresh banana:dry pseudostem=1:0.9).*

| **Yield (tonnes/ha)** | Cotton lint | Corn husk | Sugarcane bagasse | Banana pseudostem |
|---|---|---|---|---|
| China | 1.82 | 1.1 | 28.38 | 30.58 |
| India | 0.45 | 0.56 | 23.57 | 32.2 |
| The U.S. | 0.95 | 1.94 | 23.69 | 8.14 |
| Australia | 1.64 | 1.95 | 25.78 | 26.23 |
| Brazil | 1.69 | 0.81 | 21.53 | 13.53 |
| Significance | Cotton lint: banana pseudostem P<0.01<br>Cotton lint: sugarcane bagasse P<0.01 | | | |

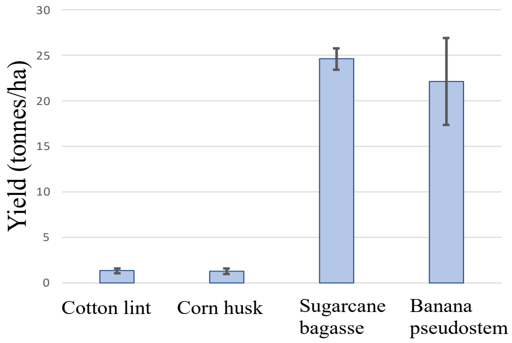

*Figure 31 The comparison of yield in dry weight of four fiber raw materials from China, India, The U.S., Australia, and Brazil. The values of corn husk, sugarcane bagasse, and banana pseudostem were estimated according to their relative weight ratio compared to the corresponding cobs, stems, or fruits.*

## 3.6 Examples of some other innovations in textile or good candidates for local IKEA stores

The company Nanollose uses industrial organic and agricultural waste to produce microbial cellulose via fermentation, which is then converted to Nullarbor™ fibers (174). Nanollose has completed the first pilot scale spinning of lyocell fibers containing 20-30% Nullarbor microbial cellulose using existing manufacturing equipment (conversation with Nanollose). The fiber is finer than silk and significantly stronger than conventional lyocell made from wood pulp. Polyhydroxyalkanoates (PHAs) are the polyesters of hydroxyalkanoates produced from food waste, organic waste from agriculture, municipal wastes, methane gas, and captured $CO_2$ by fermentation(175). Bioengineered bacteria can be used to produce shorter versions of recombinant spider silk proteins that can be isolated and spun into fibers (176). The fiber has increased tensile strength and the same toughness as native dragline silk. Synthetic spider silks can be produced by companies Bolt Threads and AMSilk using plant-based raw material or sugar via fermentation or Kraig Biocraft Labs using genetically engineered silkworms.

The cultivation of seaweeds for making algae fiber is a potentially valuable tool to mitigate climate change. In comparison to land-based crops, some seaweeds have a higher photosynthesis efficiency and biomass production rate, sequestering larger amounts of $CO_2$ (177, 178). No land, fertilizers, pesticides, or irrigation is required, and it could potentially reduce contamination in the sea. Mushroom leather, a sustainable alternative to traditional leather, is made from mycelium, grown using renewable and organic substrates, and powered by renewable energy, reducing greenhouse gas emissions, ecotoxicity, and plastic pollution (179). The grass *Schoenoplectus triqueter (L.) Palla* (Cyperaceae), with smooth, slender stems, fragrant long fibers with excellent elasticity and tensile properties, excellent heat insulation, and a cooling sensation, is ideally used for crafting bed mats, pillowcases, cushions, and floor mats, providing good sleeping in hot weather conditions. It naturally regulates humidity with its spongy-like interior. Madurkathi (*Cyperus pangorei*) fiber might be a good option for some local IKEA stores, for example, in India, with the fiber being water-resistant, non-conductive, and sweat-absorbing (good to use in hot weather). The plant grows on wetlands or marshy areas which are unsuitable for crop cultivation. Ramie (*Boehmeria nivea*) fiber is resistant to bacteria, mildew, insect attack, alkalis, rotting, light, and staining while displaying an exceptional capacity for absorption. Its strength is eight times higher than that of cotton and the tensile strength is increased when subjected to moisture (180).

# 4. Discussion

To mitigate the negative impacts of cotton cultivation, sustainable practices such as organic and regenerative farming, reducing chemical inputs, integrated pest management, and crop rotation can be employed to improve soil health. Given the significant dependence on either rainfall or irrigation for cotton cultivation, combined with the escalating frequency of extreme weather conditions, exploring avenues to enhance the management of rainfall storage (*e.g.* better-utilizing farm ponds) and shallow groundwater recharge, using water-efficient irrigation methods, reducing soil surface evaporation (*e.g.*covering with straw) and fortifying crop protection is imperative. Furthermore, using environmentally friendly processing methods, such as mechanical instead of chemical processing, can help reduce the environmental impact of cotton production. Collaborating with organizations such as the Better Cotton Initiative (BCI) is beneficial in promoting sustainable cotton farming and improving the environmental and social impact of cotton cultivation throughout the entire cotton supply chain. It is of utmost importance that India and Pakistan promptly alter their cotton farming practices and restructure their textile industry, according to their performance in cotton production (36). To maintain its position as the top cotton exporter, China must improve its water usage efficiency due to its water scarcity.

The Yangtze River Basin is the third cotton-producing region in China and it was considered to have low water stress. However, in July-September 2022, the area experienced a severe drought, with high temperatures and little rainfall, leading to more than 2.8 million hectares of crops suffering drought, with some areas experiencing a shortage of drinking water for their population and livestock (181). Cotton farming in the Yangtze River Basin typically involves planting in the spring and irrigating throughout the growing season, which spans from May to October. In contrast, the first and second largest cotton-producing regions in China, Xinjiang, and the Yellow River Basin, usually suffer from more severe drought than the Yangtze River Basin, but Xinjiang is relatively rich in water resources, such as snowmelt, precipitation in mountainous areas and runoff in rivers, some large reservoirs, and artificial water sources. The prolonged drought and heat weaves expect to be more severe in China in the next 20 years. Over the past ten years, due to factors such as changes in regional economic development and the adjustment of agricultural industrial structure, the cotton planting area in 2022 has decreased by

279.15% in comparison with 2013 in China, but the total production is stable due to the increased yield (182). This maintained production might be the result of heavy fertilization. Recently, the agricultural practice "returning forests to farmland" campaign all over China has resulted in the removal of trees of all species and ages, vines, and bamboo, as well as windbreak forests in Inner Mongolia (183, 184), and only grain crops are allowed to be grown on newly cleared land. This trend of clearing forests has the potential to cause geological disasters, soil erosion, sandstorms, and biodiversity losses, in addition to exacerbating climate change and water scarcity, which might not be beneficial for crop cultivation. Hence, the production of textile fibers extracted from cotton, bamboo, and wood may be affected, leading to an increase in the price of these renewable textile raw materials.

China, ranking first in both cotton exports (20% of the global total) and imports (16% of the global total) in 2021, utilizes its exports to generate revenue and meet foreign demand, while imports fulfill domestic needs. Despite being a major producer, China faces challenges such as changing consumption patterns, crop yields, market fluctuations, and processing limitations that may hinder sufficient cotton production. Importing cotton offers cost-effectiveness, efficiency, and source diversification, reducing reliance on a single country for a stable supply. Higher Chinese cotton prices compared to global indices incentivize Chinese textile manufacturers to import from other countries. In contrast, India exported 16.3% of the world's cotton production but imported only 1.26%, while Bangladesh imported 14.4% of the global production but cultivated only 0.074% of the world's cotton output (64). Water-intensive goods imported by many nations create strain on the water resources of exporting areas, highlighting the need for improved water resource management through collaboration among stakeholders. Given cotton's high water footprint, comprehensive efforts are required to ensure sustainable water usage and preservation at a global scale.

Despite the noted ecological benefits of lyocell over viscose, the production of viscose still outweighs lyocell. The reasons might be as follows: the longer presence of viscose (more than 100 years) in the market has led to a more established production infrastructure and supply chain, making it more accessible and cost-effective to produce in large quantities; Viscose's adaptability spans various products, including clothing and home textiles, while lyocell is primarily applicable to high-end apparel due to its higher cost. Increased competition in the future by increasing the number of lyocell manufacturers has the potential to reduce the production costs associated with lyocell. Thirdly, the uninformed demand for viscose from consumers is significant, ignoring the ecological challenges associated with its production. Nonetheless, increasing awareness of ecological sustainability in the fashion industry and among consumers is driving brands to seek sustainable alternatives like lyocell. This trend is projected to boost lyocell production, potentially surpassing viscose as the preferred choice for environmentally sustainable regenerated cellulose fibers.

Agricultural waste is abundant but it is often burned, releasing air pollutants, losing organic matter and nutrients that deprive the soil of essential elements necessary for its fertility and health, and causing other environmental problems. Before the industrialization of textile production and the development of synthetic fibers, societies relied on natural materials derived from agricultural sources for textile production. Synthetic fibers dominate the textile industry due to their lower cost and efficient manufacturing process, which enables large-scale production compared to the labor-intensive cultivation and processing required for natural fibers. However, there is currently a significant emphasis on sustainable development. Hence, exploring innovative technologies or large-scale approaches to extract fibers from agricultural waste materials, such as stalks, leaves, or husks, as an alternative to synthetic and traditional natural fibers to minimize waste and maximize resource efficiency might be the best solution for future textile production.

Bamboo farming, driven by its high market value and profitability, often involves large-scale land clearance, particularly in China (lack of agricultural and environmental standards) and the practice of monoculture planting, resulting in habitat displacement and loss of biodiversity (185). The monoculture plantations favor the rapid spread of pests and diseases, necessitating the use of chemical sprays, despite bamboo's inherent resilience. China's dominance is attributed to its natural suitability for bamboo cultivation, while importers engage with China for the sake of accessing cheaper labor (186). Forced child labor is pervasive in Myanmar's bamboo industry (186). Importing the majority of bamboo products in the UK and the US from distant locations contributes to carbon emissions. In 2021, China emerged as the largest exporter of bamboo, accounting for 69% of the world's exports, followed by Vietnam (8.09%) and the Netherlands (3.04%) (187). Europe and the U.S. have started to cultivate significant quantities of bamboo for textiles (161). Since Western consumers prefer sustainably and ethically produced products that are more commonly found in Western countries, the increasing US production of bamboo may impact Asian nations where labor is cheap, labor conditions are relatively poor and unhealthy, and farming or processing might be unsustainable. FSC-certified bamboo and sourcing bamboo species that are relatively fast-growing, pest-resistant, and drought-tolerant, are good choices. While the yield of bamboo fibers in subtropical areas is 2.5 tonnes per hectare, a similar yield of textile fibers (2.4 tonnes per hectare) is possible from poplars grown in temperate climates in Northern Europe enabling each region in the world to be more self-sufficient in textile fibers.

# 5. Conclusion

The cotton industry is facing increasing challenges under prolonged drought periods and continued hot weather. Cotton cultivation might not be environmentally sustainable, particularly in certain regions of the largest producing countries China and India, which are experiencing severe water scarcity and water and soil pollution, ultimately threatening the industry's future production. Despite efforts to reduce environmental impacts such as the Better Cotton Initiative, cotton cultivation still requires a high water footprint and large amounts of agrochemicals compared to other crops, while the fiber yield is relatively low (Fig. 28). Moreover, only 1% of cotton is produced organically at the global scale, and it may not be feasible to increase organic cotton production to meet all the industry's demands due to the cost and the requirement for uncontaminated soil, water, and land. With the estimated 702-828 million people worldwide still suffering from hunger in 2021, a sustained water crisis in China could further trigger a global food crisis (8). As such, it is imperative to release more farmland for food cultivation and explore alternatives to cotton, such as other natural raw materials that require less water and agrochemicals and are better suited to adjust to climate change. Sourcing cotton from areas with abundant water resources or efficient water management and using recycled cotton is another solution.

To address the environmental issues associated with MMCF production, responsible procurement practices should involve sourcing viscose and lyocell from FSC-certified wood, which promotes sustainable forest management, protect biodiversity and engage local communities in sustainable practices. The second necessary practice is to source viscose from regions or manufacturers with strict environmental regulations, such as closed-loop production processes, minimizing the negative impact of fiber production on local ecosystems while safeguarding workers against harmful chemicals and processes. Fast-growing trees, particularly hybrid poplars, which exhibit resilience on underutilized marginal lands, offer a viable species for textile fiber cultivation in temperate regions, surpassing eucalyptus plantations in tropical regions in desirability due to the inherent flammability associated with eucalyptus. The implementation of mixed forest plantations of eucalyptus trees combined with non-oil-bearing species, is warranted at present to avoid severe forest fires during the prolonged drought periods. The improvement of traceability and transparency within the value chain of MMCF is of paramount importance.

Introducing bamboo-based and poplar-based textiles into IKEA's product range is a favorable decision considering the environmental sustainability, including their rapid growth, high yield (low pressure on land use), tolerance to gray water, and increased $CO_2$ sequestration during cultivation. Bamboo is also supported by its species' similarities in weight and texture with cotton and linen and soft and silky features akin to silk and cashmere. Similarly to wood, it is imperative to ensure that bamboo cultivation adheres to sustainable practices and to source bamboo viscose derived from closed-loop production processes, lyocell, or mechanically processed fine fiber. In pursuit of textile products beneficial from sustainability, IKEA can prioritize strategies aimed at cost reduction in the production of closed-loop and mechanically processed fabrics and plant FSC-certified bamboo and hybrid poplar in IKEA's forest.

In order to reduce the reliance on virgin cotton and promote sustainability, IKEA can incorporate rCotton or recycled rayons blended with cotton or other natural raw materials in its textile products to reduce the virgin cotton share. Additionally, IKEA can increase cotton procurement from regions with abundant water resources or efficient water management systems and practices of a lower level of fertilizers and pesticides, such as Brazil, Turkey, and Australia. In Brazil, the conventional virgin yarns' impacts on freshwater eutrophication, aquatic acidification, and human toxicity are relatively low (36). However, Brazil is one of the largest producers of genetically modified organism (GMO) cotton globally. Turkey and Australia are known for their production of non-GMO cotton. FSC-certified bamboo, fast-growing trees, and sugarcane bagasse are sustainable sources for producing lyocell or viscose employing closed-loop production processes or adhering to stringent environmental regulations, which is deemed the optimal choice. Among fast-growing trees, hybrid poplar is a better choice than eucalypts for IKEA in the next 20 years, primarily due to its adaptability to grow in marginal regions in Europe and its inherent low flammability characteristics. Based on their strength, durability, and suitability for outdoor applications, banana pseudostem, abaca and kenaf fiber, as renewable and biodegradable raw materials, are potential substitutes for polypropylene in IKEA's textile products. Banana pseudostem is a more favorable due to its agricultural waste nature and lower water footprint during cultivation. Corn-based PLA can serve as an alternative to polyester in certain applications, such as upholstery fabrics, curtains, rugs, and bedding items. PLA is a popular material in 3D printing, which offers streamlined manufacturing with reduced raw materials, chemicals, water, waste, energy consumption, and $CO_2$ emissions. PLA may have different durability, stretch, and heat resistance from polyester, which needs to be considered when in specific textile applications. Over 90% of IKEA's polyester products are manufactured using recycled polyester materials. The application of corn husk fiber in textiles is currently in the developmental and experimental phase. Nevertheless, its great potential as a cotton and polyester alternative stems from its abundant availability, affordability, and agro-waste utilization. Mechanically produced fine bamboo fiber is also a sustainable alternative to polyester, sharing similar durability and strength, while also providing breathability, moisture-wicking and luxurious texture properties, making it the ideal material for bedding, towels, and upholstery. Coconut coir, buckwheat hulls, sugarcane bagasse MMCF & EVA, agave bagasse MMCF, and loofah fibers are potential alternatives for polyurethane foam as mattresses or pillow fillers in IKEA products. Additionally, sugarcane waste can be transformed into cellulose nanocrystals (CNCs), which can be used for recyclable waterproof coatings. *Schoenoplectus triqueter (L.) Palla* (Cyperaceae) is an excellent material for crafting bed mats, pillowcases, cushions, and floor mats that are ideal for use in hot weather conditions. For some local stores, madurkathi fiber and ramie (*Boehmeria nivea*) fiber can be considered.

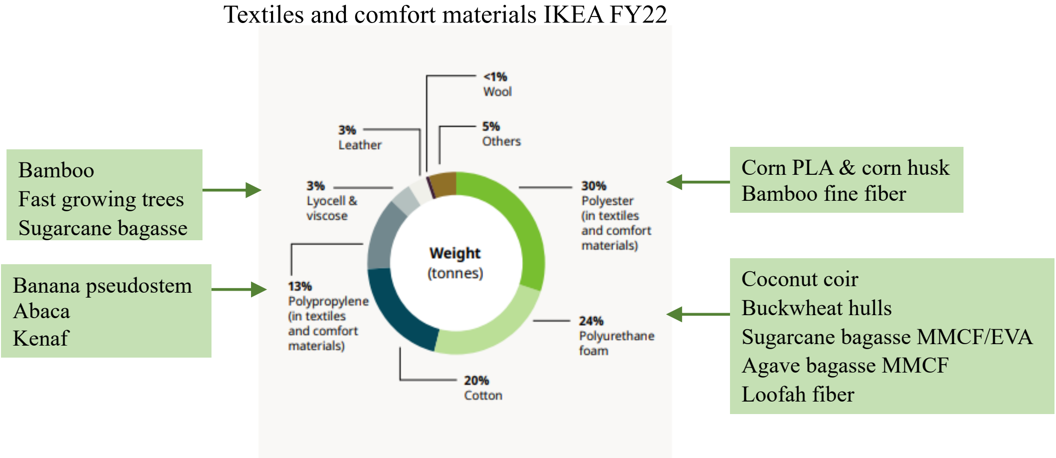

*Figure 32 The suggested renewable alternatives of textiles and comfort materials that demonstrate potential as partial replacements for non-renewable materials in IKEA products.*

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# Popular science summary

## Sustainable Textiles for a Greener Future: IKEA's Path Towards Environmental Responsibility

In a world grappling with escalating environmental challenges, the textile industry has emerged as a significant contributor to pollution and water scarcity. The ravages of heatwaves and droughts, fueled by climate change, intensify water shortages, food insecurity, and land degradation. Nowhere is this more pressing than in densely populated regions like China and India, where water stress threatens millions with limited access to safe drinking water. Amidst this crisis, the production of cotton, a ubiquitous natural fiber, stands as a symbol of the industry's impact, guzzling resources, eroding soil, and polluting waterways.

My thesis delves into the heart of the matter, investigating sustainable solutions for the textile conundrum. Through meticulous analysis and visionary thinking, this study unveils an array of innovative possibilities that could revolutionize the way we produce and consume textiles.

The journey begins with a comprehensive examination of the challenges facing the textile realm. From the environmental impact of cotton to the issues associated with synthetics and animal leather, the industry's complexities are revealed. The thesis then introduces a tapestry of sustainable alternatives, crafted from agricultural byproducts and fast-growing trees. Recycled cotton, agro-waste, bamboo, and even banana pseudostems offer the potential for circular production, reducing waste, emissions, and water usage.

The transformative potential doesn't stop there. The study turns its gaze towards a visionary destination: IKEA, the global behemoth of home furnishings. Imagine a future where the aisles are lined with textiles born from renewable sources. In this vision, synthetic fibers bow before the might of natural raw materials. Cotton shares the stage with recycled counterparts, while bamboo and hybrid poplar take center stage, celebrated for their rapid growth and minimal environmental impact.

But the path to this future is no easy feat. Challenges abound, from securing sustainable sourcing for viscose and lyocell to navigating the intricate web of supply chains. The study outlines a roadmap for IKEA's transformation, spotlighting strategies to reduce reliance on virgin cotton, enhance traceability, and champion closed-loop processes. It emphasizes the importance of responsible procurement, endorsing Forest Stewardship Council (FSC)-certified wood and stringent environmental regulations as cornerstones of change.

The quest for a greener future extends beyond product shelves. The thesis envisions a world where farmland is freed for food cultivation, and ecosystems flourish in the face of prolonged droughts. It's a call to action that resonates across industries and among consumers, urging them to reconsider their choices and embrace sustainability.

As the ink dries on this thesis, its implications reverberate far and wide. It beckons us to envision a world where textiles are not just products, but ambassadors of responsible innovation. With every fabric and thread, a path towards environmental stewardship is laid out, demonstrating that the future of textiles is not just sustainable – it's unquestionably stylish.

# Acknowledgements

This degree project at the Swedish University of Agricultural Sciences has been conducted in collaboration with IKEA. I would like to thank my supervisor Dr. Anneli Adler for her support, insights, and feedback throughout the project. I am grateful to my supervisor Anna Palmberg at IKEA of Sweden for her contribution with time, experience, and constant guidance. I would also like to thank Dr. Christoph Leibing, Ting Xie, Arvind Rewal, and Neha Madan Asthana for providing me with valuable support and data.

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