Sustainable Textiles: Production, Processing, Manufacturing & Chemistry

Subramanian Senthilkannan Muthu *Editor*

Novel Sustainable Raw Material Alternatives for the Textiles and Fashion Industry

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Sustainable Textiles: Production, Processing, Manufacturing & Chemistry

Series Editor

Subramanian Senthilkannan Muthu, Chief Sustainability Officer,
Green Story Inc., Canada

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Editor
Subramanian Senthilkannan Muthu
Chief Sustainability Officer
Green Story Inc.
Kowloon, Hong Kong

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This book is dedicated to:

The lotus feet of my beloved Lord
Pazhaniandavar

My beloved late father
My beloved mother
My beloved wife Karpagam and daughters –
Anu and Karthika
My beloved brother

Last but not least
To everyone working in making the textiles
and fashion sector SUSTAINABLE

Preface

Textiles and fashion sector's environmental impacts is quite known and well received and also acknowledged by various stakeholders involved in the entire supply chain, especially the manufacturing side of supply chain. The whole textile sector is enthusiastic and optimistic to investigate novel sustainable alternatives in terms of raw materials, processes, and approaches to make the entire textiles and fashion sector sustainable. The thrust to transform the entire sector to be sustainable is the need of the hour. This broad title of novel sustainable alternatives can be split into three subtopics – novel raw material alternatives, novel process alternative, and novel alternative approaches.

This volume is dedicated to deal with the *Novel Sustainable Raw Material Alternatives for the Textiles and Fashion Industry*. There are 12 chapters selected and published in this book to deal around the novel sustainable raw material alternatives to transform the textile and fashion sector to be sustainable.

I take this opportunity to thank all the contributors for their earnest efforts to bring out this book successfully. I am sure readers of this book will find it very useful.

With best wishes,

Kowloon, Hong Kong

Subramanian Senthilkannan Muthu

Contents

Sustainability by Using Preconsumer Textile Based Deadstock for the Development of a Capsule Collection: A Case Report

Simone Albuquerque and Maria José Abreu

Abstract With the current fashion consumption model, there is a considerable increase in the clothing manufacturing industries' generation of waste. So, it is necessary to plan strategies for sustainability within its production process. Thus, this work is necessary to indicate an alternative to reduce the improper disposal of this type of waste, coming to an economically and environmentally viable path for this type of material by the development of a capsule collection using textile deadstock waste. As for methodological purposes, bibliographic research was initially developed to provide theoretical support followed by applied research and case report. The results show that it is possible to reuse this type of waste effectively, being economically, socially, and environmentally sustainable.

Keywords Sustainability · Clothing industry · Textile waste · Economic impact

1 Introduction

The increase in the world population associated with the desire for consumption is directly related to the depletion of natural resources and environmental degradation. Overconsumption and its fast discard make it difficult for nature to replace what is removed from the environment and to absorb and/or transform the amount of waste that is being discarded.

S. Albuquerque
Fashion Design Course, Federal University of Piauí, Piauí, Brazil
e-mail: simonefalbuquerque@ufpi.edu.br

M. J. Abreu (✉)
2C2T-Center for Textile Science and Technology, Textile Engineering Department,
University of Minho, Guimaraes, Portugal
e-mail: josi@det.uminho.pt

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In this scenario, society is headed for social, environmental, and economic collapse. It is essential to raise public awareness and effective corporate and government management actions. The moment demands changes with new ways of thinking in which there is appreciation of the planet and all kinds of life.

Within this context, fashion Industry (textile and clothing) stands out, characterized as the third industry that most pollutes the environment [34], having been criticized for an unsustainable conduct as it negatively affects environmental quality and human well-being, but it should also be noted that it represents one of the most economically relevant contemporary industrial activities, generating employment and income all over the world.

In 2015, the Global Fashion Agenda and the Boston Consulting Group estimated that the fashion industry was responsible for the emission of 1715 million tons of CO_2, about 5% of the world's greenhouse gas emissions [25], as for the consumption of 79 billion cubic meters of water and producing about 92 million tons of waste [35], of which 0.18% come from Brazilian companies [36] using around 98 million tons of nonrenewable resources per year [13]. Sajn [35] warns that if measures are not taken, the tendency is to increase by at least 50%.

It is a branch of the manufacturing industry that needs to keep growing despite causing environmental impacts and damage throughout its value chain [6]. It then becomes essential to think about sustainability within its production process, such as the use of eco-sustainable and renewable materials, durability, and longevity, in addition to social attributes, including job security, fair wages, and quality of working life [5].

Also noteworthy is the inadequate disposal of its waste, which is particularly worrying, since when incorrectly managed, it becomes a serious threat to the environment and, consequently, to future generations [32]. Regarding that, it is necessary to consider not only the improvement of its production processes with the implementation of clean technology and energy efficiency but also the management of these residues as an essential condition for the preservation of natural resources.

Thus, taking the above as a reference, this chapter proposes a case study at a small scale clothing manufacturing company, located in the city of Teresina, state of Piaui in Brazil, with the objective of demonstrating the feasibility in the use of textile preconsumer deadstock in the production of a capsule collection as an alternative to reduce the improper disposal of this type of waste, coming to an economically and environmentally viable path for this type of material, as well as to seek for new alternatives to address the issues of use of solid waste and deadstock materials and contribute to regional, economic, and sustainable development.

Considering the ways in which clothing consumption is done, it is possible to affirm that the circular economy and labor practices in the fashion industry need to be reflected throughout the textile and clothing production chain. Therefore, it is necessary to evaluate the current conception of products and the products themselves, not only regarding their esthetics or functionality but also regarding the impact they have in the environment, people's health, and the useful life and the ability to be reused and/or recycled.

For a better presentation of the work, the text is organized in topics: the first topic is the introduction where the work is presented. The second topic describes the fashion industry as one of the most important business sectors for generating jobs around the world but as one of the most pollutant industries either. The third topic is showing the importance of the sustainability in the fashion industry pointing environmental management, technologies, and strategies that can reduce the impacts/damage to the environment and to society, seeking an environmental, social, and economic balance. The fourth topic is the methodology applied in this work followed by the results (topic 5) and final considerations.

2 The Fashion Industry

The fashion industry, one of the most important business sectors for generating jobs and income around the world, is part of the linear production model characterized by production, extraction, transformation, and disposal that produces tons of waste and pollutants, not taking into account the limits of nature and the damage caused to society, accounting for impacts throughout its production chain, from planting and extraction of raw materials to the final disposal of the manufactured product in addition to maintenance during the phase of use by the consumer.

It should be noted that the consumption of fashion products continues to grow. Ripple et al. [33] state that fashion consumers used 47% more clothes per capita in 2015 when compared to consumption in 2000. According to them, this increase suggests that the textile and clothing industry are oversized. It is noteworthy, however, that the COVID-19 caused an economic crisis that generated impacts in purchasing practices, especially when it comes to the fashion field.

Khati [16] reports that fashion consumers face a conflict between the desire to buy and the real decrease in purchasing power and what leads to negative emotions such as anger, distress, frustration, regret, and anxiety. But it also informs that the economic crises can have a positive regulatory impact on hyper consumption. New and future research will be able to decipher this duality.

The fashion industry must also be considered from a cultural perspective as it stands out as a code of social relations with symbolic representation and identity value, oriented to a lifestyle and understood as a cultural product that aims to stimulate consumption, collaborating for the consolidation of the capitalist society.

The fashion industry is used as a nonverbal communicator, with great visual potential, creating immaterial experiences that further aggravate the situation, as it is configured as a source of pleasure, which is culturally supported, of difficult awareness and, consequently, difficult to solve.

According to Wittman [42], through clothes, accessories, or even the body itself, the individual propagates meanings, codifies and/or expresses identities, transmits specific values, brings out the subjective expression of experiences, and facilitates transit through certain spaces. It also highlights the collective, expressing subjective aspects or even making their surface clearer. Practices on the use of fashion and discourses about it appear as capable of creating representations, in the form of image, self-image, and regulations.

And, in this scenario, the fashion industry takes advantage of people's needs for integration and differentiation to promote a continuous growth of its production. There are many attempts to make the public aware of the environmental issues involved in the production process, but most approaches are still not capable of motivating changes in behavior, as the marketing of these companies does not allow such awareness [9].

And so, this system, in addition to be contributing to the depletion of natural reserves, has been transforming the planet into a large waste deposit, and it is imperative that business society rethink on the economic model of linear production that prevails today [8].

We can already see some actions toward sustainable fashion. It's the case of the emergence and growth of new models of businesses such as thrift stores, bazaars, concerts, rentals, and exchanges, which in essence are not effective because these processes are not part of the culture of those who actually consume fashion. Han et al. [11] inform that fashion consumers are aware of sustainability issues, but sociological, perceptual, and motivational barriers prevent them from participating in the sustainable fashion product consumption. They complement by informing that this idea is built slowly and will only be noticed when it becomes part of the culture of societies, and marketing can be helpful in the diffusion of these concepts.

There is also the diffusion of sustainable fashion marketing that focuses on the promotion and consumption of environmentally correct products with the aim of raising consumer awareness of environmental issues [26], but Kim et al. [18] say that fashion consumers perceive sustainable products as inferior in terms of product attributes as it involves a cultural issue.

Thus, for fashion consumers to be interested in environmentally correct products, it is necessary to adopt practices of education, awareness, and an incentive policy capable of reducing the environmental impacts of their choices, prolonging the useful life of garments [43]. Consumer perceptions on the value of clothing must be modified through an awareness of the practices of extending its useful life, which is not yet accepted culturally in the most favored social classes, those who are effectively consumers of fashion clothing.

The raw materials most used for the manufacture of garments are cotton fabrics (natural fibers) and polyester and polyamide fabrics (synthetic fibers). Conventional cotton, in addition to being one of the most polluting crops in the world, is the one that consumes the most water, around 20,000 L of water to produce 1 kg of cotton [27].

Polyester and polyamide are nonbiodegradable materials that cause damage to the environment in their extraction and especially in their disposal process. Both are derived from fossil fuel but can be recycled, although in the production of clothing, they are usually mixed with other fibers, making recycling difficult as it makes separation impossible.

Most materials, regardless of fiber type, have impacts at some point in a garment's life cycle, whether it's the large amounts of petrochemicals used in their manufacture (such as polyester and polyamide) or by the high consumption of water (like cotton).

There are already technological fabrics in the market, materials produced through good environmental and social practices, which can be considered low impact, recyclable, biodegradable, and durable and require less washing for their maintenance. However, attention should be paid to the technology used to produce this type of raw material, as this process can cause more impact than the product from which it is recycled.

The ideal scenario is that all fibers can be recycled or biodegraded and that they make use of the minimum of resources causing the least possible impact. Current available technologies should allow government, companies, and consumers to practice recycling in such a way that makes it environmentally sustainable, ethically fair, and economically acceptable [15, 19].

However, what is observed is that the recycling of textile waste is not a reality that can be applied to all companies. In addition to being economically unfeasible, in most cases, a very precise selection is required due to the specificities of each waste.

Therefore, the control and selection of materials to produce a new product are fundamental for sustainable fashion. It is then suggested the use of materials from renewable, organic, and environmentally sustainable resources: from agricultural production with better working conditions, preferably certified; materials with reduced levels of inputs; and materials produced with less waste, among others.

Even though the sustainable focus of most apparel industries is directed toward the ethical purchase of environmentally friendly textiles, the industry must and is already looking for other paths that go beyond the concern with the use of correct raw materials.

Actions have been instituted to the production process and result in important reductions in environmental impact, but some of the strategies that try to promote the durability of fashion products such as recycling, reuse, and safe disposal, in order to optimize the end of the product's life, are limited by the cultural consumption practices of users [12].

These actions are valid, but the issue of sustainable development requires a more structural change and needs to focus on the way it is produced and how it is consumed. Vezzoli [40] states that there needs to be a rupture capable of allowing a new configuration between the actors and the structure in which they work so that a paradigm shift can occur capable of leading to a more sustainable fashion industry.

3 Sustainability in the Fashion Industry

The global fashion industry represents one of the most economically relevant contemporary industrial activities, but it presents problems involving sustainability. Kim and Kang [17] consider that sustainability is very important for this industry, as organizations consider sustainability to maintain consistent growth in their business.

Todeschini et al. [38] report that in addition to institutional interactions and community involvement, international agreements indicate that sustainability planning and practice depend on multiple actors.

In this way, these industries, as active agents in this process of environmental degradation and pressured by society, seek to show that they're searching for sustainable economic development by investing in environmental management, technologies, and strategies that reduce the impacts/damage to the environment and to society, seeking an environmental, social, and economic balance.

However, it should be noticed that these industries do not fully develop sustainability. There are specific actions, guided by marketing, but not because it is a company goal, although it is becoming increasingly essential within the clothing industry.

To adapt to the environmental context, companies must seek to incorporate sustainable practices into their production process that in addition to improving their environmental performance can also promote better economic performance [30].

Prieto-Sandoval et al. [31] report that this industry currently follows a linear production model – extraction, transformation, and disposal – producing tons of waste and pollutants, ignoring the limits of nature and the damage to society.

Pal and Gander [29] complement by suggesting that it is necessary to observe the flow of materials in the fashion system and change the sector's attitude from the largely linear model of production, sale, use, and disposal to a more circular model, reducing and delaying the flow of resources.

For Leal Filho et al. [19] and Islam and Bhat [15], recycling and reuse are also necessary as they bring numerous advantages to the environment. They complement by informing that the clothing sector is a major generator of waste and producer of raw material losses due to excess production.

However, one of the major problems faced is that not all textile waste is suitable for recycling and for the circular economy. With the advent of fast fashion, the by-products are of inferior quality, making recycling and reuse difficult and/or unfeasible.

In addition, the high price of some recycled textile fibers, due to the technology used, does not constitute a stimulus for recycling. There is also the presence of off-scourings composed of different materials that also constitute a barrier.

Thus, sustainable development must be included in the environmental, economic, social, and cultural dimensions in order to reduce as much as possible the amount of waste produced at each stage of the production process, especially textile waste, considered the most significant waste in terms of volume and impact.

Sustainable development is a way of integrating the economy, society, and the environment to the development of nations and enterprises. It assumes that economic growth must consider social inclusion and environmental protection [4].

Thus, it becomes important for design professionals and managers to consider the broader, longer-term implication of their activities, which emphasizes the need for a shift in design thinking and education about and toward sustainability [3]. In addition, knowledge of actions that promote sustainability in fashion can be useful in terms of directing innovations [37].

It is necessary to consider not only the improvement of its production processes with the implementation of clean technology and energy efficiency but also the management of these residues as an essential condition for the preservation of natural resources and the control of the material's waste for a cleaner and more efficient production [1].

Regardless of the product segment, the production process must establish a cleaner production method that can be applied in small companies, with the aim of improving their production processes, promoting social responsibility, and promoting sustainable actions [21].

The difficulty lies precisely in the fact that the methods mentioned in literature are difficult to adapt to the clothing industry since as they apply to a very limited number of industries, they are outsourced actions, making them unfeasible as ways to implement sustainability or assessing sustainability within them. It is also noteworthy that these companies are mostly small companies without capital to invest in technologies.

Thus, adequate planning and management is pointed out as the most adequate way to reduce the volume of waste produced, making it essential to prevent negative impacts on the environment and to reduce costs.

It is noticed that the recycling of textile waste is not a reality that can be applied to all industries in a massive way efficiently contributing to sustainability. In addition to being economically unfeasible, in most cases, they require a very precise selection due to the specificities of each waste. In the case of reuse, industries do not exercise control over their product after they are distributed, making their action unfeasible.

It is then necessary to work on sustainable consumption in the current economic model. Among the options pointed out, marketing stands out for its approaches that involve mass communication [7], the awareness of designers and entrepreneurs to develop products that can have a longer shelf life [10], the stimulation of sustainable consumption patterns through the awareness of a population driven by consumption and easy disposal [39], and the recovery and reuse of materials and components at the end of their life [15].

However, these business model strategies have not yet been effectively implemented, not being able to promote improvements that favor the sustainable process, although they can become fundamental actors in its implementation and dissemination. Production and consumption practices need to change. And changing the culture of entrepreneurs toward their business models and the culture of consumption that has been established in society is difficult and will still take some time.

The challenges are great, involving a culture focused on the mass market, involving both manufacturers and consumers. Fashion products can perhaps be considered the ones with the shortest useful life because they are generated within a model that extols ephemerality. They enter and exit the market in increasingly shorter periods of time.

3.1 Other Projects Developed Under This Topic

With the constant development of the textile industry, there was a need to present the urgencies that occur at an environmental and ethical level, as well as to develop best practices, such as reducing the use of chemical products; using recyclable, renewable, and/or biodegradable materials and products; and recovering and reusing products from previous collections in order to reduce waste and avoid overproduction [24].

As such, the "Re-Roupa" project, founded in 2013 in São Paulo, Brazil, focuses on creating pieces from deadstock that were considered preconsumer waste and has in mind society's awareness of importance of sustainability [23]. Figure 1 shows some parts of this project.

In a social project, the brand Levi's launched the Water™ line, which uses a production technique that reduces the use of water in the finishing of jeans by 96%. At the same time, the brand bet on a line called Waste<Less, shown in Fig. 2, in which each piece is produced using at least 20% recycled content and also an average of eight recycled plastic bottles [14].

Vintage for a Cause is a Portuguese circular economy brand with social commitment, focused on reusing textile waste through upcycling while empowering unemployed women over 50. Within a collaborative platform framework, the brand creates limited editions of timeless designs, gathering, engaging, and influencing different stakeholders throughout the value chain toward a more sustainable production and consumption.

The brand source deadstock and sustainable fabrics incorporating better practices throughout the supply chain to make beautiful vintage inspired styles at a fraction of the environmental impact of conventional fashion shown in Fig. 3.

It's not charity. It's a business strategy, or better, it's a social business model. In fact, upcycling deadstock demands skills of the seamstresses, putting all their expertise and soul in the garment construction.

Fig. 1 Re-Roupa brand pieces. (Source: [22])

Fig. 2 Levi's Waste<Less project. (Source: [14])

Fig. 3 Vintage for a Cause project [41]

4 Methodology Applied in the Study Presented

During a visit to a small clothing manufacturing company, it was noticed the accumulation of new raw material and end-of-roll waste in the stock (preconsumer deadstock), in addition to the enterprise willingness to solve or at least reduce the growing problem of backlog. As observed in this case, there is already a "new environmental awareness" on the part of entrepreneurs looking for business models that can generate positive impacts or reduce negative impacts on the environment and society [28].

In view of the situation found, it was possible to work a capsule collection for the company using this deadstock material to demonstrate the possibility of working with that material in a creative, sustainable, and economically viable way. In addition, the entire process for the creation and production of the collection was developed considering sustainability within the processes, from the creation and selection of raw materials to shipping. For [20], challenges like this are important because they point to the urgency of changing concepts and spreading the concepts of sustainability.

Methodologically, a bibliographic survey was initially developed mapping the actions that are being developed in the field of sustainability in fashion with regard to the textile waste produced and then the process of developing the collection which was carried out in five stages: research on the target audience and the brand identity, collection and evaluation of available raw material, creation and development of the capsule collection, moulage/modeling of the parts, and finally prototyping of some parts.

For the effective development of the capsule collection, the research had the collaboration of students and professors of the fashion design course at the Federal University of Piaui. As methodological procedures, the photographic record and the summarized descriptive memorial were used.

5 Capsule Collection Development Proposal: Analysis, Discussion, and Presentation of Results

5.1 Research on Target Audience and Brand Identity

For the development of any fashion collection, it is necessary to know the identity and the consumer profile of the brand. In this way, detailed research of the brand was initially carried out using the company's social networks and information provided by the marketing sector as sources, identifying some positive and other negative points.

As a way of solving the negative points identified, a rebranding proposal was developed, updating the visual identity, considering the vision that the brand would like to pass on: sustainable values; modernity; connection of the visual identity with the main styles that work toward a proposal for repositioning the brand; incorporating social, environmental, and economic sustainability; and a new logo and persona (Fig. 4).

5.2 Collection and Evaluation of Available Raw Material

The raw material used was supplied by the visited company, which collected waste from the end of the roll and useless items in its stock, donating this material to the capsule collection development project. It is noticed in the bibliographic survey the

Fig. 4 Comparison between the brand logo and the proposed logo. (Source: project development team)

Fig. 5 Raw material before and after selection. (Source: Photos by Simone F. de Albuquerque)

large amount of useless waste that is stored and/or discarded without proper destination. For Marques [20], textile waste (industrial knitted products, flat fabrics or nonwoven) from different origins needs a new destination that makes it possible to highlight them with a new value for the consumer, becoming "raw material" for a new product (Fig. 5).

In possession of the raw material, an analysis was made of the material that could be used in the capsule collection, and the material that would not be used was delivered to a social project that develops cloth dolls for donation to children in need during festive periods.

With the selected raw material, the composition of the fabrics was identified, reaching the conclusion that the company uses mostly raw material that has polyester in its composition, with preference for Crepe Morocco, Crepe Smooth, Due Crepe, Viscose Mixture, and Twill Air Flow.

In view of this finding, a more careful selection was proposed to the company when choosing the materials, informing them about more sustainable materials because polyester and polyamide are nonrenewable and nonbiodegradable materials, therefore causing damage to the environment both in their extraction and disposal process. They are derived from fossil fuel, so they can be recycled, but to produce clothing, they are usually associated with other fibers, making recycling difficult, since it makes separation unfeasible [1].

The company also makes use of many trims in its pieces, including metal plates with the brand's name. The literature informs that this type of material makes post-use recycling difficult. In this regard, the company received guidance being presented with other ways of styling its pieces.

5.3 Creation: Development of the Capsule Collection

Regarding the material, the collection was developed thinking about the color chart and the amount and size of the end-of-roll waste that was available and essentially the shape, so that pieces could be developed through modeling.

It was also considered the use of strategies that allowed the use of the same garment by a greater number of individuals, such as the placement of elastic in a part of the waist, in the back, functioning as a regulator that allows its use by different sizes.

Santos [37] have proposed sustainable design strategies so that they can be applied in the various phases of creation, development, and production of garments. For them, different strategies can be applied by companies and professionals in the areas of product design, production, service design, and life cycle.

Following, you can see the technical design of some of the pieces proposed for the capsule collection. In Figs. 6 and 7, the patchwork technique was used to make it possible to use small pieces of fabric. Figures 8 and 9 suggest the use of local

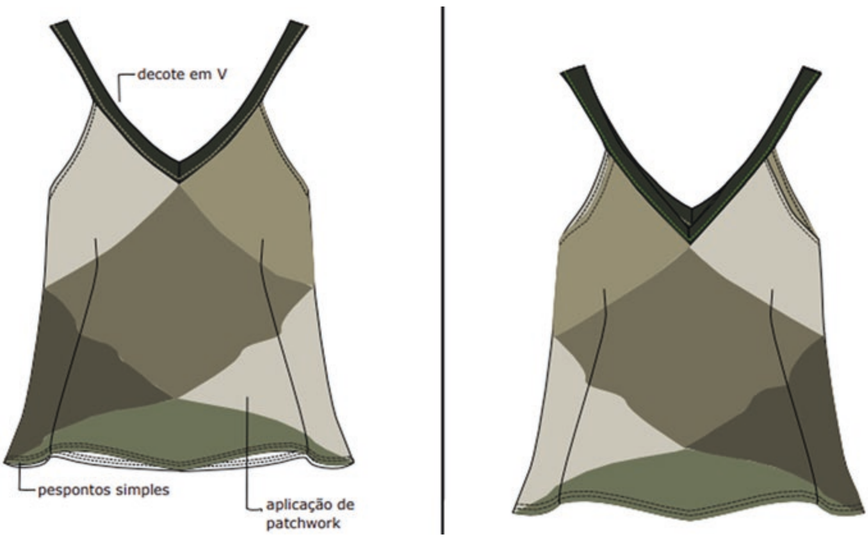

Fig. 6 Patchwork tank top. (Source: technical drawing by Maria Eduarda de M. Ramos)

Fig. 7 Patchwork tank top (prototype). (Source: Photo by Cícero de Brito)

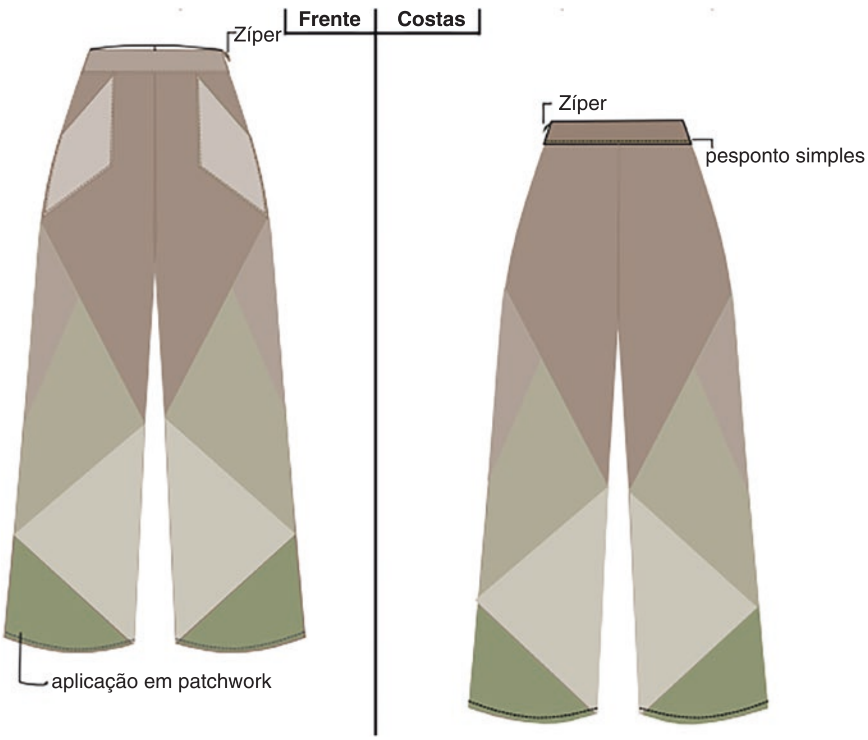

Fig. 8 Wide leg model pants with pockets and patchwork application. (Source: technical drawing by Maria Eduarda de M. Ramos)

Fig. 9 Wide leg pants with pockets and patchwork application (prototype). (Source: Photo by Cícero de Brito)

handicrafts with the application of flowers that resemble the cinnamon flower, a typical tree in the state of Piaui in northeastern Brazil. In Fig. 10, a sweetheart neckline and bell sleeves with appliqués (technical design) were cropped. The appliqués also refer to a typical tree in the state of Piaui in northeastern Brazil (Figs. 11, 12, 13, 14, and 15).

5.4 Moulage/Modeling of Parts

For the development of the pieces, flat and three-dimensional modeling techniques were used. The flat models were developed in kraft paper also coming from the company (waste). These were pieces of paper that were no longer useful to the company. And the moulage was developed with nonwoven (TNT), waste from the production of masks and gowns made during the pandemic period and that were now useless.

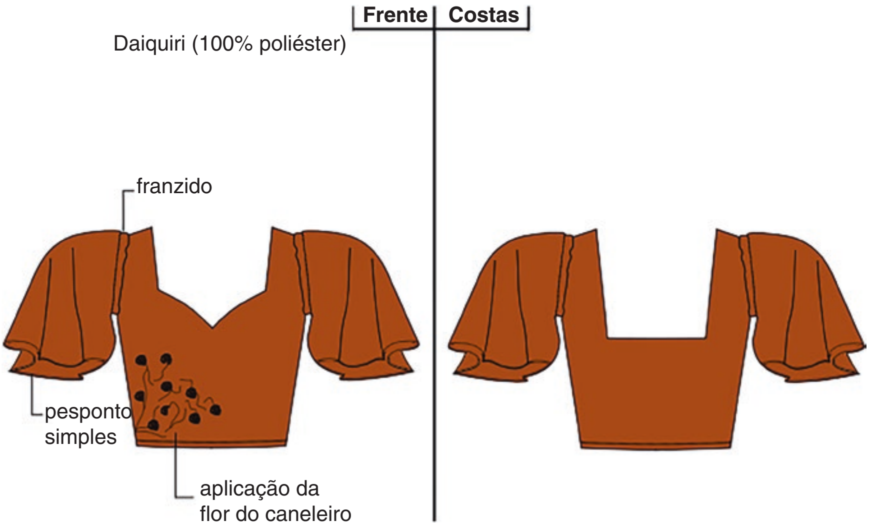

Fig. 10 Sweetheart neckline and bell sleeves with appliqués cropped. (Source: technical drawing by Bárbara Lis de C. Sousa)

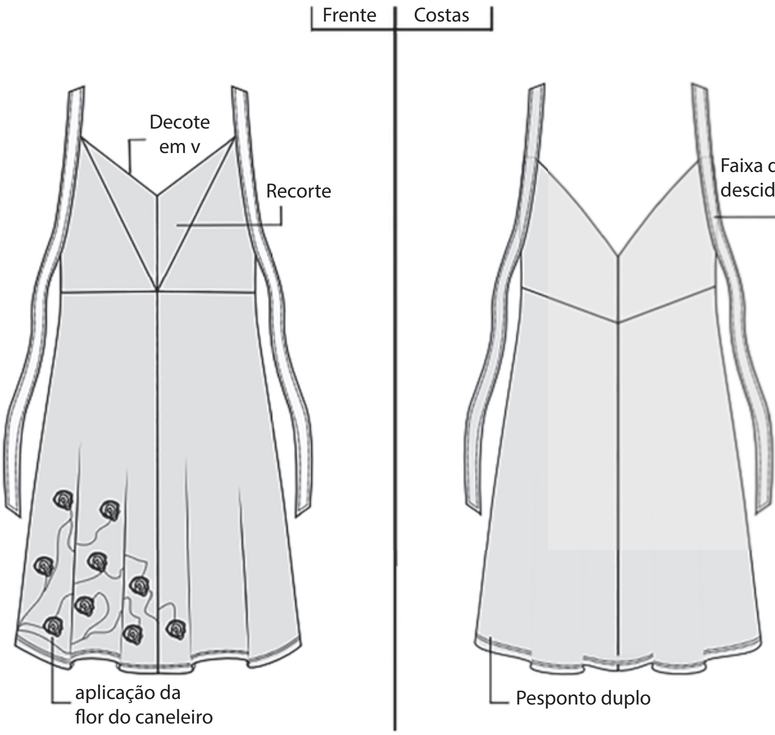

Fig. 11 A-line dress above the knee with appliqués. (Source: technical drawing by Sarah Evelyn Brito Silva)

Fig. 12 Sweetheart neckline and bell sleeves with appliqués and A-line dress with appliqués cropped (prototype). (Source: Photo by Cícero de Brito)

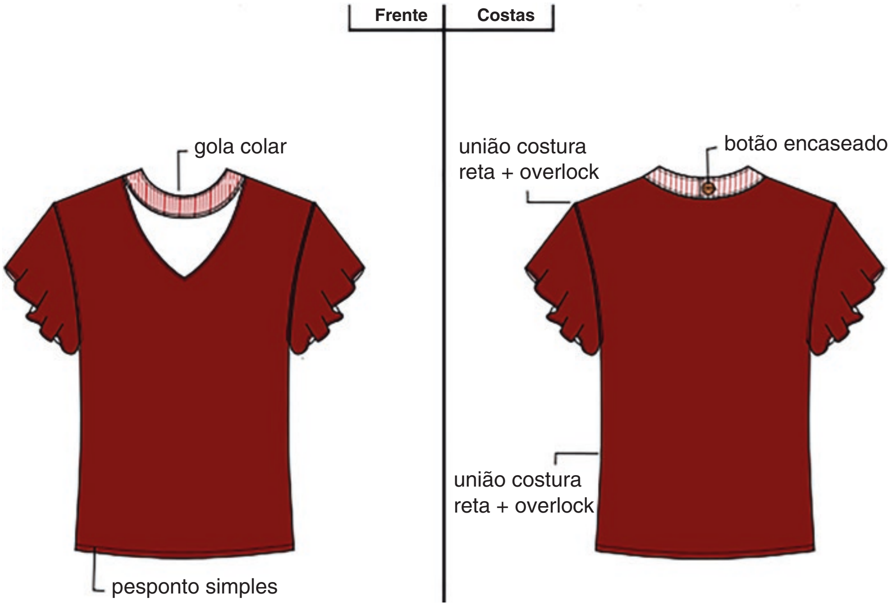

Fig. 13 Basic collared blouse with V-neckline and short flared sleeves. (Source: technical drawing by Paula Caroline A. Araújo)

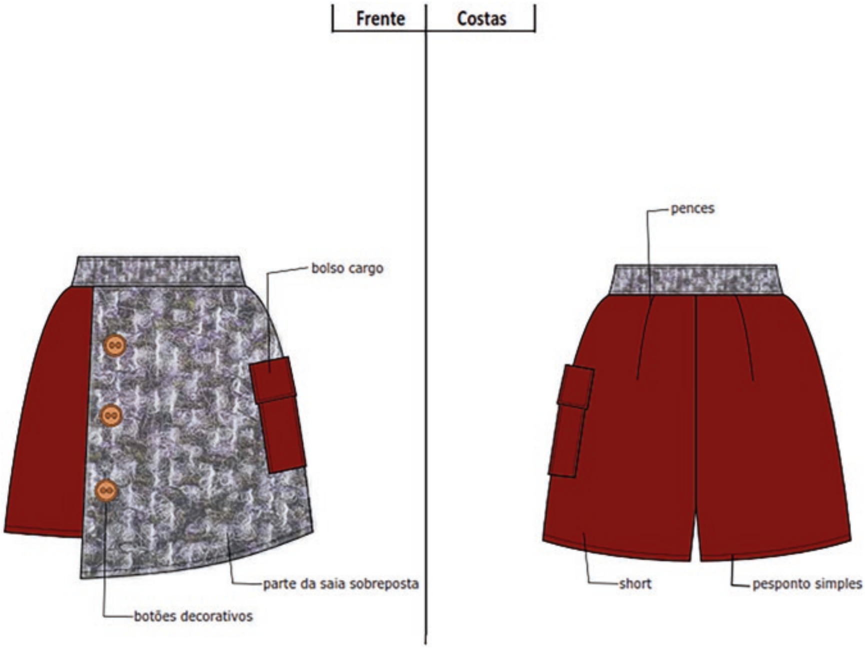

Fig. 14 Asymmetrical basic skirt short with buttons and cargo pocket. (Source: technical drawing by Paula Caroline A. Araújo)

Fig. 15 Prototype of the basic collar blouse, with V-neckline and short flared sleeves, and the asymmetrical basic skirt short with buttons and cargo pocket (prototype). (Source: Photo by Cícero de Brito)

Fig. 16 Modeling with reuse of kraft paper. (Source: Photo by Simone F de Albuquerque)

Fig. 17 Moulage using TNT that would be discarded. (Source: Photos by Ezecquiel Victor N. da Silva and Maria Eduarda de M. Ramos)

Alencar and Assis [2] highlight that among the main waste produced in the clothing industry, there are scraps, defective garments, dust from the overlock machine, plastic spools, cardboard and PVC tubes, needles, lines, lamps, lubricating oil packaging, liquid chemical canisters, dirty tows, papers from the modeling sector, etc. (Figs. 16 and 17).

6 Final Considerations

In view of the data collected in the bibliographic research, it can be deduced that the clothing manufacturing industries (mostly small ones) have a totally linear production process and a certain pattern when it comes to waste management, showing no concern regarding sustainability.

The vast majority recognizes the production of waste as an environmental damage but does not promote any type of intervention in the production process that can, in some way, reduce the amount of waste produced among them: the highlight in volume is given to textile waste.

In view of the proposal presented to the partner company of this project, the effectiveness of the action was perceived because the work developed pointed out the need to apply sustainability within the processes to reduce waste, also contributing to the company's finances and serving as an alert for the need for environmental awareness of employees and managers.

In addition, the results demonstrate that it is possible to use end-of-roll waste from the clothing industry for the development of a differentiated and sustainable fashion collection.

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Sustainable Colorants from Natural Resources

K. Nivedha and K. Kalaiarasi

Abstract In order to better understand the evolution and scientific improvements in textile dyeing throughout various archaeological periods, the dyestuffs applied to textile materials by ancient civilizations have been investigated. The utilization of sustainable natural bioresources in advanced garment developments is gaining momentum right now. Research and development in the textile industry have undergone a revolution as a result of the public's increased awareness of environmental preservation, eco-safety, and health issues. The textile industry has recently been under pressure from the public to utilize natural colorants with more advanced functions, without any negative effects on the environment or aquatic ecosystem. Natural dyes are an environmentally friendly substitute for synthetic colors. Natural dyes are increasingly being used to color textiles as people become more aware of adverse health effects of synthetic colors. Natural colorants won't cause any effluent issues when used. Natural dye, which is derived from tree, bark, leaves, flowers, and many other readily accessible sources, can provide vibrant colors. This article examines several starting materials for natural dye extraction, modern extraction procedures, surface modification approaches for improving dyeing, and colorfastness characteristics. Some artisans, weavers, and knitters employ natural dye as a distinctive aspect of their work due to the many benefits of this process. The majority of natural dyes have unique characteristics including antimicrobial and UV protection. This review paper will cover important topics including classification, extraction and dyeing, sustainability, as well as the isolated and widespread effects of bio-colorants obtained from bioresources.

Keywords Eco-preservation · Eco-safety · Sustainability · Bioresource · Natural dyes

K. Nivedha · K. Kalaiarasi (✉)
Department of Textiles and Clothing, Avinashilingam Institute for Home Science and Higher Education for Women, Coimbatore, TN, India
e-mail: kalaiarasi_tc@avinuty.ac.in

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1 Introduction

William Henry Perkin, a scientist who was 18 years old at the time and working on a malaria cure, made the discovery of synthetic colors in 1856. The word mauveine, which gave rise to the name mauve, was given to this purple dye [1]. Even though the color was temporary, it stimulated research into synthetic dyes and helped develop the color range we use today [2].

Today, synthetic dyes are the source of practically all textile colors. This is an issue because synthetic dyes were listed as one of the top 10 pollutants in the world in 2012 by the Blacksmith Institute and the UN [3]. One of the biggest contributors to water pollution is synthetic colors, and according to the survey, 200,000 tons of these dyes are released as effluents into the environment annually [4]. The risk of exposure to chemicals like chromium, a known carcinogen, which is known to cause neurological developmental and cardiovascular harm, cadmium, and chlorine compounds affects an estimated one million individuals, mostly in South Asia [5]. The main cause of this exposure is water contamination brought on by dye factories discharging untreated effluent into nearby water sources. According to estimates, textile dyeing contributes between 17 and 20% of all industrial water contamination [6].

Due to the health advantages, eco-friendliness, and age-old technique, natural coloring resources are increasingly being used to dye textiles to overcome the drawbacks of synthetic dyes [7]. Manufacturers of synthetic dyes have recently been required to limit effluent toxicity and cease production of hazardous synthetic dyes and pigments. As a result, the use of natural dyes is expanding quickly worldwide. In order to produce textiles of high quality and sustainability, natural dyes are extracted from flora and wildlife utilizing a variety of extraction processes and mordanting procedures [8]. Due to the use of natural dyeing processes, several researchers have also reported achieving UV and antibacterial characteristics.

By focusing sustainable dye, the membrane process has recently become one of the most cutting-edge procedures [9]. This procedure is a quick and crucial way to separate micro-macromolecules based on the size and shape of the molecules. It is used in the fields of biotechnology, textiles, chemical engineering, and food technology. By using membrane techniques, it improved the quality with a high yield, low energy consumption, and minimal operating conditions.

A variety of techniques, including UV radiation, microwave ultrasonic treatment, biopolishing, cationization, mercerization, gamma rays, and nanoparticles, [10] are being suggested for surface modification of fabric by scientists working in the fields of plasma treatment and application of natural colorant techniques, [11] with a focus on improving the extraction of colorants from plant sources. These methods are one of the more effective ways to replace various wet operations while using less energy, water, and chemicals [11, 12].

This review article provides a brief explanation of the different concerns of sustainable natural dyes in the textile industry, such as suppliers, extraction procedures, application techniques, modern techniques, and sustainable problems encountered in day-to-day upkeep.

2 Classification of Natural Dyes

2.1 Plant Sources

Natural dyes have historically been heavily derived from plant sources. Different plant materials, such as roots, leaves, twigs, wood, bark, flowers, fruit, hulls, and husks, were employed. The majority of plants used to make dyes also have additional uses, such as those for food coloring, medicine such as antimicrobial agents and skin care products, etc. The list below includes some of these significant and often used dyes.

2.1.1 Indigo (Leaves)

The bean family member whose scientific name is *Indigofera tinctoria* produces the blue dye from its leaves. This dye is referred to as the "King of Natural Dyes" since it has been used from ancient times to create blue colors, particularly for dyeing denim materials.

2.1.2 Madder (Root)

The dyestuff "madder" is made from colorants taken from the roots of several plant species belonging to the genus *Rutria*.

2.1.3 Cutch (Wood)

Natural yellow-brown dye known as "cutch" is made from *Acacia catechu* family wood. It is a natural dye that can be used to tan and color cotton, silk, and wool [13]. Cutch-dyed fabrics are particularly good at withstanding light and washing [14].

2.1.4 Jungle Geranium

One of the floral anthocyanins is the jungle geranium (*Ixora coccinea*). It's a member of the Rubiaceae family. It is a shrub that grows in gardens as well as all over forest terrain. This flower is native to Asia and is also known in Ayurveda as Vetchi or Flame of the Wood. By using different colored flowers, such as pink, red, yellow, and orange, to dye fabric, we were able to get various shades.

2.1.5 Kamala

The dried fruit kamala (*Mallotus philippensis*) capsules produce a reddish-orange powder that can be used to dye silk and wool, giving off vibrant orange-yellow and golden-yellow hues.

2.2 Animal or Insect Sources

Animals are a natural source of dyes. With the aid of animals and insects, people have been extracting red- and purple-based dyes since ancient times. Dried insect corpses are a key source of natural colors [15].

2.2.1 Laccifer lacca

Ancient cultures also used lac to dye animal fibers since it comes from the secretions of the microscopic insects *Laccifer lacca*, which are found on Indian tree twigs.

2.2.2 Coccus ilicis

The scale bug *Kermes vermilio* (also known as *Coccus ilicis*), which is a member of the Kermeside family, produces a vivid reddish-purple color. Both the eggs and the adult females have been used to extract the red color. This dye is frequently used in the textile, art, and cosmetic industries.

2.2.3 Coccus cacti

Dactylopius coccus is the plant that produces cochineal dye, the color that gives scarlet its hue. The colors were taken from mature female cochineal's dried corpses.

2.3 Mineral Sources

Malachite, ultramarine blue, gypsum, red and yellow ochre, and charcoal black are all pigments derived from minerals. Additionally, minerals are employed to improve and fix the fastness of vegetable dyes [16].

3 Extraction Medium of Natural Dyes

3.1 Conventional Extraction/Aqueous Method

The dye supplies from the chosen plants, vegetables, or other materials were traditionally and often extracted by aqueous extraction. The chosen dye source is either broken up into little bits or made into powder in order to increase dye efficiency [17]. After about a night of soaking in the necessary amount of water, it is then boiled to remove the color. The bath's contents are cooled to room temperature, and using trickling filter paper to remove fine plant material from the dye source can guarantee the removal of the material and greater solubility of the natural dye. The types of plants, animals, or mineral species or parts employed determine the color of the dyes recovered through this technique [18].

3.2 Supercritical Fluid Extraction

The textile industry is currently focused on safe manufacturing processes that can guarantee good end-use qualities for colored textiles as well as uniformity and specified color for natural fibers. Natural dyes and biodegradable materials are also of interest [19]. Using a lot of water is a drawback of traditional dyeing methods that employ water as the dying agent. Further development is taking considerable steps beyond the use of traditional solvent extraction technologies to address these problems. Carbon dioxide is used as the extraction medium in this method [20].

3.3 Enzymatic Extraction

Enzyme-assisted extraction (EAE) is a green strategy that is regarded as a strong complement or alternative to traditional procedures. Cellulases, hemicelluloses, and pectinases are the enzymes that are most commonly used for extraction [21]. They primarily come from bacteria and fungi, but they can also be made from animal organs, vegetable and fruit extracts, and bacteria and fungi. Higher yields that can be directly linked to the breakdown of cell walls are one of the benefits of EAE. Higher purity results from the selectivity. High catalytic efficiency, preserving the original effectiveness of natural compounds, shortened extraction times, and less solvent requirement are further advantages [22].

3.4 Ultrasound Extraction

Due to its many benefits, ultrasound-assisted extraction (UAE) is regarded as a "green method." In order to protect the heat-sensitive bioactive components of the extract from harm, the ultrasound tool performs best at lower temperatures [23]. Due to acoustic cavitation, which is more effective at lower temperatures, the ultrasonic (US) technique offers a good extraction yield at a lower temperature. Another benefit is that ultrasonic (US) treatment allows for improved functional component isolation due to mass-based transfer kinetics. To extract a biologically potent functional chemical from natural fibres used for dyeing, US treatment is clean, homogeneous, cost-effective, and time-effective.

3.5 Magnetic Stirring

The molten matrix and the reinforcing particles can be mixed via electromagnetic stirring. Additionally, an electromagnetic force can be used to disseminate the particles if the electrical conductivity of the matrix phase is much higher than the electrical conductivity of the reinforcing particles [24]. Dendritic microstructures can be diminished by electromagnetic stirring. Additionally, it may work well for distributing reinforcement particles during MMC formation [25]. An induction furnace was utilized to melt the aluminum matrix, and a mechanical stirrer was used to combine the molten metal with the reinforcements. However, the electromagnetic field used in induction furnaces stirs molten metal uncontrollably and perhaps unintentionally and cannot be used until the solidification processes are complete.

4 Characterization of Natural Dye

Ultraviolet-visible spectroscopy is used to characterize natural dyes. Absorption spectroscopy in the ultraviolet and visible wavelength bands, 180–380 nm and 380–750 nm, is used in ultraviolet-visible spectroscopy (UV-vis spectroscopy) to analyze molecules. One of the simplest methods for analyte characterization is this one. Chromophores are specific light-absorbing functional groups that are present in all significant classes of biomolecules. These chromophores are stimulated from the ground state to a higher energy level upon absorption of UV-vis light, producing distinctive spectra that help identify particular proteins [26].

Infrared spectroscopy using the Fourier transform. Based on the observation that most molecules absorb light in the infrared region of the electromagnetic spectrum, Fourier transform infrared spectroscopy (FT-IR) was developed. Wavenumbers in the 4000–400 cm1 range are commonly used to measure frequency ranges. Due to the variety of functional groups, FT-IR is mostly effective for detecting organic molecular groups and compounds. Due to their transparency, KBr salts are used to make sample pellets because they provide superior spectral resolution [27]. The most used method for determining the structure of bioactive plant extracts is FT-IR. For instance, the IR spectrum of an extract of *Euphorbia thymifolia* leaves from the Kumaon Himalayas revealed absorption bands at 3407 cm1, 1666 cm1, and 1562 cm1 for hydroxyl, carbonyl, and unsaturation, respectively [28].

Spectrometry using electrospray ionization and mass. An electric potential is provided to a flowing liquid in electrospray ionization-mass spectrometry (ESI-MS), which causes the liquid to charge and then spray. This electrospray creates incredibly tiny solvent-and-analyte droplets. The direct integration of HPLC instruments with MS is made possible by ESI. In *Tragia involucrata*, the ESI-MS method is utilized to analyze phenolic-rich fractions and find flavonoids like gentenstein 7-glucoside, iridine, orientin, dihexosyl quercetin, quercetin-3-O-rutinoside, and rhamnosyl hexosyl methyl quercetin [29].

A thermal analysis technique known as thermogravimetric analysis (TGA) or thermal gravimetric analysis (TGA) measures a sample's mass over time as the variations in temperature. According to thermogravimetric analysis, this measurement can reveal information on both chemical and physical events, such as chemisorptions, heat breakdown, and solid-gas reactions [30]. It is vital to use differential scanning calorimetry the nature of thermal natural dye component dissociation at various dyeing temperatures as well as temperature for use examined the impact of various mordants on textiles dyed with a novel natural dye in cotton and linen (Commiphora gileadensis) and presented numerical data on weight change throughout heating procedure for uncolored, coloured, and coloured cotton that has been chrome- and alum-mordanted as well as ferrous sulphate [31].

5 Mordanting

Chemicals called mordants are used to fix a dye to fibers [32]. For coloring with natural dyes, there are three different types of mordanting processes that are frequently used: pre-mordanting, meta-mordanting, and post-mordanting. Pre-mordanting involves treating the substrate with the mordant before dyeing, meta-mordanting involves adding the mordant to the dye solution itself, and post-mordanting involves treating the dyed material with a mordant.

5.1 Types of Mordants

Chemicals called mordants are used to fix a dye to fibers. Pre-mordanting, meta-mordanting, and post-mordanting are the three main types of mordanting processes that are frequently used to color materials using natural dyes. In pre-mordanting, the substrate is treated with the mordant before being dyed, in meta-mordanting, the mordant is included in the dye solution itself, and in post-mordanting, the material that has already been colored is subjected to a mordant treatment.

Metallic stains. Only naturally occurring metal salts were employed as mordants in the past. Today, however, metal salts of chromium, iron, copper, tin, aluminum, and chromium are employed as mordants. Alum, potassium dichromate, ferrous sulfate, copper sulfate, stannous chloride, and stannic chloride [33] are a few examples of frequent mordants.

Tannic acid and tannins are generally used to keep leather from deteriorating. In addition, they are utilized in mordants, stains, and glues. Vegetable tannins are astringent and bitter compounds found in plants, frequently excreted in the bark and other components (especially leaves, fruits, and galls). The extractions are either utilized directly for tanning purposes or used in a concentrated form by extracting the tanning ingredients [34].

Oil mordants are mostly utilized to create the turkey-red color from madder [35]. The primary purpose of the oil mordant is to create a complex with the principal mordant, alum. Alum is easily removed from the treated cloth because it is water soluble and does not have a preference for cotton. Fatty acids and related glycerides, including palmitic, stearic, oleic, and ricinoleic acids, are present in the naturally occurring oil.

6 Application of Natural Dyes

Natural dyes largely disappeared from the textile dying industry when Henry Perkin created a synthetic dye in 1856. Natural dyes were seldom ever employed in textile dyeing with the advent of synthetic fibers. Only cotton, linen, silk, wool, and other natural fibers were dyed using natural materials. Natural dyes are regaining popularity today as individuals begin dying synthetic fibers with some natural colors due to the increased focus on safety problems including health and environmental safety [36]. For the creation of green products with added value as well as for the environment in general, natural dyes are especially suitable and practical. Applications and future prospects for dye development are excellent. The ensuing factors are especially significant.

6.1 Health Safety of the Underwear Product

People are starting to pay attention to health safety in today's society as a result of the rise in living standards. For the dyeing and finishing of underwear, pajamas, and other clothes, specifically clothing, as well as children's clothing, health safety is a need [37]. The majority of natural colors have therapeutic properties, some may fight off infection and inflammation, some can stimulate blood flow and break up stasis, some can block ultraviolet radiation, and all are safe for use on people [38].

As a result, they acquire the new power of children's clothing and underwear that are dyed with natural colors.

6.2 Health Safety of Household Textiles

Home textile items have evolved from being affordable and useful to being practical and environmentally friendly, thanks to technology advancement. Natural colored sheets, blanket covers, towels, and other home textile products must adhere to environmental and ecological requirements and serve a medical purpose [39].

6.3 Modern Textiles

Due to their unique composition and structure, several natural dyes are utilized in the creation of new functional modern textiles, [40] including soy protein and rhubarb anti-ultraviolet fabrics [41]. The cloth is both esthetically pleasing and practical because to the brilliant, steady color.

7 Natural Dyes in Functional Finishing of Textiles

A careful balance must now be struck between the compatibility of various finishing products and the treatments and application procedures used to assure textiles with the necessary qualities. The role of the textile finisher is becoming more and more demanding. Customers all around the world are looking for apparel and other textile products that are more comfortable to wear while still being clean, hygienic, and odor-free. It is urgently necessary to do research into novel techniques for creating hygienic textile goods, in textile finishing procedures, and in related applications and issues. The use of natural dyes to give textiles multifunctional qualities, such as antimicrobial, [42] insect repellent, [43] and deodorizing, [44] is presently the subject of a number of reports.

8 Future Prospects of Natural Dye

For the weaker segment of the population in rural and suburban regions, natural dyes provide sustainable work and income for dyeing as well as for growing nonfood crops to create plants for natural dyes. The use of natural dyes has the potential to generate carbon credits by decreasing the usage of synthetic colors derived from fossil fuels (petroleum). Natural dyes typically generate gentle, glossy, and calming hues for the human eye. Natural dyes are useful for maintaining and understanding ancient dyeing techniques, preserving and restoring the history of old textiles, and conserving and restoring colored museum textiles and other textiles found through archaeology. If biotechnological advances such as tissue culture or genetic engineering enable the very high availability of natural dyes in the future, Natural dyes and mass synthesis of these colours by Microbes must first become affordable for mainstream textile processing before their use can be sustained.

9 Conclusion

The conservation and restoration of historic textiles using natural dyes than synthetic dyes (which employ violent technology) for textiles, food, safety, and other purposes has been a major manifestation of interest in natural dyes in recent years. The amount of research and development being done to standardize natural dyes is minimal to nonexistent. There haven't been many genuine attempts to produce new data on the use of natural dyes. The majority of studies in this field are led astray by empirical data provided in the literature that lacks any kind of scientific foundation or justification. Natural colors are not readily available, especially in standardized forms like paste, powder, or solutions. The standardized natural extracts have a lot of applications in the fields of textiles, food, medicine, and cosmetics. Working out suitable, standardized applications of natural dyes on textiles with eco-friendliness is a task for any educated dyer.

Consumer confidence in natural dyed textiles would increase with the establishment of adequate characterization and certification processes, which would be advantageous to both producers and consumers. There is a lot of room for small-scale dyeing units to use natural dyes if their availability can be increased through the aforementioned strategies and their costs can be reduced through a proper certification mechanism. This is because they lack the funding to set up and run the pricey effluent treatment plants required to bring the synthetic dye effluent within the regulations established by the government. Natural dyes can complement synthetic dyes as an eco-friendly alternative for the environmentally conscious consumer at the current stage of scientific development, but only for small-scale applications. They can also help the various stakeholders in the natural dye value chain units make a living because they lack the resources to set up and run the pricey effluent treatment plants required to bring the synthetic dye effluent within the legal limits.

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Tillandsia usneoides L. (Spanish Moss) Air Plant and Its Important Potential for Sustainable Technical Textile Applications

Ece Kalayci, Eda Gokmen Isanc, and Ozan Avinc

Abstract *Tillandsia usneoides* (L.), an epiphytic member of the Bromeliaceae (pineapple family), has exceptional properties and biomimetic potential for technical textile applications. *Tillandsia* are referred to as “air plants” or “atmospheric bromeliads” since they absorb water and nutrients directly from the air through the trichomes that cover their leaves, rather than from the soil or organic material. The plant uses its roots only for clings to the place where it is found. It has long, curly, grayish leaves that grow downward and usually hang from the branches of trees. The plant is native primarily to the American South and has been used by locals for a variety of purposes for many years. Although its use as a filler is one of the oldest uses, thanks to its insulating properties, the forked growth structure of the plant’s leaves and its ability to absorb moisture and nutrients from the air into the cell without needing roots, thanks to the trichomes on the leaves, are of great importance in biomimetic studies. In recent years, there have been many studies investigating its use as a biomonitor, especially in studies measuring air pollution. In addition, architectural applications have been developed that biomimetically mimic the fiber surface and cell structure and ceiling and wall systems with various properties, such as ambient moisture dissipation and ventilation. Based on these studies, the use of the unusual properties of the air plant *Tillandsia Usneoides* (L.) (Spanish moss) as a textile material and their application to textile materials as biomimetics have significant potential in terms of qualified technical textile applications. As a textile material, it has properties that are important for textile structures, such as comfort, durability, breathability, thermal insulation, and shock absorption. It also promises environmentally friendly production, thanks to its self-growth in nature, absence of chemicals or pesticides in production, natural structure, and biodegradable properties. In this chapter, the structure and properties of the air plant *Tillandsia*

E. Kalayci · E. Gokmen Isanc · O. Avinc (✉)
Textile Engineering Department, Faculty of Engineering, Pamukkale University, Denizli, Turkiye
e-mail: oavinc@pau.edu.tr

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Usneoides L. (Spanish moss), its use as a textile material, and the importance and potential of biomimetic applications were thoroughly investigated using the literature with regard to sustainable technical textile applications.

Keywords Spanish moss · Air plant · *Tillandsia usneoides* · Bromeliaceae · Biomonitoring · Technical textiles · Insulation textiles

1 Introduction

In recent years, studies on the introduction of sustainable new textile fibers in the textile industry have increased [1–4]. However, this is not a newly discovered textile fiber that we usually come across in research, but a niche fiber type with regional distribution that has been used as a textile fiber in human history since ancient times but has given way to synthetic fibers over time. Natural fibers such as milkweed fibers [5], kapok fibers [6], pineapple fibers [7], abaca fibers [8], nettle fibers [9], coir fibers [10], horsehair fibers [11], hemp fibers [12], etc. are just some of the natural fiber types that have gained popularity in recent years.

Especially in the technical textile industry, which is mostly dominated by synthetic fibers, the utilization of sustainable, biodegradable, eco-friendly natural fibers is very important to diminish the environmental impact of this industry. At this point, natural fibers with functional or high-performance properties are very rare [13, 14].

Tillandsia Usneoides L., also known as Spanish moss, is an epiphyte plant without roots that does not need soil and gets its water and nutrients from the (moist) air and raindrops [15, 16]. *Tillandsia Usneoide*s L., which wraps itself around other plants and trees in its natural habitat, has curly, gray-green, and long leaves that grow downward, usually hanging from the branches of trees [17, 18]. *Tillandsia usneoides* inhabits mainly tropical and subtropical regions with high humidity and can grow up to 1–2 m high under the right conditions [15]. The original habitat of this plant extends from Argentina to southeastern America [19, 20].

The peculiarity of this species is that it spreads itself and its habitat. This air plant, usually carried by the wind or birds, develops elsewhere and spreads to other branches, quite different from other air plants [17, 18]. Ideal locations for Spanish moss are those that do not receive direct light and have plenty of light and adequate air circulation. The suitable ambient temperature is between 14 and 26 °C. Humid environment is necessary for its survival; in a dry and airless environment, it begins to dry up [15].

The use of Spanish moss fibers as textile fibers dates back several centuries. Fibers similar in appearance and strength to horsehair were of great importance to

Native Americans, both for subsistence and for use [21, 22]. As a textile material, the fibers of *Tillandsia Usneoides* (L.) (Spanish moss) have properties that are important for textile structures, such as comfort, durability, breathability, dyeability, thermal insulation, and shock absorption. In addition, it is considered an environmentally friendly, sustainable source of raw materials because it grows in nature, no chemicals or pesticides are used in its production, it has a natural structure, and it is biodegradable [22]. Considering all these advantages, the use of air plants as textile materials and their application to textile materials as biomimetics have significant potential for qualified technical textile applications.

In this chapter, the structure and properties of the air plant *Tillandsia Usneoides* L. (Spanish moss), its use as a textile material, and the importance and potential of biomimetic applications in terms of sustainable technical textile applications were thoroughly investigated using the literature.

2 The Bromeliaceae (Poales) Family: *Tillandsia usneoides* (L.)

Tillandsia usneoides (L.) is an epiphytic member of the Bromeliaceae family (pineapple family) [16, 17, 23, 24]. *Tillandsia usneoides* is the well-known and most common of all Bromeliaceae, and it has the largest natural distribution of any bromeliad [25, 26].

Grown mostly in the southern United States [27], *Tillandsia usneoides* (L.) is called by the Native Americans as "tree hair" or "Itla-okla." The French went to America and called it Spanish beard, because it was like a long black beard of the earlier Spanish explorers [18, 28–30]. Also, Louisiana settlers named this plant Barbe Espagnol or Spanish beard [23]. Spanish moss is also sometimes called "long moss," "black moss," "Florida moss," "crape moss," "wool crepe," "barba Hispanica," "New Orleans moss," or graybeard [23, 30, 31]. Over the years, the name received its modern version "Spanish moss" [28, 29].

When compared to other *Tillandsia* kinds, Spanish moss looks like at least one *Tillandsia* or bromeliad and seems more like lichen [32, 33]. The Bromeliaceae (Poales) family contains more than 2600 species in 56 genera [25]. That contains eight subfamilies: Pitcairnioideae, Tillandsioideae, Bromelioideae, Puyoideae, Navioideae, Hechtioideae, Lindmanioideae, and Brocchinioideae [21]. The *Tillandsia* genus has more than 649 species, and these species include members with distinctive morphological and physiological characteristics. *Tillandsia* species are epiphytes that live independently of the soil, in trees, or in inert substrates such as powerline wires [17, 21, 34].

2.1 *Plantation of Air Plant:* **Tillandsia usneoides** *(L.)*

The *Tillandsia* are called as "air plants" or "atmospheric bromeliads," since they absorb water and nutrients through trichomes (Fig. 1c–e) that cover their leaves, directly from the air, instead of obtaining them from the soil or from the organic material stored in the middle part of most epiphytic bromeliads [34–38]. That means they don't need soil for growing. They absorb the nutrients in the water from their leaves, not their roots. The plant feeds on water-soluble minerals that flow from the leaves and branches of the tree it holds [18]. Roots are used by most species to connect themselves, and nothing more. *Tillandsia* can grow in places where no other plant can survive, including the power cord on the power lines. They prefer daily misting in light airy conditions and low humidity areas [30].

Spanish moss is considered by many to be a parasitic plant that damages or even kills trees. However, this is not the case at all [39]. Spanish moss uses the trees it grows on only to grow and protect itself. It meets all its living needs through sunlight and rain. The fact that it can live not only on trees, but also on various surfaces that do not contain nutrients, such as street signs or streetlights, can be considered proof that this plant is not a parasite [39]. Although this plant is not a parasite, its presence on the tree can have an indirect negative effect on the growth of the tree, as it can reduce the growth, solar radiation, and photosynthesis of the tree [40].

Spanish moss are drought, light, heat, and cold tolerant plant species, and the emergence of plant diseases and insect pests is rare. It perfectly adapts to the new environment even if its branches are broken or injured [41, 42]. These plants are especially suitable for planting in a garden perpendicular against the wall if growing is desired [43].

Plants need 70 °F (21.1 °C) or warmer air in summer and not less than 60 °F (15.5 °C) in winter. It doesn't need soil or cultivation; it just requires warmth and moisture so plants can grow easily. They can grow in greenhouses or outside in warm climates. Plants grow in full sunlight to partial shade [34, 42].

The growth pattern of Spanish moss is called the scorpion dichotomy growth pattern, which is an alternating dominant binary branching (scorpion dilemma) [42]. The nondominant branch in each branching is a leaflike branch. This can be seen in the schematic view: the shaded portion represents the stem, and the non-shaded portion represents the leaves and leaflike branches (Fig. 1a–c). The part of the stem below the dashed line contains the active meristem.

The flowers of Spanish moss are at the tip of the hanging plants [28, 29, 44]. They bloom (in South Georgia) from mid-April to the June and may not bloom when there is insufficient light [33]. It has small flowers and smells well at night [27, 30, 33].

The capsule formed later remains closed for 6 months, and its remains stay in the same place for a year. Seed formation is slow, and its dispersal is delayed until next March. Although seeds are abundant, seedlings are rare. Propagation is by garland pieces carried from one branch to another by the wind or by birds. When a piece of

Fig. 1 Photos and microscopic views of Spanish moss plant and its fibers: (**a**, **b**) Spanish moss plant, (**c**) leaves of plant, (**d**, **e**) trichomes on epidermis, (**f**) dried plant, (**g**) fiber visible through dried epidermis, (**h**, **i**) some epidermis remains on fiber, (**j**–**n**) microscopic views of fibers (personal archive)

Fig. 1 (continued)

moss settles on a branch, the living part of the stem that comes in contact with the husk dies and is shed, leaving the inner fibers that hold the plant in place [28, 29, 45].

There is an almost direct relationship between the ultimate growth of Spanish moss and the proportion of solar radiation. Humidity alone does not promote growth, but the plants die within 3–4 months in natural humidity if there is no rain. Growth rate cannot be correlated with humidity or temperature but was negatively affected by shade [46]. Spanish moss can be propagated by seed or by division. To propagate it by division, place the cut seedlings on bark sheets in a place with plenty of light and moisture. Steam the plants regularly with warm water.

There are many studies that recognize vegetative propagation as the typical method of Spanish moss propagation and multiplication. It has been examined the propagation of Spanish moss from its seeds in one of the oldest studies [42]. The collected seed pods were fully developed and germinated readily in moist filter paper. It was found that the seedlings grew very slowly during the summer months and by mid-September were small green plantlets with two small leaves. These roots grow to about 1 cm in length. The tip of the root assumes a hooklike shape and adheres firmly to the branch of the plant on which it is growing. In no case was a root observed to penetrate the host plant. It was also noted that these roots did not develop root hairs, but their cross-sectional view clearly showed the typical anatomy of a root [42, 46].

Schlesinger W. H. and Marks P. L. found in their studies that the occurrence and abundance of epiphytic Spanish moss correlates with the availability of minerals in the canopy of potential host trees [47]. Trees with high foliage leaching (e.g., cypress and oak) provide plentiful minerals (Ca, Mg, K, and P) in precipitation collected under the canopy [20, 48]. Forests containing these species have higher mineral concentrations than pine forests, and Spanish moss is more abundant. In growth chamber experiments, Spanish moss growth enhanced in response to the addition of phosphorus in the concentration range monitored in precipitation collections at this site. In addition to mineral availability, the rate of bark detachment and allelopathic effects of host trees might also influence the local distribution of Spanish moss. Therefore, mineral and bark characteristics of host trees in a favorable climatic range can be utilized to define a niche hypervolume for these species [48, 49].

3 Production of Spanish Moss Fibers

The production of Spanish moss fibers consists of harvesting, curing, and ginning steps, respectively. It has labor-intensive production steps [22].

3.1 Harvesting

Harvesting is the first step in the production of Spanish moss fiber. Harvesting Spanish moss is a lengthy process. This is because Spanish moss is usually pulled with hooks or a rake on long poles from the trees where it grows naturally [18, 19]. Another method is to collect it on the ground after storms. Most of the harvest is collected in the spring, from February to June, but harvesting can occur throughout the year, especially for those who rely solely on moss for their livelihood. If the moss is collected in winter, the yield can be higher than in summer [18].

3.2 Curing

The green moss is bought by the moss-ginning companies from the moss collectors. But green or gray moss cannot be ginned. Therefore, the collected moss is dried in the open yards and prepared for ginning. When drying Spanish moss, the mosses are piled into long stacks that are about 20 ft wide, 100 ft long, and 6 ft deep and then watered [50]. During the watering process, the pile settles 1–1.5 ft high and then it is not touched for 6 weeks. After that, it settles to a depth of 18–24 in. After this process, the outer moss is still gray, but below the surface of the pile it turns from brown to black. To get a good black product, you must wait for further curing. During curing, there is considerable heating of the moss bed due to biological activity. After curing, the moss is placed on wire racks to dry. During curing, weight loss can be 60–75% for brown moss and as much as 80% for black moss [18, 50].

3.3 Ginning

After curing, the moss is moved from the curing site to the ginning site. Further losses also occur during ginning. The gins, which vary in mechanism and design, are used to separate twigs, litter, and other foreign matter from the moss and to separate the outer cover or bark from the fiber. In the ginning process, the dried moss is fed to a type of gin that consists of grooved rollers and a toothed roller that may or may not work against a toothed concave surface.After the moss has passed through the gin, it is shaken on a wire screen or grid to remove the loose husk from the fibers [18]. Then the fibers are separated by color and purity and baled for market. The ginned black moss, which has lost 80% of its weight during curing, then loses half of its remaining weight, so that the final yield is 10 kg of black moss for every 100 kg of green moss. For brown moss, the yield is higher, but ginning can mean 60–70% loss. The size and weight of finished moss bales will vary depending on the type of bale utilized and preference for loose or tight packing. The product of a standard moss baler weighs about 140 pounds. The entire process can take anywhere from 3 to 9 months [45, 51].

4 Structure of *Tillandsia usneoides* L. (Spanish Moss)

Spanish moss consists of one or more thin stems. It is light green when wet and gray when dry. The stems and leaves of Spanish moss are curved and curly and covered with tiny silvery-gray scales which catch water and nutrients (in dust particles) from the air. The heavily scaled leaves are 0.8–2.4 in (2.0–6.1 cm) long and 0.04 in (1 mm) wide, which grow vegetatively in chain-like shape, forming hanging structures up to 240 in (6.1 m) in length (Fig. 1). The images of Spanish moss plant and its fibers shown in Fig. 1 were captured using Leica EZ4W microscope and camera. Spanish moss is famous for its interconnected ramets [52]. *T. usneoides* is a plant of Crassulacean acid metabolism and does not receive CO_2 throughout the day [53].

Spanish moss (*Tillandsia usneoides*) has water-absorbing multicellular absorption trichomes on the epidermal cells [54] which are also seen from the photos in Fig. 1d, e. In these plants, water could be stored after a rain, and organic litter can accumulate and decompose, so the scales on the funnel surface also absorb nutrients dissolved in water. Spanish moss is covered with tiny membranous scales. These increase the surface area of the plant and can absorb rainwater, mist, and even evaporating water [15, 54]. The outer covering of Spanish moss is highly absorbent and can hold up to ten times its weight in water [26]. With its small, slightly inward-sunking cylindrical leaves, much larger surface area, and relatively low storage capacity, *Tillandsia* can survive drought without a water supply [15, 31, 55].

5 Tensile Strength of Spanish Moss (*Tillandsia usneoides* L.) Fibers

The tensile properties of Spanish moss plant fibers were studied in a Tinius Olsen H10KT benchtop test apparatus according to the ASTM D 3822 standard for single fibers (indicator length, 20 mm, and test speed, 1 mm/min). As a result of the test, conducted under standard atmospheric conditions (20 °C and 65% relative humidity), Spanish moss fibers exhibited an initial modulus of 103387 N/tex, tensile strength of 270–300 N/tex, and elongation of 0.640–1.050%.

6 Uses of the Spanish Moss (*Tillandsia usneoides* L.) from Former Times Until Today

The fibers extracted from the air plant *Tillandsia usneoides* (Spanish moss) have been used for various purposes for centuries (Table 1). Although this use does not extend beyond local use, historical sources indicate that both the plant itself and the fibers it contains have been used in a variety of areas [18]. It appears that this plant and the fibers, which hold an important place in Native American history, are used to make skirts or dress-like garments worn by Native American women [18, 19, 88]. When the oldest uses of the fibers extracted from the Spanish moss air plant are examined from archeological remains and historical finds, they are found mainly in local clothing (to make skirts or gown-like garments) [28, 29], woven blankets [61], horse saddles, and ceramic pots, and it turns out that it was used mainly as a filling material. The fact that the fibers are as strong and durable as horsehair has led

Table 1 Various uses of the Spanish moss plant and fibers from the past to the present

Usage	Applications	References
Stuffing (filling) material	Furniture, upholstery, bedding, pillows, mattresses, car seats	[21, 22, 28, 29, 39, 56–59]
Binding agent	Bousillage style construction	[60]
Horse blankets	Primitive clothes	[18, 21, 61]
Traditional Native American wovens	Blankets	[18, 21, 61]
Local garments	Skirts, dresses, gown-like clothing	[18, 22].
Wadding and tinder for starting fires	Native Americans used dried moss for wadding in black powder muskets and as tinder for starting fires	[18, 21, 61]
Wrapping	Wrapping fruit and fragile objects	[21]
Insulation materials	Wall covering material bousillage	[41]
Evaporative coolers	A pump is used to spray water onto an area of Spanish moss, and a fan draws air from the surface of the Spanish moss into the building. The evaporation of the water on the wet surface lowers the air temperature and cools the building	[21]
Decoration	Decorative crafts and flower arrangements	[21, 39, 62, 63]
Ceramic making	Potteries	[64–69]
Medicinal usages	Medicines to treat gastropathy, diabetes, hemorrhoids, rheumatism, dandruff, digestive ailments because of overeating, body inflammation, antiepileptic and astringent, gastritis, throat placenta, accelerate childbirth, infant epilepsy, antipyretic, cough, hernias, measles, ulcers, arthritis, lung conditions, liver, kidney, heart, contraceptive	[19, 21, 28, 29, 70–73]
Cosmetics	Antiaging cosmetics	[21, 74]
Green roof systems	A green roof can reduce heat storage during the day and reflect heat at night. The green roof could diminish the heat transfer of buildings as energy, providing a sustainable solution to global warming	[75]
Biosynthesis	Model plant for ethylene biosynthesis	[30, 76]
Biomonitoring	Detection of pollutants in the air	[34, 37, 77–87]

to the use of these fibers as filling material instead of horsehair in products such as furniture, mattresses, etc. [21, 22].

Spanish moss fibers were used commercially from 1800 to 1930 [22]. There is even a modern use in the early twentieth century when Henry Ford utilized Spanish moss to stuff the seats of Model T Fords [19, 39]. Although many Florida residents once made their living collecting Spanish moss, the last remaining factory burned down in 1958 and never reopened [39].

There are also some tricky situations one should be aware of when using it as a filler owing to various insects such as red bugs and chiggers. If one wants to utilize fresh Spanish moss, one can get rid of these pests by boiling the plant in water and heating it in the microwave.

Due to its structure, when Spanish moss is mixed with clay, the outcome is a fabric with substantial tensile strength but difficult to work with as it could clump together and become entangled. For this reason, it is possible that potters using vegetable fibers would create containers in different ways than those using other tempering agents, and it is probably one of the reasons why there is such diversity in Late Archaic potting techniques in Southeast America. Kaal J. and Gilmore Z. studied archaeological fragments of this fibrous ware to determine the organic materials used for their manufacture and to evaluate these extraordinary pottery production conditions [64–69].

The doctors prescribed medicines from the moss to treat gastropathy, diabetes, and hemorrhoids. In the treatment of diabetes, the moss contains inulin, which is a substance similar to insulin, and when combined with other agents, it can help cure diabetes [19, 28, 29, 89, 90]. It is used to treat gastropathy, diabetes, and hemorrhoids. *Tillandsia usneoides* plants were also utilized in Mexican traditional medicine for the treatment of many disseases and health problems: hemorrhoids, dandruff, digestive ailments because of overeating, body inflammation, antiepileptic and astringent, gastritis, throat placenta, accelerate childbirth, infant epilepsy, astringent, antipyretic, cough, hernias, measles, ulcers, arthritis, lung conditions, Liver, kidney, heart, contraceptive, etc. [19, 21, 70–73]. In addition, *T. usneoides* can also be used to develop an antiaging cosmetic that supports keratinocyte differentiation in the skin [21, 74].

In the research of Fang W., Xiaosong Z., Junjie T., and Xiuwei L (2011), to balance the thermal conflict between hot summer and cold winter, they used Spanish moss in the blinds making, which is used as double skin facade (DEF), and the heat insulation of this curtain has been tested. As a result, *Tillandsia usneoides* is a suitable plant for sunshade owing to its unique properties [41].

6.1 Its Use in Air Pollution as a Biomonitor

Plants of *T. usneoides* meet all their life requirements from air and water vapor, without needing soil and roots. When the substances in the air dissolve into water vapor (moisture), they are taken up by the small trichomes on the plant and absorbed into the cell [38]. Recent studies have focused on this unusual property of the *T. usneoides* plant and investigated its use as a biomonitor for the detection of air pollution, especially in cities with air pollution problems. In addition, it is possible to discover its use in studies on nanotechnology and as a biomarker/biomonitor in various chemical treatments [37, 78]. Biomonitoring offers the benefits of sustainable and environmentally friendly monitoring.

Fossil fuel combustion, mining activities, heavy trucking, and industrial activities release large amounts of pollutants (such as nitrogen, sulfur, ozone gases, and metal compounds) into the atmosphere. When concentrations of these pollutants, which determine air quality and emission levels, increase, a major threat to human health is created. At this point, in recent years, many researchers from different cities have attempted to determine the level of air pollution in different parts of the city by using *T. usneoides* plants as biological measuring devices. The air pollution of the region was determined by studying the amount of pollutants in the structure of *T. usneoides* plant in different periods of time.

In general, cities where the *T. usneoides* plant can easily survive conduct biomonitoring studies: Rio de Janeiro (Brazil) [34, 79–83], São Paulo State (Brazil) [34, 77, 84–87], Salvador (Brazil) [91], Córdoba Province (Argentina) [92, 93], Argentina [94], Mexico [95, 96], Southeastern United States [94, 97, 98], North Carolina (USA) [99, 100], Jamaica [33], Bangkok (Thailand) [101], Germany [102], Pisa (Italy) [103, 104], etc.

Brazil is one of the countries where *Tillandsia usneoides* biomonitoring studies are carried out frequently. In a study conducted in Sao Paulo, atmospheric heavy metal pollution in the city center was investigated using the air plant *Tillandsia usneoides* as a biomonitor. Plants collected in an uncontaminated area were exposed to different sources of air pollution (industry, vehicles) in 8-week experiments at ten different locations in the city. As a result of the study, Spanish moss plant provided significant results as a biomonitor. Traffic-related elements such as Zn and Ba were detected in high concentrations in exposure areas near busy roads (cars, busses, and trucks). Similarly, the high Zn and Co content in industrial areas can be attributed to the presence of anthropogenic emission source [105].

In another study conducted in the province of Córdoba, in the center of Argentina, the accumulation of heavy metals in the air (V, Mn, Fe, Co, Ni, Cu, Zn, Pb, and Br) and different emission sources of air pollutants (cement plant, the relationship between the land use of the chemical and metallurgical industry, anthropogenic activities and/or distance to potential sources of heavy metal emissions) was investigated [93]. It was found that successful biomonitoring results can be obtained with *Tillandsia* species [92, 93].

Air pollution in the mining area of the Union of Cartagena-La, Spain, was studied using the biomonitor *Tillandsia usneoides*. Plants were harvested in five different areas along a latitude extending from the main mining area to the city and coastal areas and were studied every 2 months [106]. According to the results, atmospheric particles were found to be homogeneously distributed on the plant surface, and pollutants such as Sb, As, Cd, Zn, and Pb accounted for a significant proportion of the elemental content of *Tillandsia usneoides* [106].

In a study conducted in Georgia and northern Florida, USA, the relationship between mercury concentration in the air and Spanish moss was investigated. $164.8 \pm 8.7\%$ an enhancement in mercury concentration was found in the structure of contaminated Spanish moss in areas near the industrial zone after 2 weeks. It was concluded that biomonitoring can be performed by utilizing Spanish moss as a bioindicator in determining the mercury content in the air [99].

Another study investigating the use of *T. usneoides* as a biomonitor was conducted in Pisa (Tuscany, central Italy). Al, As, B, Ba, Bi, Ca, Cd, Co, Cr, Cs, Cu, Fe, K, Mg, Mn, Na, Ni, Pb, Sb, and Sr were studied in Spanish moss exposed to different pollutant atmospheres in different parts of the city. The results show that the elemental change in the structure of the *T. usneoides* plant reflects the level of pollution in the area to which it is exposed [103].

One of the biggest pollution problems that has emerged worldwide in recent years is plastic pollution. It poses a risk at least as great as air pollution. Plastic waste spreads in the form of micro-/nanoparticles from the oceans to the fish, into the soil, into the food we eat, and even into the air we breathe [107–113]. Recent studies show that microplastics can even be detected in breast milk [114–116]. At this point, biomonitoring studies become very important to determine plastic content as well as chemical contaminants from heavy metals, etc. In a biomonitoring study conducted in 2022, the effect of airborne particles of polycarbonate (PC), polyethylene terephthalate (PET), polyethylene (PE), and polyvinyl chloride (PVC) on *Tillandsia usneoides* was investigated. The results displayed that exposure to intact micro-/nanoplastics substantially reduces plant growth [117].

6.2 Biomimetic Applications and Important Potential for Sustainable Technical Textile Applications

Especially in academic studies in recent years, the survival of the plant without roots only with water vapor in the air has inspired biomimetic studies.

6.3 Artificial Superhydrophilic Surfaces

Spanish moss plant survives by absorbing water and nutrients, thanks to trichomes on its surface [118]. Researchers focused on the Spanish moss in order to develop a passive indoor dehumidification system [53].

The pore geometry of Spanish moss creates differences in vapor pressure and automatically absorbs water. The gaseous molecules passively diffuse and then condensate due to size and shape of pores; that is to say, capillaries convey the water to where it is needed, and this is called capillary condensation. This is mimicked by a ceiling structure with pores that attract water from the room air in the study, and these pores transport the water to capillaries and produce a passive dehumidification process [119].

The production and use of artificial superhydrophilic surfaces with this property is being studied as a biomimetic [39, 118].

6.4 Wound Healing

In a study investigating the influence of methanolic, ethanolic, and aqueous extracts of *Tillandsia usneoides* against pathogenic bacteria and the wound healing process in mice, it was found that the crude extract of Spanish moss (*Tillandsia usneoides*) showed in vitro antibacterial activity against skin infections during wound healing [120]. It was concluded that *T. usneoides* has a great potential to be developed as a new drug in the future in terms of its antimicrobial and wound healing activity. This also means that it has great potential for medical textiles, which are very popular and important in the technical textile industry.

6.5 Fabricating Artificial Composite Membranes

In a study published in *Nature* in 2020, artificial composite membranes could be produced by mimicking the trichome structure on the surface of the plant *Tillandsia landbeckii* [121]. The trichomes of *Tillandsia landbeckii* and *Tillandsia usneoides* are very similar. This means that *Tillandsia usneoides* can also mimic a similar design for an artificial composite membrane.

7 Conclusion

Tillandsia usneoides L, also known as Spanish moss, is a rootless epiphyte plant that does not require soil and obtains its water and nutrients from the (moist) air and raindrops. In its natural habitat, it wraps itself around other plants and trees. *Tillandsia usneoides* inhabits mainly tropical and subtropical regions and has curled, gray-green, and long leaves that grow downward and usually hang on the branches of trees. It can grow up to 1 to 2 meters high under ideal conditions.

Spanish moss, native mainly to South America, has been used for many years by Native Americans for various purposes, both as a plant and for its durable fibers. Spanish moss fibers, which were also used commercially for a time, were often used in products requiring properties such as strength and insulation because of their horsehair-like appearance and texture. It offers a broad variety of applications, especially as a filler. The fact that the Spanish moss plant grows spontaneously in nature, does not require additional irrigation and fertilization (which can be toxic) during its growth. Also its biodegradable and natural structure make these fibers a sustainable alternative.

Fiber extraction from Spanish moss has not been commercially available since the 1950s, as it is a labor-intensive job and is not a well-known/preferred fiber type today. However, when the fiber properties are examined and the extraordinary moisture absorption mechanism of the trichome structures on the fiber surface is added to this, Spanish moss fibers have a great potential in many fields, especially in the textile industry. Recent studies have been very successful in detecting and tracking heavy metal/micronanoplastics, etc. pollutants in the atmosphere, with the use of these fibers as bioindicators/biomonitors. In addition, thanks to the antiviral feature of the Spanish moss plant, it emerges as an alternative sustainable raw material source in the development of both pharmacological and medical textile products. In addition, although it is possible to use these fibers in sound and heat insulation, super hydrophilic surfaces can be developed, and artificial composite membranes can be designed with the biomimicized trichome structure.

Especially in recent years, research has been conducted in both academia and industry to add new alternatives to sustainable raw material sources, to industrialize them, and to contribute to natural and environmentally friendly production. Spanish moss plant also has an important sustainable raw material potential for many industries, including textile [thanks to its self-growing structure in nature, it does not require additional irrigation, watering, and fertilization (including soil) during its cultivation, as well as its natural, biodegradable, and renewable character]. Although fibers from Spanish moss were used commercially until 100 years ago, unfortunately Spanish moss is no longer one of the commercially known or widely used fiber species in recent years. For this reason, although Spanish moss fibers are recognized for their potential as an environmentally friendly and sustainable source of raw materials, there are studies in the literature that examine the environmental impact of these fibers using indices such as life cycle analysis, carbon footprint, water footprint, etc.

In this chapter, Spanish moss air plant and its structure, properties, and usage areas from past to present were examined in detail, and it was noted that it has an important potential for technical and functional textile products, especially sustainable raw materials.

In summary, Spanish moss fibers can be considered a natural and sustainable source of raw materials for a new generation, considering the structure, performance characteristics, and uses that date back to ancient times. Moreover, it is predicted that they will play the main role in many studies in the near future, both by being used as a raw material source and by mimicking their structural properties as biomimetics.

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Luxurious Sustainable Fibers

Ritu Pandey, Sarika Dixit, and Ragini Dubey

Abstract Textiles are the dynamic link between the past and present. Past is always associated with lavish and luxurious lifestyles. This perception is probably because lifestyles of the rich and influential are projected in the ancient architecture, castles, written records, and portraits. Many palaces including museums display the royal robes of the past era. This chapter presents natural fibers as collected from the flora and fauna. Environmental merits, inherent comfort characteristics, and scarce availability make sustainable textiles special and expensive. The protein fibers discussed are byssus, mud silk, muga silk, naturally colored silk, pashmina, and shahtoosh. The cellulosic fibers described in the chapter are luxurious lotus, bark cloth, fox fiber, and mud cotton. Ancient gold, silk, and precious metal fibers are also described. Physicochemical properties, chemical constituents, and marketing potential of the fibers are also included in the chapter.

Keywords Bark cloth · Byssus fiber · Colored silk · Fox fiber · Metallic textile · Mud cotton · Mud silk · Muga silk

R. Pandey (✉)
Department of Textiles & Clothing, Chandra Shekhar Azad University of Agriculture & Technology, Kanpur, India
e-mail: ritupandey@csauk.ac.in

S. Dixit
Department of Fashion Design, School of Design, Lingayas Vidyapeeth, Faridabad, Haryana, India

R. Dubey
Department of Family Resource Management, Chandra Shekhar Azad University of Agriculture & Technology, Kanpur, India

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1 Introduction

Natural fibers are generally comfortable, elegant, eco-friendly, diverse, and thus sustainable. Natural fibers do not affect the life of those involved in clothing and textile production and in the consumption. Sustainable fashion is serviceable and esthetic with easy end of life management. Textile industries should keep on innovating sustainable ways of processing textiles and utilize eco-friendly raw materials. Sustainable fiber production and usage help in improving textile quality and energy saving [1, 2]. Among the various factors, luxury in apparels is also linked with antiquity or relatively old in terms of manufacturing techniques, designs, and processing [3]. An example of old practice sustaining even today in manufacturing is the exquisite *Patola* from Patan, India. *Patola* is made by dyeing the warp and weft separately prior to weaving an exquisite colorful saree. The design, complex yarn dyeing, and weaving technique of *Patola* remain unchanged since its beginning in the eleventh CE [2]. Luxury products symbolize status of the wearer but display social inequality. Old and sustainable practices in textile processing are time consuming and labor intensive (slow fashion) which escalate its price tag. Mass production of sustainable textiles through current industrial setup utilizes recycled fibers for apparels [2]. Luxury apparel industries invest significant amounts on branding and advertising, which attracts luxury apparel consumers, but industries lack momentum in the adoption of sustainable practices. However, textile industries have taken initiatives for adoption of mandatory sustainable practices and ethics as imposed by the government. Revenue from the luxury products is projected to increase 5–6% annually [3]. Apparel industries, over the last five to six decades, have increased hundred times in terms of global revenue. Large scale expansion of the textile export and consumption globally has also attracted people in the indiscriminate use of the precious resources. Wage disparity and unethical work conditions are common in the textile industry. Millions of textile workers have to face the sweatshop condition at the workplace particularly in the developing countries [4]. Characteristics of luxury fashion in such a scenario are complex and an amalgamation of several factors. Luxury textiles have high cultural and economic values and thus are legal binding [5]. Furthermore, high quality of these products make them timeless, unrealistic [4], exhibiting valuable craftsmanship, authentic uniqueness [6, 7], signature style, and customer perspective [3, 8]. Fashion may be short-lived but luxury is timeless with exceptional quality [3, 4]. Luxury fashions include ready to wear products [7]. The United Nations Brundtland Commission (1987) defined sustainability as “meeting the needs of the present without compromising the ability of future generations to meet their own needs.” The sustainable development goals (SDGs) call for a development framework without affecting climate change by mitigating man-made hazards (SDG 13) and use of natural resources (SDG 15) [9]. Fashion firm’s turnover of luxury manufacturing industries was 300 billion euros in 2011 [4]. About 57% of Americans pay premium price for the branded goods from pro-sustainable manufacturing companies [10]. Global organic textile products (GOTS) framed the sustainable criteria for textiles including organic certification and labeling. GOTS license ensures organic status of the natural fibers from sowing and harvesting to industrial processing [2, 11]. Sustainable textile is essentially recyclable and saves resources and the environment without compromising end use requirements [2]. Sustainable textile research in the past focused on resources, materials, cleaner supply chain, digital innovations, and sustainable practices. Sustainable models emphasize on analysis of trends, challenges, drivers, and entrepreneurial opportunities [12]. One of the detailed studies on sustainable product innovation finalized the most vital success factors as fulfillment of customer expectations. Other important factors included legal compliance, green creativity, sustainable buying aspects (market acceptance, customer perspective), investment in research, and monitoring of the competitors [12]. Sustainability business models have an edge over conventional production, but this requires rethinking of resources, processing, products, and business models. This takes into account use of precious resources including crop fertilization, water use, working condition, processing, dyes, finishing chemicals, reuse, by-product utilization, and waste and end of life management. March to sustainability envisioned in Kinetics reports about sustainable supply chain in textiles. Realization regarding sustainable raw materials and processing has made the growth of such products tenfold compared to conventional textiles. Utilization of discarded plant wastes for textile fiber regeneration solves the problem of crop stalk burning [13]. Slow fashion helps the society to be more sustainable and promotes social innovations, ethics, versatility, reuse, upcycling, and local sourcing. It preserves traditional culture and skills and carries forward the same to the future generations [2, 14, 15]. Sustainable luxury aims at respecting our environment and social innovations through promotion of local crafts, art, and culture [1]. According to Coco Channel, luxury is beyond necessity. The elements of sustainability incorporated in luxurious products are an important value addition not only to the products but the society. Textile production, designing, and industry goals have always been associated with exploitation of resources and workers. The concern for workers, environment, and users in textile production took long since inception of the first anthropogenic fiber rayon. The realization has been far greater in the last 30 years compelling the textile manufacturers to be socially responsible [16]. Recycled fibers also come under the purview of sustainable fibers [2]. However, only non-anthropogenic fibers are included in this chapter, which are an epitome of sustainability. The key points of sustainability of the fibers presented are (i) directly from nature and (ii) no chemical intervention during processing. Mass production of the sustainable products will certainly bring down their cost and make the premium products within reach of the larger population. The mass production of sustainable luxury textiles needs awareness, encouragement, and incentives from the government and different other organizations.

2 Luxurious Sustainable Textiles

2.1 Bark Cloth

Bark cloth is an indigenous fabric from Uganda derived from the bark of *mutuba* tree (*Ficus natalensis*, *Ficus brachypoda*, and *Antiaris toxicaria*). It has been regarded as "Masterpiece of the Oral and Intangible Heritage of Humanity" by the United Nations Educational, Scientific, and Cultural Organization (UNESCO) in 2005 to provide identity and protection to this ancient art. The bark cloth was banned in the 1970s and 1980s in Uganda but regained production in the 1990s [17]. Bark or bast felt is known by several names: *Bugu* (Uganda), *Tapa* (Polynesia), *Impusu* (Rwanda), *Liwondo* (Tanzania, Mozambique), *Sambi/nyanda* (Tumbuka), and *Chiwndo* (Malawi). Bark cloth in Polynesia is made from mulberry [18]. Bark cloth is the world's most sustainable cellulosic cloth. The fabric does not require any special machinery or hazardous chemicals during its procurement and processing. Tree bark is given a vertical slit to doff the full length bark. The tree devoid of the bark is covered with banana leaves to heal and regrow. Next layer of the bark is ready to harvest within a year. The single tree (*Ficus natalensis*) yields 30–40 cloths in its life span [17, 19]. Bark cloth manufacturing practice involves peeling and beating of the bark. Peeled bark of *Ficus natalensis* wrapped in banana leaves is heated first to soften it. Bark is subsequently steeped and steamed in water followed by pounding by a series of special wooden mallet. The process is repeated for several months to obtain the felt larger in size than the original bark dimensions. The resultant fabric is a fibrous layer of soft and flexible bark cloth (Fig. 1a). The cloth is sun dried later for 3 h × 6 days to develop brown hues followed by repounding to smoothen the felt surface. Bark cloth is covered in iron rich mud to obtain black color and subsequently stretched and dried to retain its enlarged dimensions.

Fig. 1 (**a**) Bark cloth (Smithsonian design museum http://cprhw.tt/o/2Cynv/ Accession Number 1963-5-1 Object ID 18449423). (**b**) Mud cotton (bogolanfiniu – Collection.maas.museum – https://collection.cooperhewitt.org/objects/18449423/)

Thermal stability of the fabric is below 200 °C. Fabric thickness of the bark cloth layer is 1.084 mm and warp/weft strength is 101.7/23.5 N [17, 20]. Thermal diffusivity of the bark cloth reveals that the fabric is warmer than the cotton fabric. Moisture vapor permeability of the fabric is higher than the cotton with most of the other fabric proving it to be comfortable fabric [17, 21]. This culturally relevant, and green material has taken its journey from Uganda to the fiber artists and designers of the world. The cloth is made into a formal suit by applying a backing layer on bark cloth to make it durable (330 N) [21].

2.2 Byssus

Byssus are rare, valuable, and one of the finest fibers secreted from the *Pinna nobilis*. Fiber ends are attached to the rocky substrate of the sea. *Pinna nobilis* is a bivalve fan shaped mollusk (mussels) extending upright on the muddy or sandy ground of the sea. Byssus fiber collection from the mussels has been practiced for centuries around the Mediterranean Sea. The fiber is spun and woven to make sheer fabrics by women master weavers. The fine fabric is used to fabricate apparels and various accessories. The fiber has shining luster and distinctive golden and brown brilliant hues [22]. Byssus fiber of classical antiquity is mentioned in the bible as sea silk. The fiber is hair-tuft secreted from the byssus glands and has been described as *thalassai* in Byzantine commercial manuals. The *Book of Perfect* (ninth century) describes *thalassai* as a luxurious commodity sea silk yarn imported from Syria. Meader (2017) compiled various case studies pertaining to ancient byssus and struggled hard to clear out the wrong terminologies about the fiber due to translation errors in the past. He came up with several terminologies used for the fiber in the ancient and medieval times. The terms used for the fiber in those texts were busu, sea silk, pina silk/wool, marine silk/wool, sea wool, and *thalassai* [23].

Byssus or byssal produced from the foot of blue mussels (*Mytilus galloprovincialis*) is a collagenous keratin protein (PreCol-D, PreCol-P) fiber. Individual fiber exhibits three distinct sections: (a) proximal (crimped), (b) distal (smooth rodlike), and (c) adhesive disc or plaque attached to the substrate [24]. Byssal fibers secrete as part of a defense mechanism. Byssus fibers get adhered to the various surfaces present in the marine ecosystem at the seashore to make it out of reach of the predators mainly crabs (*Thalamita danae*). Seasonal variations affect byssus fiber strength. Strength of distal fibers is more than proximal and plaque fibers during the summer and fall [25–27].

Thermal stability of byssus (*Pinna nobilis*) is similar to silk fibers. Byssus weight is reduced 70% at 90 °C temperatures [28]. Fiber length reaches to 1 m and diameter ranges between 10 and 50 micron. Fiber cross section is elliptical. Fiber is composed of collagen protein and flames like burning hair. Fiber is flexible and its wet strength decreases by about 47%. Collected fiber bundles are washed, degreased, and combed to make it smooth and antifouling. Fibers are bleached using lemon juice. Dyeing with natural dyes is carried out during processing at the fiber stage.

Mucous of the murex glands dye the fibers naturally in red, purple, and blue depending upon the particular species of the shell and processing time. Fibers are hand spun using a wooden spindle and subsequently woven and knitted to make apparels, caps, stockings, and mittens [29]. The mollusk yields 10 cm fiber in a year and 200 g of byssus require 300 divings. The fiber spinning and weaving workshops by Chiara Vigo are operated in Sardinia for public awareness and sustenance of byssus luxurious products [30].

2.3 Fox Fiber

Fox fiber is naturally pigmented cotton fiber which is named after Sally Fox, a cotton breeder of naturally colored cotton. Sally Fox patented different naturally colored organic cotton varieties as "fox fiber." Different color shades of fox fibers such as red, brown (Fig. 2), pink, and green are available for textile production [31]. Plant's inherent genetic properties, climate, and soil variations are responsible for the color present in fiber lumen.

Generally naturally colored fibers are found to have properties like good fineness, low strength, low fiber evenness, and short length, but Sally Fox crossbred her own fibers and achieved fibers having good length, strength, and natural fire resistance [32].

Cotton lumen gets color post boll bursting. Sunrays are essential for color development which takes 5–6 days. However, long exposure to the sun causes fading of the color in some species. Most common colored cotton varieties are *Gossypium aridum* (brown), *G. gossypioides* (gray), *G. tomentosum* (reddish brown), *G. hirsutum* (green), *G. laxum* (tan), and *G. arboreum* (light brown to khaki) [33].

Naturally colored cotton is available in green, brown, and reddish brown hues. Despite economic and ecological benefits of using naturally colored cottons, the fiber utilization by industry is not common. This is probably due to limited

Fig. 2 Fox cotton mature boll in brown hue cultivated at oilseed farm of Chandra Shekhar Azad University of Agriculture and Technology (CSAUAT), Kanpur, India

Table 1 Physico-mechanical properties of natural brown and green fox fibers [34]

Fox fibers	Length (mm)	Fineness (mtex)	Micronaire	Tenacity (g/tex)	Elongation (%)	Maturity (%)
Brown						
Bulgaria	19.8	125–159	4.4	25.9	5.9	5.7
Greek	22.7	160	4	25.9	6.0	7.0
Indian	24.0	–	4.9	19.0	–	–
Turkish brown	23.9	200	4	30.9	5.9	5.8
USA	24.0	150–175	4	26.0	6.3	8.5
Green						
Turkish green	20.2	150	3.4	24.1	5.6	8.6
USA	20.6	149	3	19.6	5.2	10.6

availability. Quality parameters of the colored cotton are dependent on the fiber origin [34]. Matusiak and Frydrych (2014) classified the cotton on the basis of their physical properties. They tested 14 variants of fox fibers from different parts of the world including Brazil, Bulgaria, Greece, Israel, Turkey, and the United States and observed that fox fibers have high to very high length uniformity and breaking strength. Fineness of the fox fibers was between average to very fine. The quality parameters (Table 1) reveal that Turkish cotton in brown hues is superior to the green cotton from Brazil, the United States, and Argentina [34].

Selective advantages of naturally colored cottons over regular white cottons are unique appearance, unusual softness, flexibility, high ultraviolet protection, and luster besides environmental benefits. Larger proportion of white cottons is dyed using artificial dyes which not only harm the human skin but also environment. The color intensity of the fox fiber fabrics' brightens up with each wash cycle instead of fading away. The fiber limitations include color variation, limited availability, and low yield potential [35]. High cost of the fabric is partly compensated by exclusion of dying process. Overall quality parameters of fox fibers are comparable to white cotton fibers and therefore suitable for handlooms as well as modern cotton spinning, weaving, and knitting machineries [34, 36].

2.4 Lotus

Aquatic lotus (*Nelumbo nucifera*) belongs to the Nelumbonaceae family. Plant peduncle contains the finest fibers along its full length and is arranged circularly in the cross section. Lotus fiber is one of the oldest cellulosic microfibers having all the qualities required for spinning and weaving an exquisite garment [1, 37]. The lotus fiber was first mentioned in the Rigved and later in Buddhist and Jain texts [38]. Noted Indian literature Kalidas (fourth century CE) and Ratnakar Swamy (855 CE) wrote about lotus filaments in their famous epic *Kumar Sambhav* and *Harvijaya*,

Table 2 Physical characteristics of natural luxurious fibers

Fiber	Fineness (micronaire)	Length (mm)	Tenacity (g/tex)	References
Bark cloth	1.088 mm	–	Warp/weft 101.7 N/23.5 N	[17]
Byssus	0.0297–0.0351 mm	6.19–8.26	0.25 N	[25, 26]
Fox fiber	3.5–5	25.1–25.6	22.7–24.2	[30]
Lotus	3.69	120–1400	13.41	[37, 40]
Pashmina	9–14	40.0–60.0	11.81	[41, 42]
Shahtoosh	7–10	49.04	–	[43, 44]

respectively [39]. The fiber is finer than the best quality cotton, silk, and pashmina (Table 2). Lotus fibers do not require any chemical treatments prior to yarn formation and weaving applications. Fibers are hand-drawn, hand-spun, and hand-loom woven since ancient times. Hand-drawing involves cutting or breaking the peduncle and pulling apart the two sections. Every part of the lotus plant has commercial importance including plant leaves, flower, stamen, and peduncles [1, 37, 40, 45]. Lotus peduncles are thorny which pricks the fingers while drawing fibers from the peduncles. In Myanmar, the common practice is to soak the peduncles in water for 2 days, and subsequently thorns are rubbed off the surface using fabric, prior to fiber drawing [46]. Fiber is hand-drawn as well as obtained using irradiation, mechanical, chemical, and retting methods [40]. Fiber drawing stretches the fibers > 1000 mm with a mean fiber length value of 467 mm [37]. Fibers have natural crimps which makes it wrinkle resistant. All three types of lotus, namely, (i) flower type (thousand petals), (ii) rhizome type (edible), (iii) seed type (edible), are suitable for fiber drawing. Moisture management and comfort properties of lotus fiber fabrics are superior to cotton [1, 40, 47]. Lotus fiber drawing is practiced in Myanmar, Cambodia, India, and several Southeast Asian countries. Primitive method of fiber drawing and processing is most common by major lotus fabric production units. The cost of thousand gram lotus fiber was calculated to be $32 in India [37]. More than one lakh lotus peduncles are required to make a single garment costing around $714 (FY 2013). Two emerging brands of lotus fiber products are Loro Piana (Italy) and Samatoa (Cambodia) [1, 40, 46].

2.5 *Metallic Textiles*

Roots of metallic fibers can be traced in making ancient metallic armors. Graduated gold plates of Tutankhamun's armors unraveled in 1960 publicized at length how metallic textiles were part of everyday life in the royal courts of ancient era. The armors are reusable and can be used for several generations. Armors were richly embellished with polychrome and inlay designs and worn over regular padded garments for comfort. A portrait of Elizabeth I adorning skirted metallic armor was displayed at the tower of London long after her death in 1560 (Fig. 3a–c). Royal armories, Leeds, exhibit several such Elizabethan armors. Till then armors were

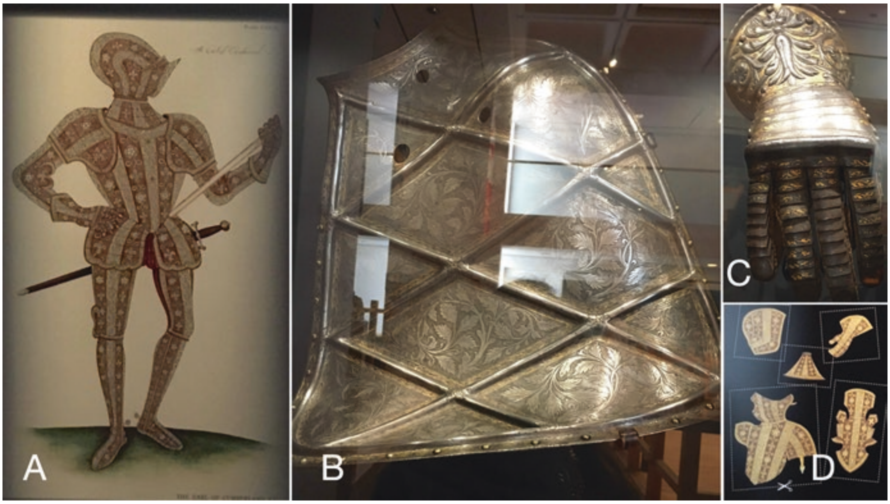

Fig. 3 Elizabethan armor displayed at Royal armories, Leeds. (**a**) Portrait of British Queen Elizabeth I wearing skirted armor. (**b**) Rose-leaf garniture design embossed on pauldron. A high fashion statement, the surface is embellished with other decoration such as gilding, engraving, and etching to highlight the design. Padded garments were worn under the armors to protect the body parts. (**c**) Beautiful metal gauntlets with individual finger plates for easy movement. Gold damascening richly decorates the small lames of this gauntlet. It was made for foot combat at the barriers. With its gold decoration embossed with acanthus foliage and reinforced knuckle plate, this gauntlet combines esthetic beauty and practicality features (Italian, 1540 CE). (**d**) Design pieces from the master armorer Jacob Halder's pattern book

associated with kings, soldiers, and royal children for donning during melee combat, jousting, court ceremonies, royal parade, and the war. Armor's' embellishments were done with anthemion, floral scrolls motifs in gold, silver, and precious stones. Regular polishing was required to maintain the sparkle of the metal armors. Metal parts of apparels and accessories preserved in early Anglo-Saxon archeological sites were clasps, pins, beads, buckles, and brooches. Metalwork was decorated with engraving, damascening, heraldry, and inlay designs [48, 49]. Gold, silver, and copper fine threads are used in *jardozi*, *kimkhab*, and *baluchari* work on bridal trousseaus in India. Current uses of metallic fibers in apparels are in the form of electronic textiles, smart textile (stimuli to environmental conditions), ultrasonic sensor, thermal absorbance, and fashionable accessories. Metal threads made of silver, aluminum, steel, tin, copper, nickel, or brass filaments are commonly used to fabricate e-textiles [50]. Metal filaments are filled or welded in conventional yarn to provide conductivity. Conductive yarns may be knitted or woven to provide surface to circuit, sensor integration, or switches. Biomedical and hygienic uses of conductive metal fibers are timely signals of sweat sensor, skin temperature, and heart and breathing rate warnings. Electrocardiogram (ECG) monitoring using fabric embedded electrodes is an alternative to conventional Ag/AgCl electrodes [51, 52]. Fabric electrodes for health monitoring systems and touch sensors were created on intarsia knits and woven fabric, respectively [53, 54]. E-textile with pressure sensor on wearable body protector has wide application in sports dress of skiing (posture detection) and taekwondo (punch impact) [55].

2.6 Mud Cotton

Mud cloth from Mali (Africa) is handwoven, hand-painted cotton fabric known as *bogolanfini*. Malian *bogolanfini* has strong significance during cultural, festival, and family events. Cloth is worn during all important occasions of life such as childbirth and marriage and finally as a shroud [56]. In this method, stripes of cotton are stitched selvedge to selvedge using whipstitch and dyed in deep yellow hue using extract of plant leaves (*Anogeissus leiocarpa*, *Combretum glutinosum*) and left to dry. Tannin rich leaf extract forming a brownish tea acts as a mordant. Geometrical patterns are formed on the fabric surface using fermented mud. Fermented mud slurry is applied on the surface in the design area and in the background using metal or bamboo sticks. The fabric is washed, and the process of applying tea, drying, mud-applying, and washing is repeated thrice or till the desired darker shades are achieved. To emblazon the design lines in white color, the design of the fabric is bleached with boiled ground peanuts mixed with caustic soda, millet bran, and water. The process turns the patterns into brown color. Subsequently the cloth is sun-tanned for a week followed by washing of the bleach solution. Eco-friendly biobleaching process helps in achieving characteristic white pattern on the dark background of the fabric [57–59]. The designs are geometrical and mostly depict animals, tools, religious stories, expressive culture, and daily life of the tribes (Fig. 1b). Cloth is used to make hunter's sleeveless tunic, stole, and women's wrap-around dresses [60].

2.7 Mud Silk

Mud silk or mud dyed silk is also known as Gambiered Guangdong silk originating in China. The production of shiny elegant fabric follows the 2500-year-old tradition and is also recognized by UNESCO in 2011 as intangible cultural heritage for its preservation and sustenance [61]. Mud silk is a natural flame retardant, antibacterial, and waterproof fabric. Mud silk manufacturing is extended beyond China – across some parts of Myanmar, Thailand, Cambodia, and Vietnam – because of iron rich river delta and plenty of sunlight. Mud cloth has a contrasting face and back side; front is visibly glossy black in color while orangish brown matt in back. The color is extracted from yam (*Dioscorea cirrhosa*) juice by repeatedly soaking and coating two to three times, and finally mud is applied on the surface, dried out, and washed off with tea water. This process is repeated about ten times, leaving a beautiful glossy black color on the top and stained orange brown color on the back. [62].

Fig. 4 Mud silk; Sophie Hong's luxurious creation "second-layer skin"/Hong silk (https://www.flickr.com/photos/2014dyes/sets/)

Mud silk is a natural flame retardant, antibacterial, and water resistant fabric due to iron-tannin complex on the surface which blocks the pores within the fabric. [63]. All these properties are attributed to the silk fabric by tannin present in yam juice which reacts to the iron present in mud [64]. Mud silk is soft to touch as compared to regular dyed silk [63]. Mud silk is choice of the designers and has reached the ramp of the fashion shows all over the world (Fig. 4).

2.8 Muga Silk

Muga silk is naturally bright golden colored wild silk produced in the northeastern states of India. Muga silk received geographical indication (GI) logo in the year 2014 to promote the traditional rich heritage of muga production. The silkworm (*Antheraea assama*) feeds on the leaves of *Som* (*Machilus bombycina*) and soalu (*Litsaea polyantha*) and several other host trees of Lauraceae family. Muga silk produced on *mejankari* tree (*Litsea citrata* Pers.) is considered as the most precious and costliest silk. Plant leaf quality (tenderness, freshness, cleanliness) and quantity determine the quality of the silk cocoon and fibers [57, 65]. The natural yellowish golden color, with a shimmering smooth texture and luster of the silk, increases with age [58]. Glossy texture and golden luster of *muga*silk are due to its prism like triangular cross section which refracts light at various angles. Higher crystallinity and dense fiber structure result in high reflective index (1.557) compared to other saturniids' filament [43]. The *muga* cultivation was given royal patronage by kings of the Ahom dynasty 1200–1800 BC. Muga silk fabrics were chief export items in the

Ahom kingdom of northeast India. Highly absorbent fiber is a prized heirloom which lasts for several generations [58, 66]. Silk production involves boiling cocoons in the presence of natural ingredients such as soapnut, leaves of *Dillenia indica*, hibiscus, and cochin goroka. It is composed of 97% of natural protein and 3% of wax and fats. Muga silk has been reported to have high tensile strength (4 g/denier), elongation, and good moisture absorbance, and it is resistant to most mineral acids except sulfuric acid**.** Elongation at break of the *Muga*silk fiber (40%) is higher than mulberry silk (15%). Muga silk also possesses many other useful properties like high resilience, longevity, drape-ability, anti-flammable, antibacterial, anti-insect, and a strong UV protection property (85.08%) [66]. Muga silk is spun and woven on hand operated spinning machinery and looms. Traditional intricate floral and birds designs are woven with *muga*silk using jacquard looms. India produced 158 t of *muga*silk in the year 2014–2016. The cost of 1000 g of *muga*silk yarn is $195–$220. Woven *muga* fabric is used to make saree, mekhla-chador (traditional Assamese two-piece saree), and accessories for ceremonial dresses and wedding rituals (Fig. 5). Technical uses of *muga*silk include parasol (85.05% UPF), parachutes, and gunpowder bags [66]. Storage of *muga* and other silk articles needs several precautions besides moth repellents and low humidity. Crease lines of folded fabric require to be changed time to time to avoid permanent lines [67].

Fig. 5 Muga silk saree and mekhla-chador (two-piece saree)

2.9 Naturally Colored Silk

Silk filaments naturally colored in bright yellow and red are boon to fashion world and environment. Many small to medium dye houses report only 25–35% dye absorption by the textiles, while the remaining is discarded in the ecosystem. It is important to note that even 5% dye escaping through treated water may adversely affect local ecology. This is the case of carcinogenic substances as the dyes direct red 28 and direct blue 22 or also flame retardants and other finishes [2]. Naturally colored silk fiber is a luxurious and sustainable fiber that does not require dye house processing and thus saves water consumption and harmful effects associated with effluent disposal.

Naturally colored silk is produced by silkworms which produce cocoons with natural pigment. Some wild silkworm varieties, such as *Antheraea pernyi* (Chinese oak tussar moth), *Antheraea yamamai* (Japanese oak silkmoth), and *Saturniidae* (known to be royal silkmoth), produce brown, green, and golden yellow pigmented silk. Some mutant varieties of native *Bombyx mori* (silk moth for producing mulberry silk) are also capable of producing different shades of pink, yellow (Fig. 6e, f), and green [68]. Silk moth (Fig. 6a) for white mulberry silk is bivoltine, whereas multivoltine for colored silk. Silk moth and cocoon of mulberry, tasar, and eri silk are shown in Fig. 6a–g. Single mulberry silk cocoon yields 800–1200 m yarn length, whereas naturally colored silk cocoon yields 600–800 m yarn length. The cost of mulberry silk yarn is $73–$80 in Indian market. Mulberry silk from *Bombyx mori* (Fig. 6a, b) is the most important fiber of sericulture industries around the world. The fiber has good mechanical performance (0.5 GPa), drape-ability, ease of

Fig. 6 Silk moth and cocoon. (**a**) *Bombyx mori* feeding on mulberry leaves. (**b**) Mulberry silk cocoon. (**c**) Eri silk moth feeding on castor leaves. (**d**) Eri silk cocoon. (**e**, **f**) Yellow colored mulberry silk cocoon. (**g**) Tussar silk cocoon

Fig. 7 Mulberry silk. (**a**) Patola saree (double ikat; warp and weft both are dyed prior to weaving, from Patola weaving workshop of Salvi brothers, Patan, Gujarat, India). (**b**) Pochampalli saree (single ikat; made with tie-dyed warp and plain weft)

processing, and sufficient supply. Traditional textile industries are using the silk since 2000 BC [69], but evidence of silk clothing dates from early Neolithic age around 8500 years back in China [70]. However, the use of silk in Harappan civilization a millennium ago puts a question mark on sericulture invention and dissemination from China [41]. Figures 7, 8, 9, 10, and 11 depict the exquisite mulberry silk textiles from India. *Cricula trifenestrata* and the *Atacus atlas* Linn found in Java, Indonesia, are known to produce beautiful durable golden color silk ranging between cream and brown [42]. Yellow color silk pigments are due to carotenes in the mulberry leaves [68]. The pigment from the carotenoid mulberry leaves gets accumulated in sericin surface layer of the silk fibers. The yellow silk pigment is composed of six carotenoids. The silk is comprised of (i) sericin (25%, gum, soluble) and (ii) fibroin (75%, fibrous, insoluble) protein. Silk industry uses thermo-chemical methods to remove the sericin which is wrapped around the fibroin. The process also fades the natural yellow color of the colored yellow silk [68, 69]. The problem of natural yellow color fading during subsequent silk processing and home laundering can be prevented by modifying the chemical structure of sericin using cross-linking additives to bind with the color pigments without affecting the pigment structure [69].

2.10 Pashmina Hair

Pashmina hair fiber is obtained from the undercoat of domesticated goat species named *Capra aegagrus hircus* (Fig. 12) native to Laddakh, India, and *Changthangi*, *Changra*, and *Chengu* in Laddakh and Himachal Pradesh, India. It is one of the finest (9–15 μm) and softest fibers used to make warm luxurious clothing [71]. Pashmina shawls are made traditionally on primitive looms with intricate designs by the local artisans of Srinagar [72]. The fiber is too delicate to absorb the power

Fig. 8 Mulberry silk. (**a**) Crepe georgette brocade. (**b**) Katan silk brocade from Varanasi

Fig. 9 Mulberry silk. (**a**) Tanchoi (satin weave). (**b**) Bandhej (tie and dye). (**c**) Mekhla-chador (Assamese)

loom vibrations generated during weaving. China is the leading country in pashmina production, contributing 70% to worldwide production. The average fineness and length of pashmina fiber is about 9–14 μm and 55–60 mm, respectively. Physical characteristics of the fibers vary from breed to breed. Pashmina fibers possess a good ability to absorb dyes and moisture [44, 72, 73]. It is a delicate fiber and is 10% weaker than the fine wool. Chemical composition of pashmina fiber is identical to fine wool and mohair fiber [74]. Single goat yields 250 g fiber in season and

Fig. 10 Mulberry silk georgette saree with floral *chikankari* embroidery using colored silk threads

Fig. 11 Mulberry silk chiffon with "white on white," all over *chikankari* embroidery

cost of 1000 g fiber is USD$35. Pashmina shawl with intricate designs and embroidery costs USD$200–$600 in the United States and Europe. In 2011–2012, India exported pashmina shawl worth $160 million [42]. Parvaiz (2013) discussed several problems regarding migration of goat farmers [75]. Arnott (2012) suggested measures to encourage pashmina hair cultivation through government support and cooperative schemes to improve the livelihood of the farmers. An eco-label for pashmina hair products will help to sustain pashmina fashion industry [76].

2.11 Shahtoosh

Fibers and shawls woven from speciality hair fiber of Tibetan antelope (*Pantholops hodgsonii*) undercoat are known as shahtoosh. Tibetan antelope or *Chiru*, a high altitude bovid, is not a domesticated animal like sheep and goat. Animal hunting to

Fig. 12 Pashmina fiber yielding goat (*Capra aegagrus hircus*) domesticated at Himalayan range

procure the fiber has rendered the Tibetan antelope an endangered species. Tibetan antelope is placed in the Convention on International Trade in Endangered Species (CITES) Appendix I, which prohibits the commercial trade of the fiber. As a result, production/import of shahtoosh is permitted only for research purposes [77]. Shahtoosh fiber is fine, soft, kinky, and smooth. Fiber is tan white in color with scales exhibiting a regular mosaic pattern. Mean thickness of the fiber is 120 μm with circular cross section [78]. There are two grades of shahtoosh: (i) fine fibers (7–13 μm) and (ii) coarse fibers (50–150 μm). There is no intermediate hair fineness in shahtoosh as in other speciality fibers. Unmatched smoothness and warmth of shahtoosh enhance its mysticism and price tag as well. Prior to the ban which was effective since 1979, shahtoosh was a prized heirloom and a lucrative commodity for elites. Shahtoosh, cashmere, and pashmina are regarded as 'ring shawls' that easily slip through a finger ring [79]. It takes about 3–5 years for an antelope to grow sufficient fur for one shawl which is around 350 g. The products made of woven shahtoosh are very delicate, and it is in demand in European and Asian markets [80]. Shahtoosh shawls cost $3000–$5000 in Indian markets and approximately$18000 in European, American, and Gulf countries [71, 81]. Advanced experimental research techniques to study the fibers and their characterization include liquid chromatography-mass spectrometry (LC-MS) and ultraviolet-visible spectroscopy (UV-VIS) [82]. Attenuated total reflection (ATR) Fourier transform infrared (FTIR) spectroscopy test is proposed to distinguish between shahtoosh, pashmina, and angora hairs [83]. Fei et al. claimed that shahtoosh is the world's noblest fiber. They can be easily detected by polymerase chain reaction (PCR) based DNA method called TaqMan. DNA profiling of shahtoosh is helpful in investigating the illegal marketing of shahtoosh products [84].

2.12 Boops Boops and Nori

Boops boops or bogue fish found in the Mediterranean Sea was the subject of an interesting study. Fibers found in the intestinal tract of the fish were tested for its chemical composition, which revealed the presence of anthropogenic and synthetic fibers [85]. Household washing machine washes off 1900 microfibers from a single garment into the ocean through waterways. These fibers also carry the chemical dyes and finishes of the fabric to the water bodies and the environment [2]. If the fabric is made of natural cellulosic and protein fibers such as cotton, jute [86], linen [87], banana, pineapple [88], silk, wool, and allied fibers [71], then it is easy to biodegrade in link rivers and ocean. But the anthropogenic fibers are nonbiodegradable and thus harming the human skin, environment, and marine ecosystem. Anthropogenic fibers and associated dyes or additives could be potentially harmful to marine organisms [2, 85]. Studies on six common fish species from Adriatic Sea showed the presence of microplastics and fibers having 64.3% polypropylene and 35.7% polyethylene in their gastrointestinal tract [89]. Commercially packaged edible nori was found to possess large number of microplastics, polyester, and polypropylene. Microplastics composed of polyester, polypropylene, and microfibers were predominantly found in commercially packaged, factory processed, and unprocessed nori, respectively [90]. Microplastic collection has been reported in aquatic macrophyte (*Lemna minor*) and algae. Freshwater duckweed can absorb 10–45 μm polyethylene microbes in its leaves and roots [91]. This could be a potential prospect for phytoremediation to reduce the microplastics from the marine environment [92, 93].

3 Conclusion

Luxurious commodity fibers are exclusive due to timeless quality, high cost, and limited availability. The sustainable processing and practices carried out during its entire life cycle are an added value to the product benefiting the environment and the end users. Natural cellulosic and protein fibers presented in the chapter are largely local handicrafts practiced at few locations in the world. Most fibers identified are linked with human needs in the ancient times and thus processed by traditional methods. The available information about fiber processing and use should help students, researchers, and textile manufacturers to initiate new small scale textile units and upgrade the existing units to achieve the goal of sustainable textile manufacturing. This is a challenging task but sure to bring dividends in the present scenario of eco-friendly measures essential in every field. Sustainable fiber production should be promoted by providing incentives for eco-friendly manufacturing. The outcome would take the industry to further heights and help masses to make use of sustainable fibers so as to ensure prosperity with health and environmental benefits. Traditional textiles around the world are sustainable and considered luxurious, and thus garment production from such fibers should also profit the farmers and designers. The pressing need is to maintain its inherent characteristics, materials, and crafts in its original form.

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Sustainable Products from Natural Fibers/Biomass as a Substitute for Single-Use Plastics: Indian Context

Surajit Sengupta

Abstract The world is now conscious of eco-friendliness to save the environment. Natural materials can only be the ideal solution for the modern world. However, the versatility, fashion, and esthetics are only coming to light now after the environmental consciousness among people. Natural fibers like cotton, wool, silk, and jute have served the human race for thousands of years. This chapter is written on purpose to present an overview of the threat of single-use plastics and their probable alternative to natural lignocellulosic fibers. The reader will discover the importance of sustainable products for the environment and our future generation. It will also help those dealing with lignocellulosic fibers in industry and academia, especially teachers, students, and technologists.

Keywords Sustainable products · Natural fibers · Single-use plastics · Agro textile · Shopping bag · Packaging

1 Introduction

Humanity has been utterly dependent on natural ingredients since their inception. In the nineteenth century, massive development in chemistry or chemical engineering discovered synthetic materials which were cheap and user-friendly. It captured the world market very fast and almost in all possible areas. From the 1960s, people started feeling the harm of artificial and chemical products after their abundant/unregulated use and disposal. Nowadays, cheap and thin synthetic sheets or spun bonded nonwovens are very popular in many countries despite the significant threat of nonbiodegradability, pollution, and water clogging due to uncontrolled disposal.

S. Sengupta (✉)
Mechanical Processing Division, ICAR-National Institute of Natural Fibre Engineering & Technology, Kolkata, India

S. S. Muthu (ed.), *Novel Sustainable Raw Material Alternatives for the Textiles and Fashion Industry*, Sustainable Textiles: Production, Processing, Manufacturing & Chemistry, https://doi.org/10.1007/978-3-031-37323-7_5

Researchers are engaged to develop eco-friendly and sustainable products to reduce the use of those products.

The world is rewarded with several types of renewable natural wealth from plants and animals. The global production of natural and synthetic fibers and their growth during the last 40 years have been shown in Fig. 1. The countries involved and their share of natural fibers are given in Fig. 2. The volume of different natural fibers available globally is shown in Table 1. Good strength, high modulus, sufficient resistance to microbial attack, low cost, and biodegradability made the natural fibers and their products suitable for industrial use. Despite that, the coarseness, rigidity, and variability of most such fibers, especially lignocellulosic fibers, hinder making fine and good quality yarn and woven fabric. Due to the coarseness and higher density of lignocellulosic fiber, products are costlier and heavier than their synthetic counterpart. Unconventional fabric, like nonwoven, has a textile structure produced by bonding or interlocking an evenly spread fibrous sheet. Using various technologies, we can make products that can replace plastic products efficiently in the field of agro textiles, shopping bags, geotechnical uses, packaging, home textiles, etc. Pulp paper and molded composites are also areas where synthetics can be replaced significantly [6, 12, 14].

Sustainability and global warming are interconnected in scientific aspects [15]. The consumer demand for eco-friendly products and processes has increased in markets of developed countries, such as the United States, Australia, and Western Europe, and also in the new markets of different other countries, such as the Middle East. It has emerging opportunities mainly because of the growth of the awareness of the adverse effect of pollution and the rise of temperature globally. Temperature rise is a great threat, but it is dangerous for this Earth if it fails to trigger the brain's alarm. The customers have to be more inclined to procure from a retailer who is

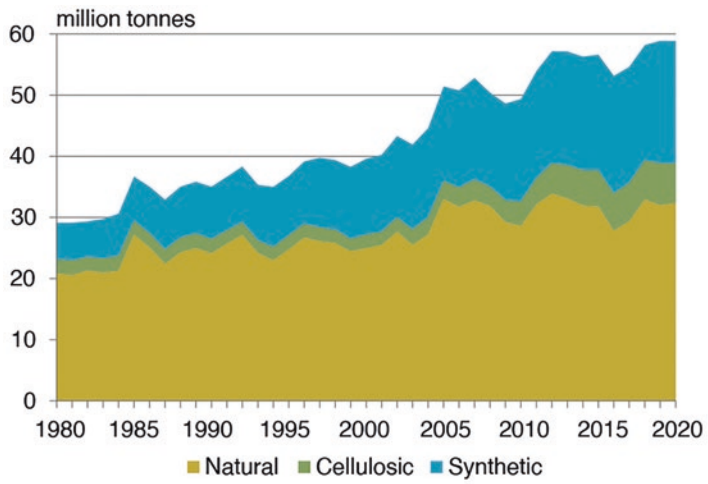


Fig. 1 World production of staple fibers. (Web source [43])

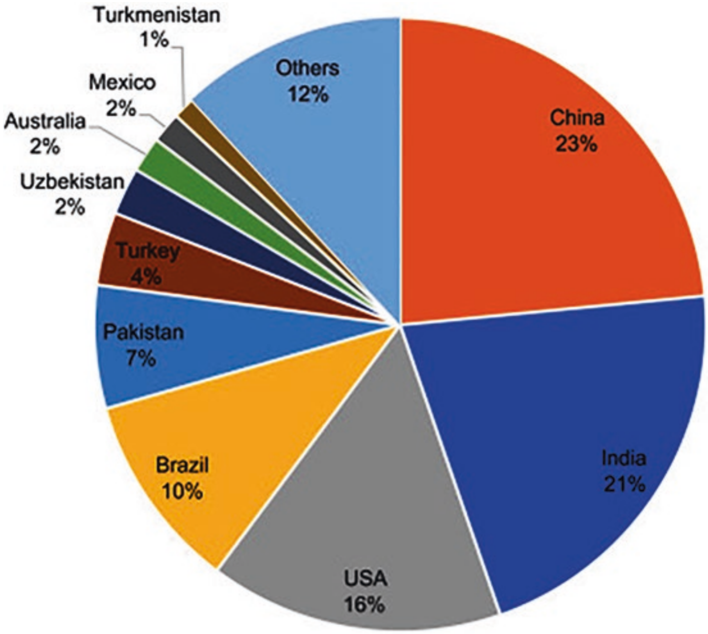


Fig. 2 Share of Natural Fiber Production in Major Countries, 2018–2019 [39]

Table 1 Fiber-wise global production

	2020	2021, metric tons	2022, est.
Abaca	75,820	82,000	80,000
Agave fibers	41,114	41,000	41,000
Bast fibers, other	230,802	229,000	229,000
Coir, without pith	1,101,500	1,120,000	1,119,000
Cotton lint	24,370,470	25,444,120	24,710,000
Fiber crops not specified elsewhere	270,000	270,000	272,000
Flax fiber and tow, ex scotching mill	976,000	1,028,000	1,006,000
Hemp tow waste	245,271	240,000	247,000
Jute, kenaf, and allied fibers	2,618,900	3,164,436	3,200,000
Kapok fiber	89,528	90,000	90,000
Ramie	60,935	59,000	60,000
Sisal, henequen, and similar hard fibers	267,600	260,000	262,000
Silk, raw	173,000	172,000	173,000
Wool, clean	1,031,233	1,033,570	1,089,900
Other animal fibers	27,000	26,460	27,000
Total natural fibers	31,579,173	33,259,588	32,600,000

Web source [44]

conscious about the environment's welfare also and not only concentrate on their financial gain [13].

This chapter is intended to present an overview of the threat of single-use plastics and their possible alternative to natural lignocellulosic fibers. The reader will discover the importance of sustainable products for the environment and our future generation. It will also help those dealing with lignocellulosic fibers in industry and academia, especially teachers, students, and technologists.

2 Single-Use Plastic: Status and Impact

Some literature says that less energy and water are used to produce plastic carry bags (web source [45]). It also generates less solid waste than paper bags for the same number of bags as the volume and weight of plastic bags are lower, which occupy less landfill space. This promotes single-use plastics to be a preferred material for commercial use (Fig. 3). Such plastic is the most popular in high use

Fig. 3 Single-use plastic bag and bottles. (Web source [48–50])

due to its easy availability, low cost, lightweight, and sufficient strength for transporting goods. Single-use plastic bags are thrown away or recycled after being used only once. It is so convenient and user-friendly that it occupies the place of the most of other packaging materials. Such plastic takes hundreds of years to disintegrate, thereby so highly dangerous for drainage system and marine life. It has been observed that out of 9.46 million tons of plastic waste generated in India in the year 2019, 43% are single-use plastics (web source [46]). It may be noted that plastic waste is one of the significant sources of pollution in many countries, and it is a proper needs methodology for recycling and reuse. More than 34 lakh tons of plastic waste was generated in 2019–2020 and 30.59 lakh tons in 2018–2019 in India (web source [47]). It is also well known that plastic does not degrade, and hence, it remains in the same landfills for years. Furthermore, plastic burning, in most cases, is harmful, as some of the plastic could release toxic fumes and harmful gases during the process. Single-use or other plastic also gets mixed up with soil, which causes soil pollution. Likewise, the presence of plastic in the water system disturbs aquaculture [16]. Different types of plastic bags have been shown in Fig. 3.

The three main reasons for spreading plastic are as follows:

1. Natural material-based products are more costly compared to plastic items mainly because of high manufacturing costs. It results in less demand to consumers for natural products, and this is a reason for the reduction in manufacturing jobs in countries like India.
2. Engineered material: its versatility in quality and wide range.
3. Esthetically superb.

Consumers are using plastics in most applications which has become a part and parcel of our society in daily life. Petrochemicals are the basic raw material of plastic production such as polyethylene, polyvinyl chloride, polystyrene, etc.

The problem associated with plastic materials is uncontrolled or unplanned disposal because they cannot be degraded by any biological process and can only be incinerated with the production of harmful gases.

Moreover

- Plastic production consumes more fossil fuels and releases more greenhouse gases.
- Plastics from petrochemicals are not biodegradable. Hence, the production and disposal of plastics cause a significant problem in many metropolitan cities globally.
- Reckless or unscientific disposal of plastic waste is a major source of environmental pollution and will harm living being (Fig. 4).
- Conventional plastic wastes reduce soil fertility, inhibit the degradation of other organic wastes, and are hazardous to animal life.
- Choking and entanglement to marine life is the effect of the disposal of plastic waste.
- Waste management processes of plastic production and uses are a costly proposition.
- Burning of plastic also emits toxic chemicals such as dioxins.

Fig. 4 Landfills by plastics and its consequence to animals. (Web sources [50])

Global plastic production is anticipated to be more than 600 million metric tons by 2036 (web source [51]). In 1990, it has been realized that plastic does not vanish after its useful life after the recovery of the Pacific Garbage Patch. A global resolution at the fifth Annual Environmental Assembly of the United Nations Environment Program (UNEP) targeted plastic pollution about 25 years back and was finally adopted by 175 countries. It is an unpleasant reality that overwhelming amounts of plastic waste surround Mother Earth [8].

From the background information, it is undoubtedly clear that there is a range of problems associated with the disposal of plastic carry bags, out of which environmental pollution is the principal concern. In landfills, heavy metals and other additives are released into soil and groundwater. Carbon footprint and degradation of plastic carry bags from municipal waste have also been a serious concern in recent years.

“Eco-functional properties” are reusability, biodegradability, and carbon footprint. It was clear that reusable products show better results for ecological aspects. Eco-impact of a product or process can be evaluated by considering the disposal system of products and their recyclability.

Another important criterion is the biodegradability. Soil burial test reveals that biodegradability of paper bags is better than cotton bags [26].

The impact on the Earth and its environment of a product depends on the production of raw material, process, use, and disposal which can be quantified by its carbon credit, measured in units of carbon dioxide emitted as it is related to climate change and the total amount of greenhouse gases produced. Studies [27] illustrate that the carbon footprint potential of different types of shopping bags is very high if no usage and disposal options were provided. In the comparison with the carbon footprint of different disposal options, it was suggested that the lower footprint results in higher percentage of reuse and recycling before landfill. It could be reduced significantly for a higher percentage of reuse. After the endpoint of reuse of the shopping bags, it should be forwarded for recycling without disposing it to a landfill. In this context, consumers' perceptions and the government's policies for facilitating recycling systems are essential in decreasing the carbon footprint of various products.

Reusable bags are always better than single-use bags in all aspects according to the results on life cycle analysis. The nonwoven bags from polypropylene followed by polyester and woven cotton bags caused fewer life cycle impacts. Bags made out of LDPE have higher impacts. It was also found that the life cycle impacts of shopping bags used by Indians were less compared to Chinese and Hong Kong people. Less carbon footprint, ecological footprint, and eco-damage result in a higher degree of reuse according to life cycle analysis [28, 29].

3 Policy for Single-Use Plastic

Nowadays, recycling of waste plastic from different sources has been promoted, and even then, the collection and recycling of plastic waste are also tricky. So, only 9% of the plastics ever created have been recycled. Although demand for plastics has risen everywhere, their disposal needs to be adequately regulated. The growing export of plastic waste from developed countries to developing countries with relatively relaxed regulations is increasing daily. At the same time, economic globalization helped establish the supply chains of plastics [10].

A much-meaningful impetus to follow international agreements on worldwide environmental as well as plastic issues was observed in the adoption of the Paris Agreement for climate action in 2015, though plastic was an important part of the UNEA's agenda since 2014. It was observed that global demand to pursue agreements increased after the outburst of the corona virus pandemic. During lockdowns, the industrial use of plastics came down to half from 4.6 MT in 2019 to 2.6 MT in 2020. It was found that the demand for single-use plastics increased manifold in the medical sectors during the pandemic. It was estimated that plastic waste, associated with the pandemic, was about 9.8 MT globally [5, 42].

In India, the elimination or reduction of single-use plastic usage was created by organizing a wide Awareness Campaign against Single-Use Plastic in 2021 under the initiative of the Government of India. Other ventures are the pan India essay writing competition on the theme of spreading awareness among school students in the country, the India Plastic Challenge-Hackathon 2021 for students of higher educational institutions, and start-ups recognized under Startup India initiative to encourage promoting the alternatives of single-use plastic items. Plastic waste management or solutions can be promoted in virtual media ([40] and Web source [57]).

Honorable Prime Minister of India Shri Narendra Modi appealed to the countrymen on India's Independence Day in 2019 not to use single-use plastics (SUP) in the country and make India free from it and to get involved in this mission wholeheartedly. Technocrats are requested to come out with alternate solutions like plastic reuse and recycling. It was urged to the shop owners not to give carry bags and the general people to be more conscious. The Union Ministry of Environment, Forest and Climate Change announced and notified Plastic Waste Management Amendment Rules, 2021, on August 12, 2021, prohibiting 20 identified single-use plastic items by 2022. To address these challenges, the government of India has banned the use of identified single-use plastic items like plates, cups, glasses, and cutlery and wrapping and packing films used in sweet boxes, invitation cards, cigarette packets, and stirrers from July 1, 2022, as per the Plastic Waste Management Amendment Rules, 2021. Plastic carry bags of thickness below 120 microns will also be considered for ban from December 31, 2022 (web source [52]). For proper implementation of Plastic Waste Management Rules, 2016, and Amendment Rules, 2021, for the elimination of single-use plastics, the state/UT's waste management infrastructure should be strengthened through the Swachh Bharat Mission by constituting a special task force by developing a comprehensive action plan, setting up an institutional mechanism by the state/UT governments and concerned central ministries/departments.

Governments of different countries have adopted different measures intending to decrease the store-level consumption of single-use plastic bags. The major categories are bans, forcing of fees and taxes, modifying product design, consumer education, and imposing retailer take-back programs. There were 271 governments in the United States in favor of plastic bag ordinances, as of September 2017. It includes 9.7% of the US population. Most of them (about 95%) encouraged the ordinances for banning single-use plastic bags; the majority of those (56.9% with a ban) were interested to add a mandatory fee on paper and/or reusable bags. In the case of fee-based ordinances, the fee is to the tune of $0.10 per bag; here, retailers are allowed to retain the collected fee. Eleven states of the United States have forced laws to prohibit local governments from regulating single-use plastic bags, as local governments continue to impose more stringent regulations continuously. Because of the success of single-use bags, local governments are also enacting similar ordinances on single-use expanded polystyrene consumer products and other single-use plastic products ([41] and Web source [56]).

4 Natural Fiber as an Alternative to Synthetic

Since the early days of human existence, hundreds of different natural things have been collected and examined as potential raw materials for their use. At that time, there was no artificial material for the use of humankind. With the advancement of knowledge, people developed a way to prepare thin sheets of clothing from long thin fibers available/extracted from natural resources like plants and animals. Therefore, humans have depended on natural fibers for about a thousand years.

The most suitable natural fibers have been selected as cotton, wool, jute, flax, and silk and have become the basis of the world's textile industries. Before the industrial revolution, the preparation of yarn and fabric was an accepted routine of daily life in the household industry. During the eighteenth century, the industrial revolution happened when wheels rotated with steam. In the nineteenth century, advancement in scientific knowledge continued the application of inventive and engineering skills to the textile processes. During the last 50 or 60 years, an increase in production speed, quality consciousness, and automation have begun to play a significant role in the textile industry. As the chemistry and physics of textile fibers were learned, a range of entirely new fibers was created, which changed the entire outlook of the textile trade. Rayon, nylon, and other manufactured fibers are being manufactured in enormous quantities, and nature's monopoly of textile fiber production has been broken. Since then, the research, exploration, and application of natural fibers have decreased slowly, and their technological development has stopped except for cotton and wool [14, 21].

Cotton, wool, and silk fibers and their products have been widely accepted worldwide. They have proven their sustainability due to recovering the drastic fall from the impact of synthetic fibers, and presently, they are abundantly used mainly in the apparel sectors. Nevertheless, the producer of synthetic fibers and products has achieved the status of a primary world industry, and consumption is continuously increasing due to process friendliness, tailor-making opportunities, low cost, and esthetics. Concerning these qualities, natural fiber cannot be competitive with synthetic fibers [1]. So, more knowledge, and education regarding natural fibers, highlighting their positive qualities, i.e., eco-friendliness, renewability, biodegradability, sustainability, hygroscopic nature, dyeability, low carbon footprint, etc., is required to regain the lost reign of natural fibers. Moreover, research and availability of many underexploited or unexploited natural fibers can explore new avenues and improve the market share of natural fiber-based products.

Natural fibers can be classified into three main categories as per the source, such as (a) vegetable fibers, (b) animal fibers, and (c) mineral fibers.

Vegetable fibers originated from plant sources and are used in the major proportion of all natural textile fibers. Important vegetable fibers are cotton, flax, and jute. The major material of these fibers is cellulose, which is an important structural material in the plant world.

Animal fibers are originated from animals either as hairs of sheep, goat, rabbit, etc. or as filaments spun by cocoon creatures. Wool is the most popular fiber in this category and is used to produce warm garments. These animal fibers are based on proteins which are complex substances available in animal body.

The use of mineral fibers is very restricted in the textile trade. An example of this category is asbestos. It is used to prepare industrial fabrics. The advantages and disadvantages of natural fibres have been listed in (Table 2).

Despite those, man has taken fiber-forming substances like cellulose or protein from nature and then manipulated them into a fibrous form. Natural cellulose is the base material of artificial silk. Similarly, a natural polymer made from the proteins of peanuts, milk, maize, and soybean makes protein fiber. However, their processing/manufacturing could be more eco-friendly though the products are biodegradable [17].

In particular, many research and promoting strategies have been adapted for cotton, wool, and silk. They have already established apparel and fashion textiles as sustainable fiber, which they have excluded from the discussion in this chapter. The following essential fibers are jute and flax, which are lignocellulosic. Jute has been industrially successful in making packaging and carpet-backing for century-long but presently suffering steep competition from synthetic and losing its past glory. Flax production and utilization are limited in very few areas and slowly decreasing. The discussion in this chapter is restricted to lignocellulosic natural fibers because they have an enormous probability of replacing petroleum-derived manufactured fibers or sheets in furnishing and industrial uses to make this universe pollution-free. In this context, it is an important task to understand those fibers scientifically, in addition, to explore new fibers and apply the knowledge in suitable applications. The researchers have conducted many research works.

Table 2 Advantages and disadvantages of natural fiber products [30]

Advantages of natural fibers	Disadvantages of natural fibers
1. *Environmental aspects*	Low impact strength
Renewable resources	Variation in quality
Low energy requirements during production	Weather sensitive
Carbon dioxide neutrality	Poor moisture resistance
Disposal by composting	Swelling in moisture
2. *Biological aspects*	Low durability
Natural organic products	Poor fire resistance
No dermal issue for their production	Price fluctuation
Do not pose a biohazard upon disposal	Quality varies on agricultural practices
3. *Production aspects*	
Nonabrasive	
Great formability	
4. *Component weight issues*	
Lightweight	
5. *Financial aspects*	
6. *General aspects*	
Good thermal insulation	
High specific strength	
Good sound insulation	

5 Scopes for Replacing Single-Use Plastic

5.1 Carry Bag

Currently, carry bags of single-use nonbiodegradable polymer (mainly polypropylene and polyethylene) are used as shopping bags for carrying vegetables, raw non-veg items, groceries, sweets, clothing, prepared food materials by outlets, etc. Various such products have been developed using natural fibers, and their biomass can play an essential role as an alternative to single-use plastic. The natural fiber-based carry bag has great potential. It may be prepared from the fabric of different structures and constructions. The bags are made of different shapes and have attractive colors (dyeing and printing) depending on their end uses. Such carry bags are limited due to nonavailability, higher cost, and higher weight. It can be used only for nonliquid and non-powder items if it is not laminated. Since jute and cotton are available in plenty, they are mainly used to prepare such carry bags [24]. However, other lignocellulosic fibers can also be used, but the supply of those fibers is scanty for commercial production.

5.1.1 Woven Shopping Bag

Bags made of cotton or jute can be safely disposed of after several uses. Such bags possess considerable strength and dimensional stability to carry the sufficient weight of dry materials. Cotton bags can be used to make the bags lighter. Bleaching, coloration, and multicolor weaving and printing make the bags more attractive depending on the uses and with additional cost. Such bags are the popular choice in the existing market, and their demand increases with time.

However, the bag's air and water impermeability are essential for carrying powdery or liquid material. That is why a thin (about 5 microns) polyethylene film is laminated. The synthetic content is about 2–4% on a weight basis. Lamination can also be done with aluminum foil or bioplastics.

Table 3 shows some of the bag constructions.

Bags available: shopping bag, lunch bag, side bag, ladies bag, decorative bag.

Different types of woven bags are shown in Fig. 5.

5.1.2 Nonwoven Bag

The National Institute of Natural Fibre Engineering and Technology, Kolkata, has developed nonwoven lightweight bags from jute and mesta fiber. The nonwoven textile structure is produced by the bonding or interlocking of an evenly spread fibrous sheet. Adhesive bonding or thermal bonding nonwoven technology has been used to make the fabric of 100–150 g/m^2 and 70–90% cover from bast fiber. Though the strength is lower than woven fabric, it has sufficient strength and is covered with

Table 3 Construction and capacity of woven bag

Code	Fiber	Dimension (cm × cm)	Thread density		Yarn count tex	Fabric areal density g/m^2	Bag weight g	Carrying capacity kg
			Ends/cm	Picks/cm				
A	Jute	38 × 30	3.1	2.4	320	300	175	15
B	Jute	35 × 33	5	5	240	250	96	8
C	Jute	30 × 25 × 10	4	4	300	280	110	8
D	Jute	30 × 19 × 12	4	4	300	280	75	5
E	Jute	25 × 12.5 × 5	5	5	240	250	48	2
F	Cotton/jute	30 × 25 × 10	10	5	15 × 240	165	45	4
G	Cotton	38 × 30	8	8	30 × 30	100	25	2

Fig. 5 Woven carry bags. (Report, 2020 [18])

Fig. 6 Jute nonwoven fabric and bag [35–37]

lower weight to carry 2–4 kg of material. Nonwoven fabrics and bags made of jute/natural lignocellulosic fibers are shown in Figs. 6 and 7.

Bag Using Water-Soluble Adhesive

Polyvinyl alcohol, an environmentally friendly water-soluble adhesive, can be used effectively [36]. It has film-forming properties and no odor and is nontoxic. It is resistant to grease and oils and possesses high tensile strength and flexibility. Adhesive bonded nonwoven fabric with an areal density of around 120 g/m^2 has been developed with improved functional properties using jute fiber and polyvinyl alcohol in the impregnation-squeezing-drying-curing technique. The treated nonwoven fabric is used as a lightweight carry bag. Tests like a creep, repeated wetting, drop, and resistance to atmospheric conditions show better properties than commercial plastic carry bags. However, the developed PVA bonded jute nonwoven carry bags are heavier in weight, costlier, and prone to more moisture absorption and have no water-repellent/waterproof attribute compared to plastic carry bags. In such fabric, 94% is a natural fiber with 120 g/m^2 areal density, 49 g bag weight, and 4–5 kg carrying capacity [35].

Fig. 7 Different types of nonwoven bag [35–37]

Bag Using Hot Melt Adhesive

A sustainable, flexible nonwoven fabric has been developed using jute and low-melting polylactic acid (PLA) fibers. The thermal bonding technique has been used to soften/melt the PLA component, which acts as the matrix/adhesive in jute fiber reinforcement. The property comparison with commercial plastic bags shows that the developed jute-PLA bag is better in many performance-oriented aspects. Fabric is flexible, strong, and dimensionally stable, with about 90% cover. Three types of bags with carrying capacity of 2.5, 5, and 10 kg were developed. No significant change was found after 10 wetting-drying cycles; hence, the bags are also considered reusable. As the process and raw material used in developing fabric are eco-friendly, the developed bags would also be sustainable and green products. Like jute, a thermally bonded biodegradable fabric has been developed using mesta and polylactic acid (PLA) fibers. To reduce the cost, polypropylene (20–30%) can be used in place of PLA, considering the environmental factor. The areal density of fabric is 130-160 g/m^2. The, bag weight from that fabric and its carrying capasity are 58–60 g and 6–7 kg respectively [38].

Water Impermeable Nonwoven Carry Bag

Thin polyethylene (about 5 microns) or bioplastic laminated fabric has also been developed from nonwoven produced by applying heat. Here the nonbiodegradable part is about 10% in the case of polyethylene. The fabric is stronger, more dimensionally stable, lighter, thinner, and impermeable. Its areal density is about 80–100 g/m^2. It can be used for specific purposes where water and air permeability are not required. Natural fiber acts as a reinforcing material. The properties of the developed fabric are better in many aspects considering their application as a carry bag. Performance tests of the developed bag of creep, repeated wetting, drop, and exposure to the atmosphere exhibited better properties than commercial plastic carry bags. Carrying capacity is about 7 kg. Dyed natural fiber can be used for esthetics. Aluminum foil laminated nonwoven sheet and bag out of it can be used for preparing food material (hot also) from food outlets in place of single-use plastic container or packets, which is used abundantly nowadays. Figure 8 shows polyethylene and aluminum foil laminated bags.

5.1.3 Open-Structure Bag

Lightweight and low-cost open-structure bags from natural fibers have been produced to carry vegetables, fruits, and packed materials from markets, shops, and supermarket outlets to carry up to 2 kg (Fig. 9). Mainly coarse yarn from natural fiber, preferably jute, can be used by plain weaving or leno weaving or warp knitting technology. Property-wise, it may be inferior to synthetic but serves the purpose well. The availability of such types of bags is scanty at present. However, whenever cost, as well as the environment, will be given importance, such types of bags will come up in the future days as single-use disposable bags.

Fig. 8 Bag from laminated nonwoven (polyethylene and aluminum foil). (Report, 2021 [18])

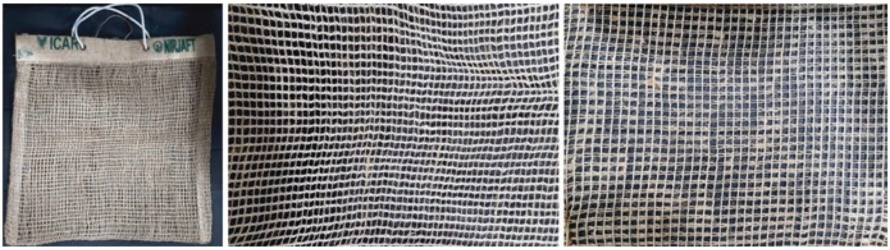


Fig. 9 Open-structure bag made by plain, leno, warp knit. (Report, 2019 [18])

Table 4 Physical properties of the paper produced from jute pulps [7]

Pulping process	Yield (%)	Folding (number)	Tear index (mNm^2/g)	Tensile strength (KN/M)	Elongation (%)	Breaking load (KM)	Bursting Index ($KPam^2/g$)
ASAM	59	300	11.33	3.84	3.36	5.55	4.77

5.1.4 Paper Bag

Low-cost paper may be one of the suitable alternatives for single-use plastic. Its use in the market as carrying bags, files, folders, greeting card, shopping bags, visiting cards, posters, etc. is visible, but the market share is at most 5%. It is costlier and heavy than plastic material.

Paper is a layer of entwined fibers, held together by the natural internal bonding properties of cellulose fibers, lifted sheet by sheet on mold in the suspension of fibers in water with or without sizing. Good quality paper is made from woody materials. Successful attempts have been made to prepare paper from nonfood biomass like grasses, cereal straws, corn stalks, bamboo, bagasse, and lignocellulosic fiber waste or the whole plant. The non-wood fiber material is a vital fiber source in areas where forest resources are scarce. Low-quality flax, hemp, jute, kenaf, cotton, and sisal fibers may be good sources. The leaves of certain plants, such as banana leaves, sisal, abaca, sugarcane leaves, etc., are a valuable source for pulp and papermaking because the ample cellulose, high α-cellulose content, low lignin content, and high ultimate fiber length make natural fibers eminently suitable for making good quality paper. Sticks, on the other hand, have higher lignin content than fiber and short ultimate fiber lengths similar to rice straws. So whole plants are, therefore, more suitable for making handmade paper boards [23]. The alkaline sulfite anthraquinone methanol pulping method is generally used following the beating, dipping/lifting, couching, pressing, drying and cleaning, calendaring, and cutting. The properties of paper and bag have been shown in Tables 4 and 5. Figure 10 shows the paper bags from jute pulp [3, 22].

A nationwide drive is required to replace single-use plastic with paper wherever possible. A significant issue in this venture is the increasing demand for paper, which has left a big gap between demand and supply.

Table 5 Jute pulp bag performance [7]

Areal density (g/m^2)	Bag size (L × B × T) cm	Weight (g)	Maximum carrying capacity (kg)	Printability	Dimensional stability
157	40 × 29 × 7.5	69	2–3	Yes	Yes

Fig. 10 Paper Bags from jute Pulp [7]

The non-wood fiber materials have the following advantages as pulp and paper-making raw materials: (i) renewable resources, (ii) smaller lignin content than wood, (iii) need of low temperature with low chemicals, (iv) small-scale manufacturing possibly, (v) additional economic benefits from the food crops, (vi) resource conservation and less pollution, and (vii) less energy requirement [2].

Fig. 11 Molded products from natural fiber/biomass pulp. (Report, 2021 [18])

5.2 Molded Products

Many plastic molded cutlery items, such as plates, spoons, straws, bowls, cups, glasses, and plate cover, are used commercially in shopping malls, restaurants, online food delivery supply chains, etc. In this context, natural fibers can be used to develop a lightweight biodegradable paper. Low-quality natural fiber and other biomass from the plant have ample scope for making molded cutlery products, e.g., bowl, plate, thali, and other items. Using leaf and residual biomass would be environmentally friendly and have excellent potential for rural entrepreneur development. In this direction, banana plant pseudo stem can also be used in making paper of different areal densities. The tenacity and puncture load of banana stem paper board are 2.63 cN/tex and 199 N, respectively. Such paper can be then successively used for making different molded cutlery items as shown in Fig. 11. These products are very much comparable in size and weight with the biodegradable/nonbiodegradable commercial similar paper products. Similarly, jute fiber-based paper can also be used for making molded products (Fig. 11).

5.3 Flat Carpet Underlay

Carpet is an expensive product made of woven/nonwoven structure from wool/synthetic fiber. The global carpets market was valued at around USD 84.3 billion in 2017 and is expected to reach approximately USD 107.9 billion in 2023, growing at a CAGR of slightly above 4.0% between 2017 and 2023. The resiliency of such carpets depends on their structure and pile configuration. Nowadays, flat-woven carpets are pretty standard, along with resilient underlay. It is a layer of cushioning laid beneath the flat-woven carpet. Underlay is mainly used to increase the performance and durability of carpet, provide underfoot comfort, and provide insulation against sound, moisture, and heat. Underlay is generally available in 7–12 mm thickness, and its durability is about 10–12 years. Generally, underlays are made of polyurethane foam, rubber, felt, and crumb rubber (recycled rubber produced from automotive and truck scrap tires). The use of underlay reduces cost and improves performance. Synthetic underlay slowly releases toxins (volatile organic compounds) over its lifetime. It increases with the rise of temperature. It is dangerous material if caught fire. It produces a lot of smoke, which carries many toxic chemicals. They have a low thermal conductivity, so they are difficult to cool down.

Felt underlay (from recycled textiles) is a traditional choice and has high wool content, making it suitable for insulation. It should have a noise reduction of 41db and excellent heat retention with 2.96 Tog (Fig. 12).

The promotion is essential in favoring natural or recycled fiber-based underlay for our environment and safety. It will help in the value addition of natural fiber, the production of a cost-effective product, and the development of an environment-friendly product.

5.4 Agrotextiles

Agrotextile is an emerging sector of the twenty-first century, with an expected market size of 13.04 billion by 2028, registering a healthy CAGR of 4.7%. Single-use synthetics are extensively used in agricultural practices like mulching, protection from sunlight, windshield, harvesting, protection from birds, etc. Massive amounts

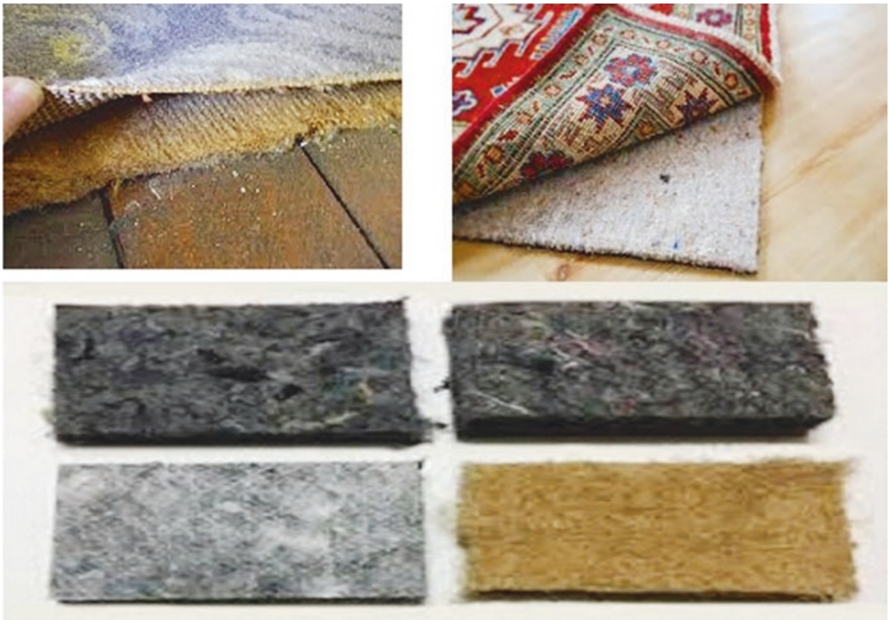


Fig. 12 Commercial and natural fiber-based underlay. (Report, 2021 [18])

of plastics are disposed of daily in the fertile field after using it in agriculture. It is famous as "plasticulture" in the agricultural process. The materials are mainly polyolefin, polyester, and polyethylene in the form of nets or sheets or woven cloth. Synthetic sheets and nets with better durability, malleability, lightweight, and low costs have gained immense popularity worldwide. Despite multiple benefits that the material offers, researchers expressed their concerns about plastics, as they are associated with high levels of waste and leakage to the environment due to inadequate end-of-life treatment, low recyclability and reusability rates, and high potential of disintegration into microplastics. It leads to a gradual decline in soil health, loss of productivity, soil infertility, desertification, and reduced agro-diversity. It poses a serious concern to the sustainability of the food production system. It posed a serious threat to our environment for its nonbiodegradable nature.

Jute has been used in packaging for about 200 years. Presently, for the development of diversified uses, jute is becoming popular in the form of woven, knitted, or nonwoven. The main application areas are soil erosion control, organic matter addition to soil for improved soil life or structure, evaporation loss, weed control, soil temperature control, and landscape formation.

Jute-based agrotextile is eco-friendly and sustainable and also results in low carbon footprint due to the low use of man, machine, power, and waste generation. Jute-based agrotextiles add nutrients to the soil and also act as a barrier to erosion. All these criteria are in favor of sustainability. It can withstand solar and UV radiation much better than synthetic fibers. Jute needle-punched nonwoven has been used in many trials by different organizations and observed very positive results.

The abovementioned properties of natural fiber agrotextiles are the main factors to consider in sustainable agriculture, which can be customized for different crops and agroclimatic zones. Efforts have been communicated [35–37] regarding the performance comparison of jute nonwoven mulching with control and existing various natural as well as plastic materials. It reveals the great potential of natural fiber nonwoven in agriculture. The following photographs are needle-punched fabrics from jute (Fig. 13).

The potential of jute like natural fibers and needle-punched nonwoven made out of such fibers for agrotextiles has been shown in Fig. 14.

Fig. 13 Jute needle-punched nonwoven fabric [34]

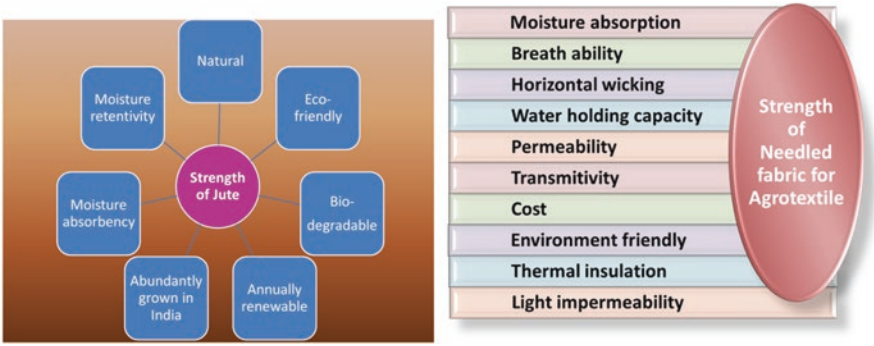


Fig. 14 Strength of jute fiber and needled nonwoven from jute on agrotextile [37]

Fig. 15 Broccoli and strawberry in jute nonwoven mulch [37]

5.4.1 Mulch Fabric

Mulching is a laying of sheetlike material to cover soil for weed control and soil moisture retention. It is a common practice in agriculture to use a synthetic sheet for mulching (mainly polyethylene). It has been widely practiced for producing many widely spaced crops and vegetables. It is also used to control weeds and reduce the need for herbicides and soil microbial population.

It was suggested that the best mulching product for strawberry cultivation is mesta/jute nonwoven from 500 g/m^2 areal density, 190 punches/cm^{2}punch density, and 10 mm depth of needle penetration compared to other experimental fabrics, including plastic sheet and jute woven fabric. It was observed with better biomass and growth, better moisture conservation, higher yield, better weed control, better soil temperature control, and improved nutrient enrichment. The higher initial cost of nonwoven is fully accounted for the higher return in the end. Waste-based nonwoven of mesta fiber further improves plant quality, fruit quality, and yield. Other observations in using natural fiber nonwovens are as follows: after about 2 months in the soil, fabric loses strength but makes a solid layer over the surface, which performs well for up to 5 months. This coating resists the shifting of soil particles during rain/thunderstorm or blowing of strong wind which results in decrease in soil erosion. Due to higher absorption and transmission of water, fiber absorbs excess water, and it is transmitted evenly throughout the fabric (Fig. 15).

Similarly, several studies show better performance in jute mulch fabric than the plastic sheet.

Natural fiber-based nonwoven mulching materials are gaining importance for application in agricultural and horticultural crops due to their various positive effects on crop and soil health. The core challenge is the availability of natural fiber and nonwoven in large quantities in the open market. Processing of natural fiber through a nonwoven system is another challenge as the technology is not so much popular.

5.4.2 Horticultural/Nursery Bag

It has been observed that scrim cloth reinforced waste jute needle-punched nonwoven of 350 g/m^2 is suitable for a nursery bag which can be used in germination and transportation of seedlings (Fig. 16). A flower germination experiment using the fabric mentioned above shows that leaf dry weight increases by 24%, soil loss reduces by 17%, soil nutrient increases by 6%, and plant growth increases by 27% after 1 month when it is compared with a plastic commercial bag. After about 1.5 months of germination, it can be planted directly into the soil with the bag. For plastic bags, the plastic is to be removed before plantation. During the cutting and removal of plastic, there is a possibility of damage to the roots, which is detrimental to plants. Jute-based nonwoven allows roots to grow without any obstruction as it can penetrate the jute nonwoven.

Table 6 shows the experiments with different types of nursery pots with respect to plant growth and leaf parameters.

Table 7 shows the optimized properties of needle-punched jute nonwoven fabric for nursery pots.

Table 8 shows the product for jute agrotextiles.

Fig. 16 Jute nonwoven horticultural pot [37]

Table 6 Plant and leaf parameters on different horticultural pots [37]

Treatment	Plant height, cm	No. of leaf	Leaf length, mm	Leaf width, mm	Leaf dry weight, g
Mud tub	11.65	8.9	51.3	46.3	2.06
Plastic bag	8.12	6.4	47.2	38.7	1.43
Jute bag	10.74	8.3	50.7	44.5	1.97

Table 7 Nonwoven fabric properties for nursery pots [37]

Type of nonwoven	Needle-punched with scrim backing
Area density, g/m^2	350
Density, g/cc	0.18
Fiber grade	TD6/waste
Needling density, punchs/cm^2	200
Depth of needle penetration, mm	12
Breaking tenacity, cN/tex	0.63
Breaking strain (%)	10
Sectional air permeability, cc/s/cm	105
Thermal insulation, tog	0.46

Coarse and low-cost wool from sheep can also be used as nonwoven. In an experiment with watermelon seeds, the plastic sapling bags yielded only 12% germination, while coarse wool sapling bags showed 41% germination. The germination of watermelon seeds was four times higher than plastic sapling bags over 15 days. The plant height, leaf number, and leaf area were significantly higher ($p < 0.5$) than the plastic bags. The bag can offer air and moisture to pass through, which gives natural conditions for a sapling to grow better. The bag can retain moisture for a long time without being wet. The degradation rate of the bag is slow (3 months). Even after degradation, the material offers nitrogen to the soil, which enhances soil fertility. The sapling bag ensures more than 50% moisture retention with a moisture content of 13% and a regain of 16%. The seed germination rate of the woollen sapling bag is higher than 50% compared to plastic bags.

5.4.3 Protective Cloth in Agriculture

In several instances, HDPE tape woven fabric is used as animal cover. After several uses as packaging, woven jute sacks can be further used as cold-protecting cover for pets. In India, such use is a century-old practice, especially in higher altitudes. Jute and similar lignocellulosic fibers and products are excellent thermal insulators due to their fine structure. It is well understood that nonwoven structure produces higher warmth compared to woven sacks. It is also lighter in weight due to its pore size distribution and low density. Therefore, woven and nonwoven fabric can be used depending on climate and availability as a protective cover for pet animals, e.g.,

Table 8 Product for jute agrotextiles [37]

	Seed bed	Nursery cover	Weed management
Type of fabric	Woven	Woven	Nonwoven
Weight (g/m^2)	300	400	300–500
Threads/dm			
(warp)	12	34	–
(weft)	12	15	
Width (cm)	122	122	150
Thickness (mm)	3	4	2–4
Open area (%)	65	40	–
Coverage (%)	–	–	100
Tensile strength (kN/m)			
Warp	10	12	2–6
Weft	10	10	

Fig. 17 Animal cover and fruit cover. (Web source [55])

cows, dogs, horses, etc. Moreover, it improves the comfort of animals compared to synthetic material (Fig. 17).

Jute needle-punched nonwoven cover can also be used to protect fruits from damage during transportation due to impact, in place of synthetic material. It protects soft fruits from abrasion and mild shock due to its compressive resiliency and impact resistance. Jute needle-punched nonwoven can be used for apples, oranges, pears, guava, etc. The fruit remains healthy for a longer time due to the breathability and thermal insulation property of nonwoven.

5.5 Geotextiles

Geotextile is the prefabricated textiles for solving geotechnical problems. It is the integration of engineering of civil and textile structures for enhancing the interactive performance of soil and structures. The use of geotextile has increased notably over the last 30 years. The global geotextile market size was estimated at USD 6.72 billion in 2021 and is expected to register a CAGR of 6.5% in the coming years. The form of geotextile sheet is of different types, such as woven, nonwoven, knitted, knotted, or stitch-bonded fibers or yarns. The sheets are air- and water-permeable and flexible in nature and have fabric-like appearance. The major functions of such materials are separation, filtration, drainage, reinforcement, and erosion control. Presently, costly, nonbiodegradable synthetics are dominating the worldwide market share (96%) of geotextiles. There is tremendous scope for use of natural fibers like coir, sisal, etc., in some selective areas, namely, strengthening rural roads, pond slope stabilization, etc. Another opportunity of using union fabric from natural fiber-based yarn and synthetic yarn and subsequently growing the grass over it may be adopted for riverbank protection and hilly slope stabilization [11].

At present, jute geotextiles are emerging development in the geotechnical and bioengineering areas. According to functional needs, the fabrics are engineered with different designs, shapes, sizes, and compositions using both synthetic and natural fibers. Geotextiles are multifunctional and location-specific. Biodegradability, eco-compatibility, and improvement of soil fertility and texture are the important concerns which are considered by bioengineering. Natural fibers are favorable in some applications. In agrotextile, such fabrics not only are beneficial for erosion control but also facilitate vegetative growth, de-weeding, landscape formation, etc. However, it may be noted that in most cases, a geotextile plays multiple roles; however, sometimes it may function in a significant role, but at the same time, it does some secondary functions also [19].

Trial shows that natural fiber-based geotextile (preferably jute, mesta, sisal, coir) can be used in (i) road or railway subgrade stabilization, (ii) riverbank protection, (iii) land reclamation, (iv) soil reinforcement, (v) hill slope stabilization, (vi) soil layer separation, etc. It may be woven, nonwoven, knitted, knotted, or a combination of any of those structures, depending on its uses.

Using jute geotextiles is an efficient alternative to the conventional method regarding capital investment and recurring maintenance costs. The jute geotextiles, even after many years of its application, perform their designated functions and help in the natural consolidation of the soil with good vegetation. However, the faster biodegradability of jute products is the most critical disadvantage. However, their life can be extended by different treatments and blending with durable fibers. So, it is possible to prepare engineered jute geotextile with permissible biodegradability and required specific strength, porosity, permeability, and transitivity according to use and location. The performance of jute geotextiles depends on soil composition, water quality, water flow, landscape, etc. The kind of jute geotextiles needed is determined by the physical situation and application. In comparison with synthetic geotextiles, jute geotextiles have some advantages, particularly in agro-mulching and similar areas where quick consolidation is to take place. It is used for erosion control and stabilization of rural roads where the main adversity is natural and seasonal degradation caused by rainwater in monsoon, strong wind, and temperature fluctuation in summer and winter. Jute geotextiles act satisfactorily as a separator, reinforcing agents, and effective drainage along with control in soil erosion and crack generation. Moreover, lingo-mass is formed after the biodegradation of jute, which improves soil organic content, fertility, and texture. The vegetative growth enhances further consolidation and stability of the soil. So, jute geotextile sustains modifying the microstructure of soil. One such open, netted, heavyweight (300–1000 g/m^2) textile is suggested for this purpose.

The soil surface of barren land, steep slopes, hilly areas, banks of rivers or canals, etc. are required protection from erosion. Such control fabrics are generally in the form of woven or nonwoven. They are designed to maintain the soil and prevent its removal due to high-velocity wind, drainage of rainwater, tides, and waves in the river or seabed, etc., until vegetation is established, which will prevent further erosion. Such geotextiles should have sufficient permeability to allow the water to flow and penetrate, so that hydrostatic pressure can be relieved. Another important point is to retain the silt and soil particles over it and/or under the armor (if armor is used) as well. The fabrics should be thick and have high abrasion resistance, tearing strength, and good cohesiveness between the surface of geotextiles and soil. In case of low topographic gradient and dry-land area, biodegradable geotextiles may be effective if used, and removal of them upon restabilization of the soil (usually within 6 months to 2 years, depending upon the climate) will not be necessary. Sometimes, grass seeds are spread over the soil before fabric laying, or seedlings/shrubs are planted to accelerate the vegetation. Table 9 shows the product range available for jute geotextiles.

Jute geotextiles (JGT) can be described as natural fiber engineering material to meet technical and functional requirements for soil-related problems. It is the natural, economical, and eco-friendly answer to geotechnical problems. There are several advantages of jute geotextiles arising out of their inherent, distinguishing characteristics, which make them eco-compatible and soil friendly for end uses in soil consolidation, road construction, riverbank and coastal protective work, construction of earthen embankments, slope stabilization, soil erosion control, reclamation of wasteland/land filling, etc.

Jute geotextile finds its application in the area of civil engineering:

- Erosion control of surface soil.
- Stability of embankments (roads/railways/flood).
- Strengthening of subgrade in roads.
- Protection of banks of rivers and waterways.
- Subsurface drainage.
- Soft soil consolidation.

Reasons for low market demand for natural fiber geotextiles

1. High productivity of synthetic geotextiles as compared to jute geotextiles.
2. Heavy weight.
3. Consistent supply of jute geotextiles is not ensured.
4. Durability of jute geotextiles is much lower than synthetics.
5. Types of cloths have not yet been identified for different uses, locations, and soil conditions.
6. Cloth parameters have not yet been standardized.

Table 9 Product range available for jute geotextiles [4]

Properties	Type		
	Open mesh woven geotextiles (for control of surface and erosion)	Typical woven geotextiles (for separation and filtration)	Nonwoven geotextiles (for filtration and drainage)
Weight (g/m^2)	292–730	760–1200	500–1000
Threads/dm (MD × CD)	12–7 × 12–7	102 × 39	
Thickness (mm)	3–7	2–3	4–8
Open area (%)	60–40		
Width (cm)	122	76	150
Strength (kN/m) (MD × CD)	10–12 × 10–12	20–21 × 20	4–6 × 5–7
Elongation at break (%) (MD × CD)		10 × 10	20 × 25
Pore size (O_{90}), micron		300–150	500–300
Coefficient of water permittivity (10^{-3} m/s)			3.4–0.34
Water permeability at 10 cm waterhead (l/m^2/s)		50–20	
Puncture resistance (N/cm^2)		380–400	
Water holding capacity (% on dry weight basis)	400–500		
Durability (years), max.	2	1–4	1

Advantage of jute for geotextile use

1. High modulus.
2. Heavy weight of jute helps in much better anchoring with soil.
3. Biodegradable.
4. Much less photosensitive.
5. Being agro-resource material, the natural fibers add nutrients to the soil after decomposition, which helps to enhance the growth of vegetation.

Disadvantages of synthetic geotextiles

1. Generally low modulus (high modulus synthetic fibers are very costly).
2. Poor cohesiveness with the soil.
3. Closed structure inhibits vegetation growth and inhibits natural growth of flora and fauna.
4. Sometimes lighter than water.
5. Not biodegradable under the soil.
6. Badly damaged on exposure to sunlight.

5.6 Packaging

Single-use plastics are abundantly used in the packaging during transportation and covering materials to save from rainwater. It can be substituted by biodegradable flexible fabric from natural fibers with or without coating or lamination for required stiffness, shape retention, and water resistance. Moreover, rigid packaging can also be made from fiber plant biomass such as particle board, paper board, corrugated sheet, etc.

6 Environmental Impact Analysis of Natural Fiber Product

Global climate change is a major concern throughout the world. The development of a protocol to cope with this led to a series of international meet of climatological experts from different countries resulting in a transition to a more environmentally sustainable economy and a major renewable resource; i.e., lignocellulose fibers, derived from the structural plant tissues, are expected to play an important role in this transition. The markets for fiber crops, such as coir, jute, and sisal, have experienced substantial erosion since the introduction of synthetic fibers. However, due to increased awareness regarding climate and growing demands for green products, several new markets for fiber-reinforced composites in automotive industries, building and construction materials, and biodegradable geotextiles are emerging with the ecological image of cellulosic fibers as a driving force for innovation and development. Environmental impact is a crucial factor in sustainable production. Life cycle assessment (LCA) is one of the most commonly used tools to analyze the environmental impacts of a product or process from its cradle-to-grave approach. According to ISO 14040, LCA is defined as the "compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle." LCA has been increasingly adopted by textile companies, including umbrella organizations like the European Commission, to assess the environmental impacts of textile products.

In India, jute is an important lignocellulosic golden natural fiber, and four million people are dependent on jute for their livelihood. Development of this sector focuses on positioning jute as a superior and eco-friendly material. To meet the challenge of the establishment of an eco-friendliness image of jute for capturing growing global markets of eco-friendly material as a substitute for synthetic material, the development of eco-label protocols of jute and jute product is imperative on the basis of life cycle assessment. LCA of the jute production system represents the emissions and extractions of nutrients to and from the soil and water as well as some important biogases to the air considering inputs and outputs of production system boundary to the environment. Transport of jute goods and disposal of end products by end users also increase the carbon footprint of the atmosphere. LCA of jute and heavy-duty jute sacking bag are reported on basis of carbon balance. An experiment was conducted in the farmers' fields of Nadia district to take an observation of the Jute crop (variety JRO 524) at 20 days' intervals from the date after sowing (DAS) during its growing period. Conventional packages of practices were followed, and the input-output of nutrients was analyzed. Jute production systems as a whole are assessed for their environmental consequences. It has been estimated during the jute cultivation, retting, and fiber extraction process that 6.347 of CO_2 per ha was fixed. During various processing of the jute for making bags in the mill and transport of the jute bag to end users and after disposal of the used bags, the emission of CO_2 was estimated to the tune of 1.77 t and 2.225 t, respectively. Thus, net carbon fixation has been estimated as 2.352 t CO_2.

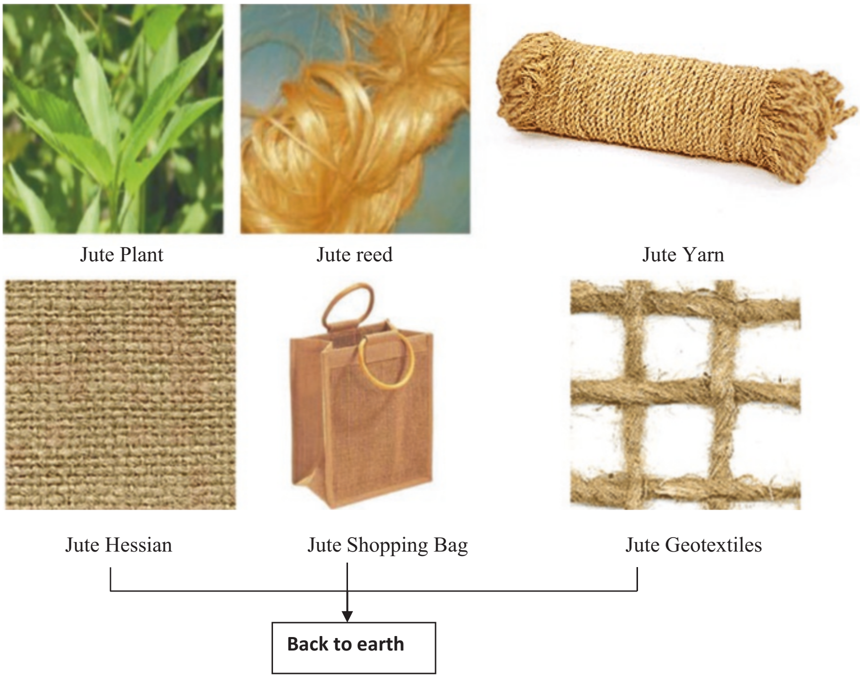
On the other hand, a considerable amount of water is consumed during the retting of jute, fertilizer, and pesticide industry and during different processes of production of jute sacking bags. After converting the water consumption to energy equivalent and subsequent carbon footprint to CO_2 equivalent, it was estimated that 2.238 t CO_2 was emitted into the atmosphere. Thus, jute production, processing, and conversion into bags are carbon neutral, which maintains the status of jute as an environment-friendly natural fiber. Eco-labeling of jute on the basis of LCA analysis can contribute to the enhancement of raw jute farming, fiber marketing infrastructure development, diversified product, and entrepreneurship development in the country.

For sustainability, any process or product should have to pass through a sustainability matrix considering the environmental, economic, and social impact [33].

7 Life Cycle of Jute Shopping Bag

Jute is a natural, biodegradable, renewable, and environmentally eco-friendly plant fiber. It is available from the bark of tropical plants belonging to two species *Corchorus capsularis* and *Corchorus olitorius*. It is golden in color and shiny in luster.

The best producing place of jute depending on soil quality and climate is the Bengal delta. The plain alluvial soil and water logging at the time of cultivation are most suitable. Jute is grown in warm (26–40 °C temperature) and wet climates (70–80% RH) during monsoon. The cultivation of jute is labor-intensive and needs care. The land is ploughed thoroughly, harrowed repeatedly, and manured properly. In the months of April and May, seeds of jute are sown just after rain. The seeds germinate within 7 days and then plant growth starts. The plants become mature after 4 to 5 months. Then they are cut down and tied up into bundles. These bundles are submerged underwater for about 15 days. The end time is judged manually, checking the stage of its decay. Then the bark is peeled off, washed, and dried in the sun. The reeds are off-white to brown and 2–4 m long. Jute reeds are tied in the form of bundles which is ready for sale in the market. For exports, the bundles are pressed to make 180 kg bales [32].



This jute reed is then processed through a series of machinery to make yarn or fabric. The ultimate product is then prepared using machines or manually. During the manufacturing of jute products, the raw materials are not subjected to any harsh physicochemical treatment, and hence, it assures the same input materials in their ultimate end products. These products, after use, can be safely disposed of in the soil or nature as it degrades naturally. It does not cause harm to the soil but instead adds nutrients. If burned, it emits the fume which is generated by burning wood. Jute does not have any effect on the human body and Mother Nature as a whole. At the end of its life, it goes back to nature. It is suitable for different applications, namely, industrial yarn, fabric, net, sacks, packaging, construction, and agricultural sectors. Major use is in bags and sacks for packing almost all kinds of agricultural products, minerals, cement, etc.; wrapping fabric of different materials; and backing fabric for carpets [25, 20].

There is a similar life cycle for all other lignocellulosic fibers. There is a minor difference in extraction in fibers of pineapple leaf, banana, sisal, ramie, etc. The cultivation and harvesting of cotton fiber are different, but it is also available from the plant. Other important natural fibers are wool and silk. The wool is sheared from the body of sheep which are reared scientifically. Silk is available from silkworm which is cultivated by a process called sericulture. As these fibers are different in their properties, the product-making processes are also different. But all such fibers follow a similar life cycles as stated for jute in Fig. 18.

Fig. 18 Life cycle of jute shopping bag

8 Campaign Against Plastic

The "Jute not Plastic" political campaign was begun in Switzerland in 1976. A non-denominational and politically independent organization, the Bern Declaration, collected 1000 signatures in 1968 in favor of it. The campaign includes education with the implementation of specific projects of development cooperation. It decides that jute bags will be produced by women's cooperatives in Bangladesh and sold in Switzerland. These bags will be used as an alternative to plastic bags. The campaign demonstrated jute bags consumes one-fourth times energy consumption than plastic bag. Therefore, jute bag facilitates 20-fold energy-saving compared to plastic bag.

The jute bags are generally considered impractical as they are heavy and rough and smell unpleasant. Hence, despite many advantages, it is popular in packaging only. Due to environmental pollution caused by synthetic bags, a bag made out of natural materials has remained relevant for all time. In recent years, the need for this change has intensified, and many retailers have reduced or banned the use of plastic. In some countries, government policies have also encouraged in favor of natural products. The antiplastic bag norm was highlighted by Clapp and Swansto [8]. The ban started early in the South and the North globe. But later, it has been delayed due to the interference of the plastic industry. Since 1991, grocery stores in Germany started to charge for plastic bags. They have introduced the pricing technique to reduce the consumption of plastic bags [31]. One direct effect was that the easily transportable fabric that started in Germany is called a “jute pouch,” though it is made from cotton. This term was popular because it is thought that the commodity which people used to carry grocery shopping is a jute product without knowing the genesis of the bag.

9 Current Market Scenario and Futuristic Approach

During the last 50 years, the yearly consumption of natural fiber has become doubled, whereas synthetic fiber consumption has increased more than six times. During the same period, the natural fiber market share decreased by 29%. The projected trend is not at all optimistic for natural fibers. To understand the trend in textile fiber consumption, some consumer-focused studies have been undertaken. It shows that natural fibers are in the favorable conditions in consumer awareness and preference. In most countries, consumers expressed that clothes should be made from natural fibers, and for that, they are ready to pay a higher price. Consumers choose natural fibers as the preferred material for current fashions and comfort. The market shows that the seller can sell at a much higher price, just informing the presence of natural fiber in the product. The price of natural fibers is highly variable. Even then, it can be said that ramie, hemp, and flax are more costly than banana, jute, and sisal followed by abaca, coir, kenaf, pineapple, and nettle.

Stagnation or declining the end-user demand impacts every segment of the natural fiber supply chain. The survival of related industries, as with any product, depends on the condition of its market share. That is also true for natural fibers and their industries. Retailers are constantly assessing the available product and market demand. The shifting of the market toward alternative products has a severe impact on millions of people employed in the textile supply chain of natural fiber, especially those who are from the developing world.

To combat this situation, the following actions may be taken:

- Well-planned marketing strategy, execution, and constant market research with highly qualified people.
- Stability in raw material prices.
- Technological intervention to make a better product at a lower production cost.
- To explore the uses of by-products.
- To develop a market-demanded diversified product.
- R&D intervention to develop better fiber.
- Product with better esthetic and functional properties, R&D intervention needed.
- To remove the main drawbacks of natural fiber.
- To convert the disadvantages into advantages by selecting a proper application.
- To understand consumer buying behavior zones.
- Branding of products.
- Logo highlighting positive points, e.g., eco-logo.

- Effective consumer advertising in different media.
- Celebrity endorsement.
- In-store promotions.

10 Bioplastic: Status and Opportunities

Several countries around the globe commemorated the "World Environment Day" with the theme of "Beat Plastic Pollution" in the year 2018, due to the precarious condition of plastics. Environmental awareness, regulations, and societal concerns have imposed the development of environment-compatible new products. Under these circumstances, the decision-makers, researchers, and producers of the plastic industry are interested to develop biodegradable and renewable resource-based plastics to replace nondegradable petrochemical plastics. Creating general awareness about bio-based plastics is a desirable goal, in the present context.

Bioplastics are a new generation of bio-based and biodegradable polymers derived from plants and microorganisms. The basic raw materials for bioplastic production are monomers like sugar, disaccharides, and fatty acids. These renewable resources are modified and processed into bio-based plastics. Here, biological systems are used, viz., microorganisms, plants, and animals, or they can be synthesized chemically from starch, cellulose, and lactic acid. Figure 19 shows bio-based plastic products.

The nonrenewable fossil fuel resources are preserved, and the environmental pollution generated out of it is minimized in the large-scale production and utilization of bioplastics. Furthermore, it reduces the carbon footprint and waste management systems through organic recycling or harmful chemicals. The bioplastic industry has been initiated long back in the mid-nineteenth century. The celluloid, which was initially developed to replace ivory in 1863, is the first bioplastic which was casein-based. However, it was overtaken by the petrochemical industry, and it became the main source of plastic materials.

The interest in bioplastics was revamped 20 years back, and researchers have developed biodegradable and compostable thermoplastics, such as polylactic acid (PLA) and poly-hydroxyl alkanoates (PHA). These were mostly new polymers compared to petro-based polymers (polyethylene) or blends with cellulose and starches.

(i) Starch-based bioplastics: ever corn and nature works were the first bioplastics which were invented from maize starch.
(ii) Cellulose-based bioplastics: the polymer of glucose called cellulose was used where the glucose units are linked by β-1,4-glucosidic bonds.
(iii) Polyhydroxyalkanoate-based bioplastics: the resource is plant-based starch, and polyhydroxyalkanoate (PHA) plastics are produced by microbial fermentation processes.
(iv) Fossil fuel-based bioplastics: biodegradable plastics can also be made from petrochemical raw materials. Here, poly butyrate adipate terephthalate (PBAT) is used for manufacturing bioplastics.

Fig. 19 Bio-based plastic products: (**a**) polylactic acid, (**b**) polyhydroxyalkanoate. (Web source [53, 54])

Challenges of Bioplastics [9]

- Low capacity – commercial demands for some applications are huge, and producers are unable to meet up in the present context.
- Recycling of fossil fuel-based plastics makes bioplastics uncertain in advantages.
- The production and supply network of petroleum-based plastics are well-established. The networks for bioplastics are not developed enough to replace synthetics considerably.
- The intensive agricultural practices of nonfood crops are inhibited due to ethical issues.
- The cost of production of bioplastics and the capital investment for production are much higher which restricts progress.

Many companies are investing in the research and development of new technologies to reduce the end-user cost of bioplastics and for easy adoption. In June 2020, Lygos, Inc. of Berkley, California, and Praj Industries Ltd. based in Pune, India, signed a memorandum of understanding (MOU) under the aegis of which Lygos's proprietary yeast will be codeveloped to facilitate the production of lactic acid, finally polylactic acid (PLA) bioplastic. In September 2019, the global technology leader in lactide monomers and polylactic acid, Total Corbion PLA, which is a joint venture between Total and Corbion, announced to enter the Indian bioplastics market in technical collaboration with the Konkan Speciality Polyproducts Pvt. Ltd. Industry-academia interaction has been made through various R&Ds by a joint venture between the Indian Institute of Technology, Guwahati (IITG), in 2019 to develop biodegradable plastics from oil and biorefinery streams. Around 18 states in the country have enforced a ban on single-use plastics, which will create an excellent opportunity for the bioplastic industry in the future. India bioplastics market is segmented into biodegradable plastic and nonbiodegradable plastic based on the product and by application. Rigid packaging, flexible packaging, textile, agriculture and horticulture, consumer goods, automotive, electronics, building and construction, and others are application segments of India on bioplastics. The packaging segment is expected to account for almost 60% of the overall market share to become dominant in the Indian bioplastics market. Bioplastics are extensively used in the manufacturing of bottles, loosefill, cups, pots, blows, flexible films, and other products. Rigid and flexible packagings are the two most common types of bioplastics used in packaging. Finished products from bioplastics are used in packing fresh food, dry snacks, candy, bakery goods, juice bottles, and meat trays, as well as coatings for beverage cups, films, and card stock. India's bioplastics market is projected to grow at a CAGR of 23.91% to reach US$ 754.648 million by 2025 from US$ 208–475 million in 2019. Another report indicated that the Indian bioplastics market was valued at US$ 320.13 Mn. in 2021 and is expected to reach US$ 1060.77 Mn by 2027 at a CAGR of 22.1% during the forecast period. Increasing environmental consciousness is one of the prime factors for the profound growth of the Indian bioplastics market.

11 Conclusion

Any natural item or process is a gift to mankind. Nothing can be ignored or wasted. Man's primary duty is to have proper and optimized use of it. From the beginning of the human race, they are learning from nature. Even in the present day, we are using bioinspired computing for sustainable processes and product development. Improper conversion and utilization of natural products or processes are harmful to society though they can give an initial benefit. Proper eco-environmental auditing is essential before the release of any product or process. In this context, all the natural fibers have enormous potential if we can use them judiciously. The known natural fibers have also proven their sustainability from the ancient age without harm.

Without reuse or well-established disposal systems, the carbon footprint potential of synthetic shopping bags is very high. It has a great impact on the environment. It was found that the carbon footprint values were lower in a higher reuse or recycling and controlled disposal at the end of life opted. It shows that higher reuse could significantly scale down the carbon footprint. Once the shopping bags reached the point where they can no longer be reused, they must be forwarded to recycling options, rather than being disposed to a landfill.

In conclusion, the strategies are suggested to use products from natural resources to remove plastic by introducing alternatives of natural products on a microscale level, i.e., in everyday life, as a symbol of environmental and social awareness. The bag made of jute is still considered a sustainable consumption nowadays. This bag has the potential for integrating many diverse cultural and social groups into everyday life and fashion. The campaign of jute against plastic is successful in terms of the widespread use of natural fiber-based bags and the number of people who identified with this bag as a lifestyle symbol.

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Sustainable Approaches for Non-apparel Textile Products Used in Sports

M. Gopalakrishnan, D. Saravanan, K. Saravanan, V. Punitha, and S. Mounika

Abstract Sustainability is the highly demanded practice for continued success in the manufacturing and consumption of different products. In order to reduce the carbon footprint and the energy demands, manufacturers are turning to sustainable approaches in their products. Major brands, already, have turned to sustainable approaches and practices in their manufacturing processes and products either by increasing the life cycle of the product or by reusing the recycled products. Sports textile is one of the major areas of technical textiles where textile materials are used in artificial turfs, sports rackets, balls, shoes, and many more products related to sports and games, besides sportswear. Reused and recycled materials are extensively promoted and used in various sports related products. In this chapter, approaches and methods used to introduce/improve the sustainability of the products are discussed.

Keywords Artificial turf · Sustainability · Shoe · Recycle · Reuse · Carbon footprint

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M. Gopalakrishnan (✉) · V. Punitha · S. Mounika
Department of Textile Technology, Bannari Amman Institute of Technology, Sathyamangalam, Tamil Nadu, India

D. Saravanan
Department of Textile Technology, Kumaraguru College of Technology, Coimbatore, Tamil Nadu, India

K. Saravanan
Department of Textile Technology, K S Rangasamy College of Technology, Tiruchengode, Tamil Nadu, India

S. S. Muthu (ed.), *Novel Sustainable Raw Material Alternatives for the Textiles and Fashion Industry*, Sustainable Textiles: Production, Processing, Manufacturing & Chemistry, https://doi.org/10.1007/978-3-031-37323-7_6

1 Introduction

Textile materials play an important role in engineering applications. In sports, textile materials are used in different forms with varied functions. Textiles are used as novel substitutes for improving the performance and quality of the material, increasing the life span, and reducing energy and cost. Nowadays, the demand for sports is increasing day by day due to various reasons. Due to the increase in demand and nonavailability, the regular materials and natural turfs are not adequate to meet the demand. A new material with good quality and protection against injury and sustainability is demanded by many players and manufacturers. Various non-apparel textile materials like caps, shoes, football, volleyball, cricket, sleeping bags, sports rackets, helmets, sports net, gloves, turfs, pads, mats, etc. are used in the sport.

In this chapter, how the artificial turf has evolved in different timelines from natural turf to synthetic turf will be discussed. The sustainability of the turf changed by incorporating the new materials in the artificial turf. The properties of different generation artificial turf have been explained in this chapter on sustainability aspect. Injuries and abrasion behavior of artificial turf are elaborated for its sustainability. Materials and properties of other textile materials used in sports like socks and helmets have been explained to enhance the life period and performance of equipment.

2 Natural or Synthetic Turf?

Natural turfs used in lawns, golf courses, and athletic fields require a huge volume of water to maintain the turf. Artificial turfs first came to prominence in 1965, when AstroTurf was installed in the newly built Astrodome in Houston, Texas. Uses of similar surfaces became widespread in the 1970s and were installed in both indoor and outdoor stadiums used for playing baseball and football in the United States and Canada. Artificial or synthetic turf is a synthetic or semisynthetic or combination of natural and synthetic surfaces manufactured with synthetic fibers as a substitute for the natural grass or natural grass together with synthetic grass in a synthetic base [1–7].

Artificial turf is mainly used on sports fields because they can support heavy use and require no irrigation or trimming. Domed, covered, and partially covered stadiums may require artificial turf because of the difficulty of getting grass enough sunlight to stay healthy. Artificial turf has its downside as it has a limited life, has periodic cleaning requirements, uses toxic chemicals from infills, and has some heightened health and safety concerns [8].

Most “real” turf/grass is used in concept of the lawn but also has important role in the agriculture and horticulture settings. It originated in England in the 1600s and by the 1700s was regarded as a “status symbol.” This was due to the extreme care and maintenance it required. This was long before the invention of mowing machines so nicely clipped and cared for lawns where it is much more difficult than today's maintenance. The advantages of natural turfs are dwindling as artificial turfs become more attractive in terms of appearance and maintenance aspects. Natural turf is also a source of food/fodder to many insects and animals. Real turf requires a lot of water to maintain lush green lawns, and that becomes difficult during drought periods. Real turf is also susceptible to many diseases and undesirable grasses growing together. However, real grass has proven, in studies, that it is a safer playing surface for athletes, but with the advancements of artificial turfs, this is becoming statement of the past [9].

There are different types of grasses along with many cultivars adapted to desired areas. The grasses are divided into two subgroups: cool-season grasses which prefer air temperatures ranging between 60 and 75 °F and warm-season grasses that prefer temperatures ranging between 80 and 95 °F. Cool-season grasses have a high growth rate in the spring that slows down during summer season but gradually rises during the fall [10].

Bluegrass is the most commonly used cool-season grass in the United States and has excellent recuperative and reproductive capacity and develops a dense turfgrass stand with excellent color. Kentucky bluegrass, although it has a slow seed establishment rate, has a shallow root system and requires a high amount of nitrogen and water and necessitates high maintenance, often susceptible to diseases such as summer patch and bill bugs [11]. *Ryegrass* produces a very high-quality turf, has a rapid germination and establishment rate, and can tolerate a very low mowing height but doesn't tolerate cold conditions and is susceptible to fungal diseases such as gray leaf spot [12, 13]. *Fescue* turf is known for its heat, drought, and wear tolerance. It is the most drought hardy cool-season species and is fairly well adapted to shaded areas. Fescues have a coarse texture with poor density and a poor recuperative ability from drought and injury [14].

Artificial or synthetic turfs offer better solution whereever the environmental conditions are not amenable for natural grass growth and places where low maintenance is desired (no mowing, or watering). Artificial turf systems necessitate less maintenance activities in terms of irrigation and trimming [15, 16].

3 History of Artificial Turf

Artificial grass or turf is one of the fields in which the synthetic fibers have been used [17]. Monsanto of the United States first used the artificial grass in 1964, originally called as *Chemgrass* with the high-density knitted nylon product that can support sports activities under the translucent roof structures [18].

Ground covering system, in an artificial turf, includes main turf, marking strip, and boundary strips together with connecting tapes [19–21]. The artificial surface comprises a base woven or knitted or nonwoven fabrics with an open structure to firmly secure upright tufted ribbons and porous structure for drainage of water [2, 5, 7, 21–26]. Fillers of different grades are spread evenly over the pile fabric to cover the surface of the backing fabric and to provide resiliency for absorbing impact shocks from foot traffic and other sports activities on the grass surface [7, 27–30]. From plain synthetic surface to the latest fourth-generation turfs, the synthetic sporting surfaces have undergone a transformation and gained wider acceptance in spite of many criticisms. New generation synthetic sporting surfaces multilayered structure comprising sub-layer, deflection layer, and upper grass layer.

First-generation artificial grass, with high-density and low pile height fibers, was developed in mid-1970s [31, 32] and was used in hockey ground in the 1976 Olympic [32, 33]. These first-generation turfs were made of coarse nylon yarns that often caused wounds and friction under dry conditions. This first-generation artificial turfs opened avenues for new synthetic sporting surfaces though they themselves did not provide a pleasant sporting experience [34] (Fig. 1).

Infills decide the energy absorption, elastic efficiency of the surface, and hence suitability for sports, which in turn safeguards physical integrity of the turfs and safety of sportsmen using the field [28, 35, 36]. The filler allows the outer layer to retain its porosity, and the depth of the infill layer varies depending upon the end use from 50% to 80% length of synthetic ribbons from the backing to the free ends. Various infill layers used in the synthetic turfs are categorized into three groups, namely, first, unfilled layer/water based layers that do not contain any particulate materials but necessitate frequent wetting; second, the sand-dressed layers with filling up to 5–8 mm of the tips of the grass surface with fine sands that remain unseen; and third, the sand filled layers that offer hard and rough field, in comparison with other two types, which in turn reduce the speed of balls [27, 37, 38].

A low-density medium pile height artificial grass, filled with sand in between the fibers to provide the stability, represents the second-generation artificial turfs [39], a kind of pitch that potentially provided control on ball bounce. Such second-generation artificial pitch was first installed in Queens Park rangers of soccer club [40]. Polypropylene based second-generation turf has some applications in soccer, but the first-class soccer lost the priority due to bounce produced in the second-generation artificial turf [41]. The bounce is too high when compared with natural turf, and also the issue of footing of players is also not reliable. The first-generation high-density low pile pitches were suitable for hockey, but the second-generation pitches were not ideal for soccer tournaments [42] (Fig. 2).

Fig. 1 Artificial sports turf – first generation

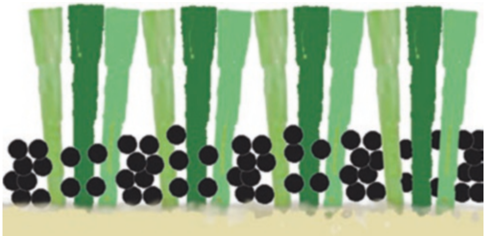

Fig. 2 Artificial sports turf – second generation

In the artificial turfs, good shock absorption properties are obtained with an infill mixture of sand and rubber or a mixture of sand and cork or a mixture of sand, chalk, clay, rubber, and cork, further added with chippings [1, 21, 22, 28–30, 43, 44]. Top course of infills are made up of resilient granules larger (15–30 mesh particles) than at the bottom (about 40–70 mesh particles) [21, 35]. Ground rubber particles of different types and grades like butyl rubber, butadiene-styrene copolymer, butadiene-acrylonitrile copolymer, low-density ethylene-octene copolymer, rubber mixed with carbon black, natural rubber, and vulcanized rubber [26, 28, 45] are used in combination with sand [36]. The amount of polyolefin elastomer content varies between 40% and 50% by weight [29, 43, 46]. Further improvements are achieved using a rubber mat having rubber particles adhered together by urethane, latex, or other binding materials to create a flexible, perforated cushion.

An important advantage of the synthetic turf is that the surface can be rendered more sliding-friendly, i.e., coefficient of friction can be varied using different fibers and their combinations, to reduce the incidents of burning wounds with uniform handle and softness to touch (the low resilience polyethylene yarns with polypropylene yarns). The fibers/fibrillated tapes used for grass surface may be of polypropylene [4, 20, 23, 24, 35, 36, 47–49], polyethylene [36], copolymers of polyolefins [50, 51], Teflon coated polyethylene [52], nylon [53], and melamin-phenol-formaldehyde molding compounds. Synthetic grass blades are made preferably using the combination of textured and non-textured filaments [5, 13], mixture of soft and stiff ribbons [19, 21, 53], monofilaments [36] twined with fibrillated yarns, and the natural grass planted to intermix with the synthetic grass structures [6]. Textured grasslike fibers have a pile height at least 25% less than the pile height of the non-textured pile [36]. Textured grasslike fibers are tufted into the primary and secondary backings with a tuft bind to the primary and secondary backing.

Ribbon structures [19, 21, 28, 29] comprise an alternating mixtures of stiffer ribbons and softer ribbons to provide a natural surface texture, where the stiffer ribbons have a linear density up to 11,000 D and a thickness of 100 μ, while the softer ribbons are of at least 5600 D to 10,000 D with a thickness of about 80 μ [5, 19, 23, 36]. Individual monofilament yarns and/or mono-tape yarns cut from the films are used together to achieve a natural look of grass with varying thickness [36, 47]. The fibrillated yarns are twined around the individual monofilaments so that the composite yarn has an outer surface formed by the fibrillated yarn, with a linear density of 2000 dtex to 20,000 dtex and a thickness ranging from 60 μ to 100 μ. At least 40% of the composite yarn is formed by individual filament yarns, while fibrillated yarn forms minimum 30%.

Synthetic ribbons are made from the slit tapes, and upper portions of the ribbons are longitudinally split into free strands, while lower portions are laterally linked to a lattice structure [19, 21, 24–26]. Strips of ribbons are attached by strips of bonding material applied to the back of the mat, and a particulate material is laid on a matrix of the synthetic grass at least two-thirds the length of the ribbons [19, 25, 46]. Ribbons/fibers have a length about twice as long as the spacing between the rows [Prevost, 2004] that extends between 0.25″ and 1″ above the particulate layer, with the total length of at least 4.5″. Grasslike coverings are made from thermoplastic materials that can be welded onto mesh like thermoplastic substrate [29, 30, 35, 44, 54], with an areal density of 30 g/m^2 to 150 g/m^2.

Longer ribbons or grass structures allow a thicker layer of particulate materials that can eliminate the need for a resilient pad and make installation of the surface simpler and cheaper. Improved synthetic grass surfaces are provided by widely spaced rows of ribbons measured from center to center, of between 8 and 50 mm, in the more closely spaced rows. Wider ribbon row spacing can also cause balls to roll more like they roll on grass, thus improving playing qualities, and this extends the life of the surface with respect to resiliency, wear, and abrasion of the ribbons and improves the drainage. Wider ribbon row spacing facilitates the seaming process, making it easier to loosen the particulate materials for replacement. Wider row spacing of grass in combination with longer ribbons allows better cleat penetration and easy release and improves the playing qualities and reduces risk of injury also.

Third-generation carpets were based on the longer pile fibers of 35 mm to 65 mm filled with both the sand and rubber granules [55]. These third-generation carpets were first introduced in late 1990 in Europe. These carpets are based on softer polyethylene fibers to take a normal stud on surface for soccer and rugby. These third-generation turfs provide added safety to the players due to the usage of softer rubber polyethylene infills [56]. These pitches are preferred for sports where a player falls or slides into the ground, as safety measures [38] (Fig. 3).

4 Fourth-Generation Turfs

The latest developments in these types of turf are coming under the fourth-generation synthetic turfs. Modifications in the existing turfs include use of monofilament fibers, and fibers with textures at variable length without the sand infill are used for rugby and soccer sports [57]. Examples of this fourth-generation soccer, hockey, and tennis facilities are now available in Victoria, and the first prototype of long-pile pitches for football/cricket turf under the Australian rule are also being installed [58, 59].

Fig. 3 Artificial sports turf – third generation

The artificial grounds filled with infill and without infill are majorly used in hockey. The sand infill is used in longer and less dense pile surfaces [49]. The grounds are normally watered before the start of game for unfilled pile surfaces [42]. The third-generation low level synthetic turf used for soccer with rubber or sand infill on a longer pile surface sometimes is sufficient to play the hockey. High-level hockey players prefer to play on unfilled watered pitches to minimize the burn and scrapes. Moreover, the hockey ball rolls and bounces faster in unfilled pitches than the filled one [60]. A study was carried out on three different hockey grounds to analyze the temperature rise in both dry and wet conditions. The increase in temperature on a sand and rubber infill grounds in dry conditions is Less and it is high on a synthetic ground. However, the abrasion was high on a sand infill grounds. The temperature rise is less on wet grounds and also the abrasion [61].

Sand-dressed instead of a sand filled grasses used in second generation are a variation which reduces the sand content approximately 50% to 80% to the regular sand filled pitches for hockey ground [47]. Such turfs move the ball faster due to reduced sand fill, and this reduces the abrasion and wounds when a player falls into the pitches [62]. The use of polyethylene fibers in the artificial grass is installed in international hockey grounds and tested for global level competitions [63].

An 80-mm-long pile turf infills up to 60 mm to absorb the thrown objects like shot put, hammer, javelin, and discus in the athletic grounds without damaging the thrown objects [64]. An artificial reddish sand is used in tennis court turfs due to the development of synthetic clay and reddish sand in artificial grass to minimize the compaction [65].

With more than 5500 synthetic turf fields currently in use throughout the United States, millions of students have the opportunity to practice and play on a sports field that can always be counted upon. Simultaneously, thousands of homes, businesses, golf courses, municipalities, and public spaces have turned to synthetic grass to provide a lush, attractive landscape solution that requires minimal resources and maintenance while saving millions of gallons of water each year. Consider the following benefits [66].

5 Injuries and Artificial Turf

Injuries are part of sports that need to be minimized to have a long term physical and mental health [67–70]. The previous generation turfs are connected with increased chances of injuries in abrasion and lower limb ligament. Introduction of softer polyolefin fibers drastically reduces the skin and abrasive type of injuries compared to the natural turfs. Still, some studies related to skin related injuries in artificial and natural turf reported that the natural turf is more prone to injuries than the third-generation artificial turfs [71–75].

Sliding is an essential element in sports grounds like hockey, cricket, rugby, and other sports. The player has to dive and slide over the turf for certain period of time for reaching the ball when it is moving from the player at fast [76]. When sliding over the synthetic turf, heat is developed and causes injuries like burning and scraping [77].

6 Disposal of Artificial Turfs

Global usage of artificial turf is increasing around 20–25% every year; however, life span of artificial turf is limited, and it is expected to provide good support for a period of around 5–10 years [8, 78].

The waste artificial turf consists of polyethylene fibers as artificial grass fibers, polyethylene or polypropylene carpet backing, and polyacrylate cross-linking agent and fillers as adhesives. The fibers polyethylene, polypropylene, and polyester used in artificial turf are not possible to process thermally since the melting points and viscosities are different for these fibers. Moreover, the adhesives used in the turf are also insoluble and infusible. Besides, the artificial turf consists of crumb rubbers and sands as infill to provide the cushion to the turf [78, 79]. Incineration, landfill, and recycling are used to dispose the waste artificial turfs. Among these methods, the landfill needs large land space and it contaminates the water resources [80, 81], while incineration releases a number of toxic gases.

First step in recycling of waste artificial turfs is separating the parts. Cheng pointed out the waste artificial turf can be shredded, opened, and converted into a usable material for extrusion, or these can be again used in artificial turf manufacturing [8].

Solid state shear milling and inlaid pan milling methods are used to pulverize the polymeric materials into powders [79, 82–84]. The recycled waste artificial turfs are made into ultrafine powder and extruded to wood plastic materials to replace the polyethylene products [79].

7 Socks

Sock is an item of clothing worn on the foot that can reach the ankle and calf to provide warmth and also help to avoid blisters and extend the life of shoes. Most athletics includes socks as a standard component. Basketball, soccer, and cricket are among the sports that demand socks as part of the uniform [85]. Socks are among the most crucial parts of apparel, despite its apparent secondary status. Socks are a sort of knitted clothing that completely or partially encloses the foot and leg. Socks come in a variety of styles and are used for everyday athletic and medical purposes. There are many different colors, sizes, and materials for socks. Some of the key properties and functions expected from socks are listed in Table 1 [86, 87].

Key performance and quality component in socks are the raw material, decided based on health conditions and allergic issues. Since, for instance, some fibers are helpful for diabetic patients while others may create allergy issues, some fibers are helpful for a limited amount of time before causing health issues. Also, the customer is made comfortable by the overall appearance of the socks. Socks made of acrylic or synthetic materials are probably suitable for athletes or those who are very active [88, 89]. Following are some various fabric kinds to look for in sports socks:

Natural fibers such as cotton and wool are mostly used. While cotton by itself is inadequate for a sports sock, it becomes significantly more robust and adaptable when combined with additional materials. Wool is regarded as one of the best and most expensive materials for socks, because it is soft, non-itchy, breathable, and odor-resistant. For winter sports like hiking, skiing, or snowboarding, merino wool is a popular choice because it is recognized for retaining heat when wet. Synthetic fibers like nylon and acrylic are used together to create a cushioned, sturdy sock. Nylon gives it durability, while acrylic contributes to comfort and support. Both fibers aid in wicking away moisture [90].

8 Characteristics of Socks

The greatest socks available today are a blend of several fibers and textiles that increase durability, avoid odors, and keep your feet dry. The qualities required depend on the seasons and the kind of activities engaged by a person [91].

Table 1 Functions and properties of socks [86]

Function	Property expected
Warmthness	Protection to legs, toe, and muscles
Wicking	Wicking the sweat during vigorous running activities
Flexibility	Enhanced stretch
Flexural rigidity	Better durability

- Support and cushioning to shield from blisters.
- Temperature to provide or ensure warmthness and keep skin dry.
- Compression to promote circulation, enhance blood flow, and provide more oxygen to the muscles.
- Slippage and bunching to snug in the right places.

9 Sports Socks

Socks are designed to go with physical activities, and also there are specific shoes developed for walking, running, and climbing used with appropriate socks. Jogging and running are the common movements in high-intensity exercise and sports that cause higher strain on feet. By absorbing moisture and cushioning the feet, socks help to maintain the general health of your feet while increasing blood flow and reduce muscle pain. Improper socks often result in swelling or athlete's foot and excessive perspiration leading foot fungi. Cotton socks absorb moisture, become saturated, and dry slowly, which potentially lead to blisters, hot patches, and chafing. Fibers or combination of fibers and the type of yarns that the socks are composed of have a direct impact on breathability, comfort, and durability.

Football players' socks are one of the important elements in the sports and are not simple regular socks because they ensure optimum fit and protection while playing. Football players use cushioned socks, made to provide a secure grip, protection, and comfort. Football socks are constructed from materials (fibers and yarns) that make the players comfortable to wear and provide a snug fit for sporting performance. Football socks could be either *over-the-calf style or crew design*. Over-the-calf pattern is the significant sock style that offers superior protection for individuals besides keeping athletes warm. Comparatively, *crew design* kind of socks provides better coverage than ankle socks and is suitable for hot weather as it allows the players' skin to breathe. Additionally, it enables the player to drain perspiration rather than fabric naturally. Key features expected from the football socks are that (i) it should be sweat-wicking, (ii) it should provide a grip on the knee and fit properly over-the-calf for adequate protection, and (iii) it should be comfortable for the wearer [92].

Different manufacturers use various combinations of materials to manufacture football socks. One of the socks available in the market has 3% spandex as a necessary component. It comes in several color combinations and has a crew length that will reach mid-calf. Polyester socks are ideal for a variety of sports, including basketball, lacrosse, soccer, and many more. Polyester together with elastane provides a compression fit. In the case of polyester/cotton blends, sock's breathable poly-cotton construction provides the wearers optimum warmth and comfort, while nylon/polyester with elastane is often used in tube pattern for perfect fit. Cotton/nylon with spandex is also used to produce socks suitable for warmthness, with air permeability, and that maintain dry skin [93].

In the case of tennis, characteristic requirements of socks includes (i) light and strong, (ii) contoured fit while moving about the court and (iii) substantial heel pocket, additional cushioning, and/or arch support. Natural mohair or antimicrobial characteristics of merino wool and ultrafine, high-tech performance yarns act as a barrier between the skin and the shoe when combined. Right placement of ventilation panels results in a clean, dry conditions. Socks are also finished with antimicrobial finish for odor-free conditions [94].

Breathability is a crucial factor for socks meant for volleyball players, similar to other sporting activities, since volleyball is a physical activity that causes more perspiration. Socks that can wick the moisture are mostly constructed from synthetic materials like polyester, nylon, spandex, and Lycra. Synthetic fibers don't absorb moisture, which in turn reduces chafing and blisters. Although some natural fibers like merino wool are naturally breathable, we were unable to identify any merino wool socks that fit the criteria for our list since they didn't sit high enough on the leg to allow for the comfortable use of kneepads. While playing volleyball, the players are often required to cut-and-jump, and hence enhanced padding in the heels and under the balls of the feet is expected from socks [95].

10 Pads and Helmets

Traditionally, cane, leather, and cotton were used as cricket pads, while modern cricket knee pads are made up of high-density foam, which makes them secure, lightweight, and easy to wear. Shins, ankles, and knees of the batsmen are protected by modern batting pads, which are fastened to the leg by straps that go around the calf. Additional pads are used around other parts of the bodies depending upon the protection that a player expects while playing. High-density foam is utilized for several reasons that include lighter in weight and easy to transport. A wicket-keeper in the cricket is required to wear knee and shin pads for better protection that are thinner than the pads used by the batsmen for better movement and to reduce the likelihood that a ball would get stuck between the knee roll and the thigh [96].

In the case of hockey, the players endure high amounts of force while checking or being checked that leads to significant injuries. In order to protect themselves from injuries, players wear helmets and pads. A goaltender becomes vulnerable and may lose the balance if they wear the improper pads. Hockey pads often are made up of a hard outer shell with softer inner shell for cushioning, similar to football pads. Outer shell is made to disperse the force of the strike and prevent it from being concentrated in a specific region, while inner pad is often constructed of foam that facilitates in lowering the force, which a player might encounter after a collision. The foam structure makes the collisions less elastic, as kinetic energy is transformed into other types of energy (heat) which lessens the impact.

Hockey goalie pads differ slightly from regular hockey pads, comprising of thicker foam, without differentiating hard outer layer. While goalie pads aid in shock absorption and injury prevention, they are also made to prevent pucks from deflection. Goalie pads are made of thicker foam than ordinary hockey pads, which makes collisions even less elastic and causes even more kinetic energy to be converted into other kinds of energy, reducing the puck's ability to rebound as far [97].

11 Wrist Bands and Helmets

The main purpose of wristbands is to absorb sweat of the players and prevent it from getting on their hands, e.g., tennis players or athletes. The wristbands that athletes wear come in a variety of designs, and their sporting activities benefit from the ability to maintain surface friction and grip. Such comfort is crucial in the case of tennis, where the players must grasp racquets for extended periods of time. In addition, wristbands can also be used to wipe sweat from the forehead or face. Basketball players prefer using arm sleeves – an extended version of wristbands. Spandex is added to cotton and nylon combinations to offer enhanced performance and a perfect fit, while flexible width and sweat-absorbent properties of wristband are well-liked. Wristbands meant for badminton players, are made of extra-thick fabrics made of cotton (70%), polyester (23%), and elastane (6%) or cotton (80%), nylon (14%), elastane (5%) and viscose (1%) for soft texture, comfort and durability.

Helmets have a cushioned interior and a rigid exterior shell and are required for effective diffusion of shocks and to protect the brain and head of the players. Many helmets are equipped with visors or cages. Visors are composed of transparent plastics, designed to shield the face and eyes, while allowing clear vision, while cages completely enclose the face and are composed of metal or composite mesh. More protection is provided by cages at the expense of vision [98].

12 Conclusion

Developments in the manufacturing of newer fibers offer improvements in the manufacturing of synthetic sportswear, sporting surfaces, and accessories. Though synthetic surfaces do not support proliferation of microbes, periodic disinfection is recommended to control their population. However, in the case of artificial turfs, effect of creep, chemical and environmental degradation of grass surfaces, mechanical damages due to repeated sporting activities, and changes in the properties of infill substances due to prolonged use of such surfaces need careful analysis. Developments in manufacturing processes enhance the comfort levels provided by various sports accessories and improve their performances.

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Cotton Fiber and Its Sustainable Alternatives

Vandana Gupta and Saloni Gupta

Abstract Cotton fiber is known as the white gold of India and every state thrives on it in many ways: farming, textile, craft, or basic utility products. A shift in the popularity of cotton is seen in the twenty-first century which came up with unprecedented opportunity in terms of technology and new material due to the harmful environmental effects of cotton. Search and application of new fibers such as bamboo, linen, banana, jute, ramie, pineapple, hemp, and lotus by the textile and fashion industry has made these fibers as some of the important alternatives for cotton due to their additional advantage not only as a textile material but also due to their sustainable developmental life cycle. This chapter is a compilation of many studies and researches conducted in the field of sustainable alternatives for cotton, and it explores the ability and inability of these fibers to substitute cotton.

Keywords Cotton · Natural fibers · Environmental pollution · Lotus · Banana · Alternatives · Sustainable

1 Cotton and Its Production

Cotton is such an important fiber which is with mankind from inception. It is a thread which connects many generations and civilizations, and in every way, it is woven into our lives. Cotton is around us and most of the things surrounding us contain cotton. Digging into the production process of cotton from field to fabrics, its application extends beyond textiles and apparels. It is the most abundantly produced fiber, grown in warm climate in northern hemisphere, and accounts for nearly 90% of globally produced cotton [39]. It plays an important role in textile and

V. Gupta (✉)
Chitkara Design School, Chitkara University, Rajpura, Punjab, India

S. Gupta
Guru Jambheshwar University, Hisar, Haryana, India

S. S. Muthu (ed.), *Novel Sustainable Raw Material Alternatives for the Textiles and Fashion Industry*, Sustainable Textiles: Production, Processing, Manufacturing & Chemistry, https://doi.org/10.1007/978-3-031-37323-7_7

handloom industry which is predominantly cotton based, providing livelihood and employment to millions of farmers and families [97]. Largest area of India is under cotton cultivation compared to other countries. States like Andhra Pradesh, Punjab, Karnataka, Haryana, Maharashtra, Gujarat, Tamil Nadu, and Madhya Pradesh are predominantly agricultural centers for cotton production [55]. Cotton is grown in different varieties, some of which include *Gossypium arboreum* and *Gossypium herbaceum* (these two are known as Asiatic cotton) and *Gossypium hirsutum* and *Gossypium barbadense* (these two are known as new world cotton). *Gossypium arboreum* and *Gossypium herbaceum* are grown in Asia, and *Gossypium hirsutum* is known as American cotton, whereas *Gossypium barbadense* is known as Egyptian cotton [50]. It is important to note that *G. hirsutum* contributes about 90% to global production and India is the only country producing all the four varieties on a commercial scale. The manufacturing process of cotton involves many steps starting from the collection of fibers from farms after harvesting in the form of bales to carding, combing, roving, and spinning to develop yarns which are then converted into fabric. Few finishing processes such as sizing and desizing are employed to create a yarn suitable for weaving. Further warping is prepared, and weaving is done on handloom or machine loom as per the market requirement. [15] From preindustrial revolution till date, cotton is a protagonist among all other fibers. But its sustainability concerns need to be dealt. This chapter explores the changes taking place in textile and fashion industry in context to raw material for textile and garment production. The amalgamation of new fibers with the existing fibers and showcasing the possibility of replacing cotton are shared in this chapter. The author also shares the importance of cotton in today's sustainability era over other natural fibers.

2 Application of Cotton

Cotton is natural hollow fiber, soft, and cool and has variety of applications due to its absorbent (can hold 27 times more water than its weight) and breathable properties. It is also known for its strength (especially when wet), good dye absorption, as well as good abrasion resistance. It can withstand high temperature. Such properties make it ideal for many applications not only for textile and apparel industry but allied industries as well. The raw material obtained from agricultural field is converted into textile materials and other usable products such as seed oil. Fabrication methods like weaving, knitting, nonwoven, macramé, and braiding all use cotton as one of the important fiber for the production of textiles. Textiles/fabrics made with cotton include broadcloth (fabric of medieval world, tightly woven ribbed fabric used for making home decors) and mercerized cotton (treated with caustic soda to improve the luster and strength of the fibers; used for hotel linen, apparel, etc.). Egyptian cotton is unique in itself as it is grown in the region of Nile delta in Egypt which provides the ideal conditions to produce long, strong, and high quality cotton as compared to other produced cotton. Associated with luxury, the Egyptian cotton is preferred for hospitality industry. Chenille can be made with any type of raw material but commonly made with cotton and have fuzzy appearance. It is delicate and requires handling. Sateen is made with cotton woven in sateen weave. It has glossy luster and soft feel and is used as luxury fabric. Muslin is a sheer and loosely woven cotton fabric. Another fabric is corduroy, which comes in various weaves and is extremely durable and used for curtains, cushions, trousers, etc. [23]. With such diversified cotton textile possibilities, cotton have many direct applications (hospitality, medical, fashion, home textiles, handloom and handicraft) and indirect applications (film and animation industry, events management industry, agriculture, automobiles). Cotton possesses the superior properties of high strength, absorbency, and color retention and is termed as white gold of India. It is also reported as the world's most important natural fiber with global textile revenue of 39% in 2021. This can be attributed to the versatile nature of cotton [86]. The medical industry takes advantage of cotton properties like absorbency, breathability, heat absorbency, as well as perspiration by using products like towels, wipes, coats, gauzes, swabs, napkins, dental treatments, medical cotton, etc. [5, 67].

In the hospitality industry and home textiles/interior textiles, the inherent properties of cotton like high absorbency and easy care (laundry) are important factor for comfortable stay of customers, as many products used in hospitality industry are made up of cotton fiber. Compared with other fibers, the strength of cotton fibers increases when it comes in contact with water due to the presence of hydrogen bonds in its molecular structure [59], thus exhibiting durability and reusability of towels, napkins, curtains, and bedsheets. The hospitality industry thrives on customer satisfaction in terms of comfort and aesthetics of the ambiance which can be maintained by durable and aesthetically pleasing textile material used in kitchen as tea towels, dish cloths, aprons [10], uniform of staff and housekeeping, and other interior textiles such as bed linens, curtains, terry towels, etc. [7]. One example of the use of cotton as an indirect application is the film and theater industry. It is true that no theater or stage is complete without a curtain. Cotton fiber and yarn are used as curtain due to its durability and easy maintenance [94]. Other applications of cotton fiber are seen in sports industry as canvas shoes and children shoes, inner layer of inflatable balls, and stitching thread made of five to six plies [62]; automotive industry as interior part of automotive and composites; and agricultural industry as mulch mat produced by the by-product of cotton ginning [12].

3 Sustainable Traditional Cotton Costumes

History suggests that cotton is an important part of our traditional textile and used to develop textiles that were considered as sustainable. The Indian traditional textile industry is dependent on cotton for raw material to develop different end products such as saree, running material, etc. Handloom involves wooden frames used by the skilled weavers to weave textiles using naturally sourced raw material. Manual process is implemented and thus no electricity is required to run the machine, making it the most eco-friendly process of producing textiles. Traditional garments developed under the ruling of different emperors were largely functional and designed keeping in mind the dimensions (length and width) of the textiles that were prepared on handloom of that region. The natural resources available also played a very important role. In such a diversified country such as “India,” each region and state has its own fashion and style which is visible in the garments. Manufacturing involved minimum wastage of materials and various varieties of costume exhibiting sustainability existed in different cultures [58]. The seam stressors and the craftsman were highly skilled in developing garments with few seams and features which allow developed garments to be worn differently or having different utility features [49]. The details of traditional linear cutting methods in northern India are well documented. This method involved use of geometrical pieces to create garments which resulted in little negative spaces around the pattern. A design technique was discussed which results in minimum wastage at the design stage. It is important to note the garments which were made during different dynasties used cotton and wool as raw materials. Examples of such garments are kalidaar kurta (made up of fine muslin) with chikankari embroidery and jama and angrakha during the Mughal rule [38]. Another garment is churidar pajama which is worn below the waist. The skill to create this garment involved converting the fabric into a bias fabric and then adding minimum stitch and cuts to develop the garment. Saree (jamdani of Bangladesh, chanderi of Madhya Pradesh, kasavu of Kerala) is another textile/garment which is one of the most important examples of sustainable cotton textile or zero waste fabrics, especially considering the pre- and postconsumer waste. [8]. It is an important part of women’s identity, legacy, and memories, as well as sharing traditional values. It’s a rectangular textile and its origin is inscribed in the manuscripts. When it comes to stitched garments, a saree is a rectangular piece fabricated on a handloom ready to be worn after it leaves the cloth beam of the loom. No stitch is required, thus making it the most sustainable and zero waste garment. In ancient times, saree was draped in such a manner that it created full covering to the body. Each draping style showcased different culture and tradition. Apart from this, 5–6 yards saree doesn’t leave its sustainable characteristic to this point; rather, it can be worn by different body types and in different styles depending on the occasion. History is the evidence that limited resources were kept in mind while designing and making garments in any culture. Japanese kimono dress is cut from rectangular shapes of patterns which leads to zero wastage. Our traditional Indian garments like paneled skirt (lehanga) and tunics for men and women (kalidar kurta) are some of the best examples of how not to waste fabrics in the pattern cutting process. These garments were comfortable, gave interesting silhouettes, and didn’t give up on the fitting aspects to the wearer. Similarly, ancient costumes of Roman and Greeks were rectangles or circles that were draped around the body without much of cutting and stitching involved. People respected and took care of such fabric which was made by skilled craftsman with patience and hard work on hand operated looms and is put to the best usage [29]. Some of the other sustainable textiles which were developed by using cotton and other natural resources as raw material are given in Table 1.

Table 1 Traditional textiles developed by using cotton

Traditional textiles	
Ajrakh of Bhuj	Ajrakhpur, Bhuj, is the place where this unique art is performed with the help of intricately carved blocks and use of natural dyes developed in days to give the required color. Brands like Fabindia, Anokhi, and iTokri are using the raw material for developing the trend based products for the global market [26, 87, 91]
Kala cotton of Gujarat	Initiative taken by creating Khamir brand is a platform giving opportunities to craftsman to share their skills and unique products with consumers and craft enthusiasts. Running fabric and products made by using kala cotton are organic and eco-friendly and made on with handloom [48]. The installation of cotton bud and raw material is displayed in the walk through of this traditional ambience as shown in Fig. 1
Jamdani saree of Bangladesh	Is a unique product developed by the skilled artisans of Bangladesh. Weft and warp yarns woven on handloom producing a transparent yet elegant effect with base and design combination [43]
Bagru of Rajasthan	Ancient art, performed by Chippa community of Bagru near Jaipur. The block printed patterns and fabrics are developed by using dark color patterns on the off-white background through indigenous methods. Brands like Jai Texart, The KINDCRAFT, and Gaatha use the unique characteristics and esthetics of Bagru art for developing commercially viable products for consumers [41, 88]
Rogan printing of Kutch	Referred as Chapala in Kutch, rogan is the native of Nirona village. The products developed by this art are unique as the embossed effect is developed by using a thickened paste (prepared by using all natural products). The designs developed on the fabric through imagination with no tracing are used to achieve the meticulously made design. Mr. Abdul Gafur Khatri is awarded with the PADMA SHRI National Award and has preserved the art by passing it to generations [74, 89]
Mashru textiles of Surat	A belief of Muslim community gave rise to the Mashru fabric, manufactured by using silk and cotton yarn in such a way that the silk is prohibited to touch the skin. The fabric has cotton at bottom (or innerside) and silk on the top (front side of the fabric), giving both comfort and shining effect [33]

4 Environmental Issues of Cotton

Developments in the textile sector have played a major role in the increase of environmental problems [90]. According to United Nations Conference on Trade and Development (UNCTD), the textile industry, after oil and gas industries, has been condemned to be the second most polluting industry in the world [37]. Production of any material at every level of processing is always associated with generation of some form of pollutants and waste in our environment [63].Textile industry is no different in this aspect. It involves a lot of processes right from the cultivation of the fibers with high consumption of resources like water, fuel, and considerable amount of energy and where a variety of chemicals are utilized to treat the fibers to reach the final fabric [77]. More than 1900 chemicals are used in the production of clothing, out of which many are classified as hazardous to the health of humans and ecosystem. Significant amount of waste (packaging and solid waste) and pollutants is generated in almost every phase of the textile manufacturing process like spinning,

Fig. 1 Cotton fiber display in Khamir, Post Village Kukma, Taluka Bhuj, Kachchh, Gujarat 370105, India

weaving, dyeing, finishing, garment manufacturing, and even at consumer end [90]. High CO_2 emissions, land degradation, pollution, use of landfill space, hazardous chemicals, and overexploitation of natural resources by the global textile industry cause unimaginable harm to the environment as shown in Fig. 2. It pollutes the Earth and renders it useless and sterile in the long run [22, 37]. Moreover, around 30% of microplastics found in our oceans come from the textile industry. [37]. It was estimated by Pulse of the Fashion Industry report that in 2015, the global textile and clothing industry was responsible for the consumption of 79 billion cubic meters of water, 1.715 million tons of CO_2 emissions, and 92 million tons of waste generation, and under this scenario, these numbers would increase by at least 50 % in coming years [78].

Although cotton is a natural fiber and cotton textile industry can be considered as unparallel among other natural fibers due to its many inherent properties and diversified applications, still there are many reasons which have allowed the consumers and manufacturers to think about its usability in textile and allied industry in coming years. One of the problematic reasons related to cotton is that it requires huge quantities of land, water, fertilizers, and pesticides to grow [22]. Starting from the field (agriculture perspective), there are many environmental issues related to cotton production as shown in Fig. 3.

Farmers with less knowledge and literacy involve in the use of pesticides and fertilizers which are not only hazardous for health but also are hazardous to consumer and environment at later stage. The water footprint during cotton production is huge as cotton is an irrigated crop and not only utilize huge amount of water but also affect the regional freshwater resources. The best example is the Aral Sea which have reduced in size to a great significant [24, 46]. It is also reported that the cotton producing countries have been affected by the Stalinization [95]. Apart from this, the processes involved in cotton production lead to air, water, as well as noise pollution, affecting eco-system and health of workers. Health of the workers in the

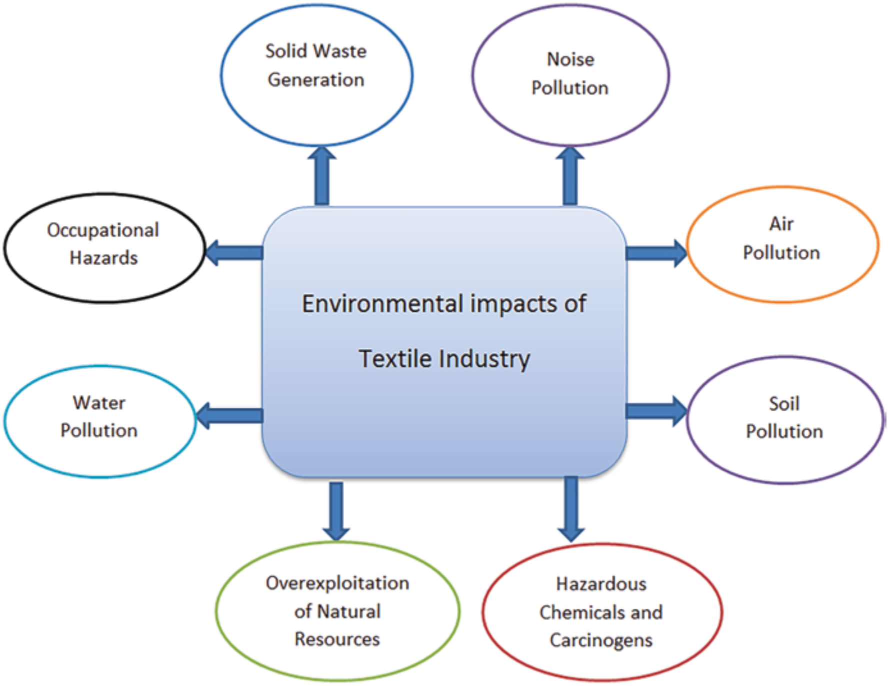

Fig. 2 Environmental effects of textile industry

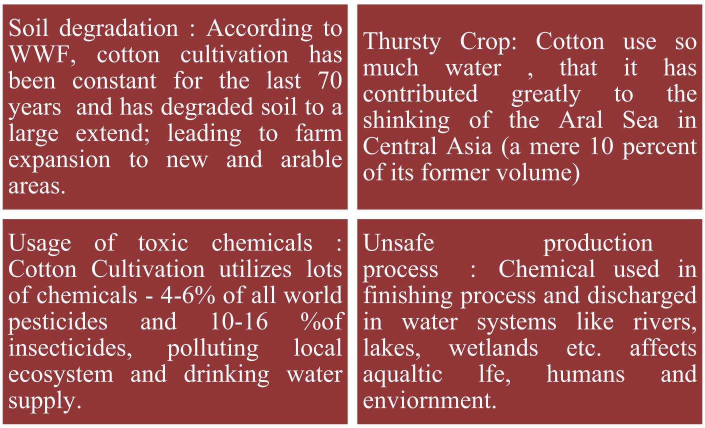

Fig. 3 Harmful effects of cotton production and textiles [64]

textile industry is affected on their exposure to dust, chemicals, noise, and ergonomic conditions. Severity of these issues also depends on climatic conditions, working environment, gender, and age. Workers engaged in the processing and spinning of cotton are exposed to significant amounts of cotton dust and also to particles of pesticides and soil, thus leading to respiratory disorders including coughing, wheezing, shortness of breath and chest constriction, chronic bronchitis, etc., and exposure to cotton dust for a high period can lead to byssinosis (brown lung) [17, 40]. Such reasons have led to the development and application of new eco fibers as alternatives of cotton, which are discussed in the coming section of the chapter.

5 Cotton Fiber Alternatives

Sustainable production is related to the production process which is in line with the nature. The process and material should fall into renewable category and help nature to recover in its own phase. Therefore, clear attention should be paid to the input and output of textile industry [25]. The new alternative has recently occupied its place in textile and apparel industry but also is part of automotive as well as other allied industry in the form of natural composites, replacing glass fiber [60]. The use of lignocellulosic fibers such as sisal and PALF as low cost and lightweight composites is well reported [51]. To analyze why few fibers and materials are considered as cotton alternatives, it is important to understand their properties and applications. Below are few fibers which are making their place as alternative to cotton in fashion and other related industries.

5.1 Lotus Fiber

Lotus (*Nelumbo nucifera*) being the most ancient angiosperms is a spiritual flower and has deep connection among the Hinduism and Buddhism religion [1, 54]. It is considered as the symbol of beauty, prosperity, and fertility and used to describe feminine beauty especially the eyes [54]. In earlier times, Cambodian monks used to wear the natural dyed lotus textiles which were converted into fabric after plucking the stems from the lake of Kamping Poy near Battambang [3]. It is obtained from stem and is the only fiber which falls in the category of nano-/microfiber due to its inherent nature [13]. Healing properties (astringent, emollient, diuretic, tissue inflammation, homeostasis, hematemesis, epistaxis, hemoptysis, hematuria, metrorrhagia, diarrhea, cholera, fever, hyperdipsia, etc.) of lotus plant are well known [82]. The textiles made from the same also provide health benefits [61]. Lotus fibers are distributed inside the lotus stem and covered with waxes, pectin, and some lignin. These impurities are removed during the preparation of lotus fiber [47]. The use of lotus fiber to develop rare fabrics is in existence from centuries in countries like Thailand and Myanmar. The produced fabric is comparable to linen and silk in its luxurious look. The processes used to develop the fabric are all manual and time-consuming. Myanmar is known for the production of lotus textiles (fiber, yarn, and fabric), completely through manual process using all natural tools and materials [3].

The manual process used to prepare lotus fabric involves following steps:

(i) Lotus stems are plucked and collected
(ii) The stems are cut, snapped, and twisted to expose the fibers. Around 20–30 fibers per stalk are rolled to prepare a single thread/yarn.
(iii) The rolled fibers are placed on bamboo spinning frame as skeins and prepared for warping.
(iv) The prepared yarns are then converted into handwoven fabric on traditional Thai or Burmese frame looms. For quality fabric production, the yarns are made at least 40 m long and coiled in plastic bags, whereas weft yarns are wounded on bobbins made up of bamboo.
(v) The weaving is conducted on frame loom.

It is important to note that 40,000 stems are used to prepare 3000 m of thread, and with the help of which, 1 meter of lotus fabric is produced [61]. Studies also reveal that lotus is one plant which is somehow similar to human body conditions and therefore helps in restoring natural harmony [3]. The research shares interesting facts about properties and potential of lotus fiber. The moisture content in lotus fiber is around 11.3–12.32%, resulting in soft fabric. This percentage is much higher than cotton and pina [68]. It is considered as one of the most ecological fibers as the waste is converted into a quality textile. It doesn't use resources like harmful chemicals, electricity, fertilizers, etc. during its production. Study conducted by Pandey et al. 2020 on cellulosic fibers on lotus peduncle found that the fineness of lotus fiber was 0.22 tex and had helical structure along with the similar chemical characterization with cotton making it one of the finest fibers with promising quality. Chemical characterization of the lotus fiber shows presence of cellulose and similarity with cotton fibers [68, 70]. Lotus leaf is known for its self-cleaning properties, due to the presence of various hydrophobic hairy structures (wax crystals) of 20 nm. Due to the presence of these structures, the water forms a drop, instead of a film, and rolls down the leaf attaching all dirt particles from the surface along its way, leaving the leaf surface absolutely clean. Jaipur based company Hero's Fashion Pvt Ltd. has produced a No Mark Lotus shirt with naturally stain-resistant property. Due to this property of lotus fiber, the shirt does not require much washing leading to increased durability and thus is environment friendly. To develop such textile, hydrophobic nanotechnology is used, replacing the traditional sprays which leave textile rough and unbreathable. The shirt has the ability to just roll any kind of spill; it may be coffee, wine, ink, etc. It is well known that the cost of naturally made material is high and so is the case of No Mark shirt, which costs around 58.50 euros, but the quality and sustainable features of the product make it worth buying [84]. Fascinated by the wrinkle resistant and breathability, quality luxury brand Loro Piana developed line of jackets made of lotus fiber fabrics costing up to $5600 for the market of Japan and Europe [21]. Another brand Samatoa is known for bio-textiles and ethical fashion recognized by the UNESCO in 2012 and awarded by seal of excellence for producing unique textiles like lotus fabric. It involves the skills of women of Cambodia and provides employability and livelihood to them. The company's lotus fabric production process is 100% eco-friendly and consumes no resources which cause pollution. Thus, it is one of the luxurious fabric, part of textile and fashion industry [93]. Designers such as Bijiyashanti Tongbram from Manipur have also experimented with this unique raw material and have developed many products like scarfs, stoles, neckties, etc. with the help of ten women including herself who are working under her brand “Sanajing Sana Thambal.” The designer’s work was appreciated by PM Modi during Mann ki Baat radio program. Such new resources and support by the government have opened a new avenue for such unique textiles [73].

5.2 Banana Fiber

Banana is a tropical climate crop and grows quickly, as tree takes 9 months to give fruits and stand tall [76]. This crop is harvested two to four times a year, discarding the stems as waste. The qualities of banana tree make it as one of the most appreciable raw material not only for textile and fashion industry but allied industries as well. Each part of the plant is useful. Leaves are used in hospitality industry as plates; fruits are edible; central part of the banana tree is suitable to make medicine; and the waste bark bears a huge amount of fiber which is extracted to create yarns converted to develop fabrics. [72]. Studies reveal that banana fiber based textiles are viable in the fashion industry, with a wide range of applications possible with banana fiber which includes sleepwear, casual women’s wear, bridal wear, as well as home decor applications [76]. Looking back into history, the use of banana fiber (*Musa balbisiana*) for the development of the products through weaving is seen in Ryukyuan or Okinawan culture in Japan. The Japanese word “bashofu” means “banana fiber cloth.” It is an important part of the identity of Okinawan both as cloth and garments. Since 1974, bashofu is considered as one of the important intangible cultural properties [28]. It is very interesting to know how the artisans are connected to this fiber and have given their heartfelt dedication to create the same, to revive the same, and to sustain it for the future as well. The fabric is one sustainable material not only because of its raw material but also because of the process and tools (made of bamboo) used to prepare it. Growing the ito-basho plant, harvesting its fibers, forming and dyeing the yarns, and weaving through ikat technique are all done with hands and by using natural raw materials. This labor intensive work is still being performed by 101-year-old Toshiko Taira in her studio where she patiently splits and joins fibers to make yarn [14] (Fig. 4).

One important brand working by utilizing the waste banana bark is BANANATEX® (Fig. 5). BANANATEX® is the world’s first durable, technical fabric developed from a naturally grown abaca banana plant in the Philippines. With many awards in its basket, this brand was launched in 2018 and developed safe and ethical products. The company’s 3 years of research have provided solutions and contributed in sustainable development [34].

The process (Fig. 6) involved is sustainable as the fibers are extracted from the waste bark by hands; fibers were extracted and dried and then converted into yarn and fabric of required quality, utilizing no chemical in the production. The material

Fig. 4 The conversion of fiber to fabric, an old tradition of Japan [14]

produced is strong and durable, embedded with other properties like being soft, lightweight, and supple. The products are developed with its natural color and can be made waterproof with the application of natural wax coating (Fig. 7).

5.3 Pineapple Fiber

Pineapple is a perennial plant, having height and circumference in the range of 3–6 ft. The plant grows with scaly fruit and radiating leaves, which grows well in tropical and subtropical region. Cultivation of pineapple plant was originated in

Fig. 5 BANANATEX label. (Photo credits: © Lauschsicht)

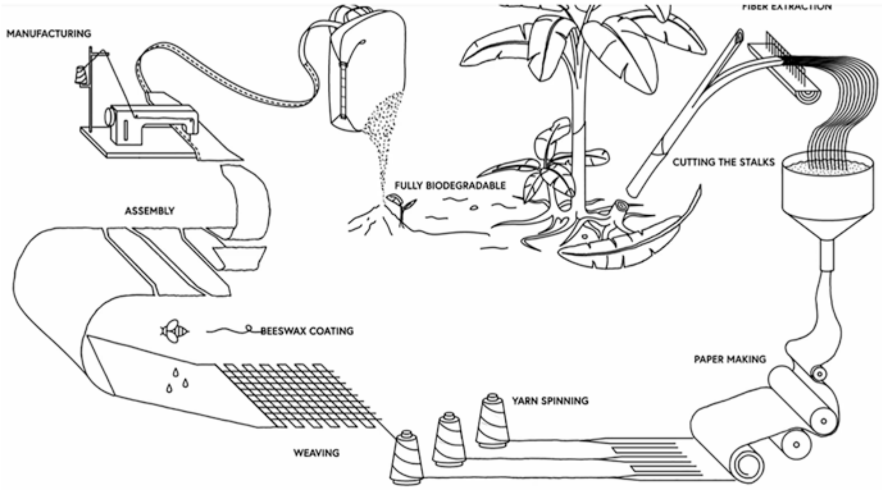

Fig. 6 BANANATEX product process

Central and South America, primarily for fruit. Costa Rica showcases maximum product capacity of 68.15 tons/hectare. The discarded leaves, postharvesting, is then utilized to obtain smooth, silky fiber by employing manual or mechanical method (Fig. 8) followed by decortications. The fabric prepared by using pineapple fiber is termed as "pina fabric" [69]. It is considered as a superior textile and is used for products like table linen, bags, mats, clothes, and handmade paper [45]. A study revealed the desirable properties of pineapple fabric after blending it with cotton (as warp) yarn, which is suitable for eco-niche apparels [44]. The mechanical properties studied by Tamta and Mahajan (2020) also revealed its possible applications in automotive industry, construction material, as well as furniture. A study revealed the desirable properties of pineapple fabric after blending it with cotton (as warp) yarns. The fiber is also reported to be cost-effective (by product of agriculture) and eco-friendly with good strength and chemical composition with cellulose (70–82%), thus having similar properties like cotton and being one of the promising alternatives to cotton [85].

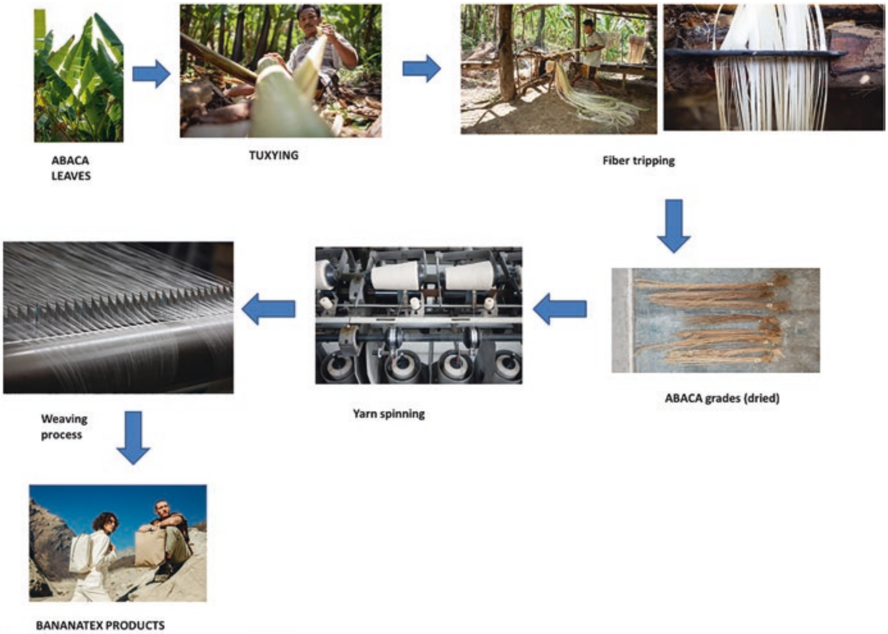

Fig. 7 BANANATEX manufacturing process. (Photo credits: © Lauschsicht & © Yves Bachmann)

5.4 Hemp

Hemp fiber is one of the important sustainable and versatile fibers with antibacterial, durable, and natural air-conditioning properties. Its production process is eco-friendly with the ability to grow fast by consuming very less or no amount of water. It can also be considered as a cost-effective plant as compared to cotton, as there is no use of herbicides, pesticides, synthetic fertilizers, or GMO seeds. Different surroundings/region in which hemp is grown provides the opportunity for textile artist to develop different types of fabrics. Warmer and drier area will provide hemp which can be converted into sturdier fabric like burlap. The popularity of hemp fabric is evident due to its properties over other fibers. Fabrics made with hemp have the following quality:

1. Durability.
2. Flexibility.
3. Do not lose their shape easily.
4. Naturally antibacterial.
5. Best heat capacity, thus providing comfort to wearer in summer (cool) and winter (warm).
6. Easily dyeable with good color fast properties. Study conducted by Lee et al. (2009) revealed that in the comparative analysis of cotton and cotton blend, the

Fig. 8 Mechanical pineapple leaf extraction

cotton and hemp blend exhibited better exhaustion values and better buildup than cotton and therefore can be used as an important alternative for cellulosic fibers especially cotton [52].

Apart from the benefits it has as a textile material, hemp plays a vital role in improving soil health by replenishing the vital nutrients and by preventing soil erosion. In 2005, it was suggested by researchers that, as hemp has the properties which can contribute in environmental pollution reduction, therefore more powerful and aggressive marketing is required for its popularity and application [81]. The shift can be seen after a decade where many mainstream brands like Adidas, Quicksilver, and Patagonia have developed products with the composition of fibers including hemp [92]. Neha Rao, designer and head of Bombay Hemp Company (BOHECO), is an active change agent who has started working with hemp fiber for her product range made of purely hemp or that blends with other natural fibers. The majority of the part of the raw material is sourced from South Asian countries like China and Afghanistan as hemp production is not yet legal in India. If compared with cotton on agricultural grounds, the hemp is economically viable as it provides higher yield crop with an average of three times more metric tons per hectare. Such factors and its sustainable properties make it one of the prominent competitors to cotton [80].

6 Cotton as Protagonist

The current scenario suggests that the above new natural fibers mentioned as cotton alternatives are part of many brands around the globe and have set themselves in shelves of wardrobes as well as retail shops. Still, studies suggest that the conversion of these fibers into different types of textile products requires the amalgamation of other natural fiber especially cotton. The blending of these new natural fibers like kapok and cotton in ratio of 3:2 resulted in better mechanical properties [9]. Pineapple and cotton exhibited better yarn tenacity property due to the cotton fiber fineness than pure pineapple fiber [42]. It is important to mention that not only the virgin cotton is used to develop fibers but pre-consumer recycled cotton in 50% ratio is used to develop viscose staple fiber [79]. It is reported that due to the stiffness of banana fiber, spinnability becomes an issue to convert it in yarn and fabric. After enzymatic treatment and blending with cotton and other fibers, its applications can be improved [18]. Research is also done to analyze and develop banana woven fabric by using cotton/banana ratio of 70:30 and 50:50 [30]. The blended nonwoven material of banana and cotton is also reported which suggested to be used for lead and zinc adsorption for environment pollution reduction [6]. The similar case is seen with hemp fiber in context to spinning particularly when 100% hemp is used to create a textile material [2], as the fiber is hard and have less cohesiveness. A study conducted by Liu et al. 2011 revealed that the fabric developed by exploring the properties of cotton (softness and fineness) and hemp has resulted in a product which has moisture absorption, air permeability, and antimildew and antibacterial as well as UV protective properties and is ideal for sports industry [53]. This and many such applications clearly explain that the cotton will always remain the protagonist in textile and apparel industry in coming decades.

7 Cotton Revival Initiatives

The demand of natural fibers seemed to be in oblivion, with the advent of synthetic fibers during industrialization. But due to the inherent and unique properties related to comfort, quality, and esthetics of cotton, silk, and wool, these fibers remained in demand for decades. Literature shares the importance of cotton in earlier days by explaining the growth of cotton fiber in comparison with population, where the production increases with the increase in population in 1990 [20]. In current scenario, considering the environmental effects of cotton fiber and consumer preferences for cotton, a new wave is there which has led to revival of cotton fiber by introducing innovative techniques like nanotechnology, microencapsulation, and natural dyes and prints in the production of cotton textiles. Literature reveals that the consumers still prefer natural fibers over synthetics all over the world, much because of the environmental factors and their natural behavior. Analysis of preference suggests that cotton is preferred by Mexican (75%), Japanese (80%), as well as US consumers [16]. To meet the demand and to satisfy the consumers, the textile and apparel industry has undergone research and innovation to modify and improve the material properties. Microencapsulation and nanotechnology are two important innovations which have provided multifunctional properties in textiles in the last few decades.

Microencapsulation deals with the production of microlevel capsules, embedded or coated in textiles, providing the required delivery of active ingredients as per the activity [19]. On the other hand, nanotechnology is the science of nanomaterials, performing and providing functionalities at nanoscale when combined with textile material [83].With the use of these and other technologies, many functional properties are added in the textiles keeping comfort and safety of the consumer in mind. Excel FR and UltraSoft® fabric are developed by using 12% nylon and 88% cotton and manifest fireproof properties [32, 35, 36] Outlast® fabric uses phase change technology to provide comfort by regulating body temperature as per the outside environmental conditions. The use of silver based finishes allows change in solid to liquid and vice versa. Such temperature regulating fabrics are part of products (footwear) developed by Nike and other companies producing upholstery items [31, 65]. Another important functional textile is the Wicking Windows™, developed to solve the problem of oversaturation and perspiration in the sportswear garments made from cotton fiber. It works by transferring moisture away from the skin to the outer surface of the fabric, thus providing the feeling of dryness and comfort [57]. Similar technology is TransDRY® in which cotton yarn is treated to exhibit water repellent property [11]. Also, it is known that cotton is comfortable to wear due to its high absorbency. This property also reduces its ability to be worn in the rainy season. STROM DENIM™ made up of cotton and with water repellent finish exhibits water repellent properties, by maintaining its other desirable basic properties [71].

Cotton can be grown in different varieties, and some of them include genetically modified cotton, organic cotton, colored cotton, etc. Looking into the availability of cotton varieties, cotton also exists naturally in different colors. Cotton lint in nature exists in three colors – white, brown (presence of phenolics and tannin), and green (presence of caffeic and cinnamic acids) – which develops with the interaction of opened bolls with sunlight [4, 56]. Naturally colored cotton contains color as part of the lumen, and therefore the developed cotton does not require dyeing. Shades of brown and green can be obtained naturally, reducing the pollution load of the textile industry. Keeping the future requirement of sustainable goals for clean water and sanitation, textile industry and researchers are developing new varieties by crossing white linted strain with colored strain of *Gossypium hirsutum*. The produced hybrid exhibited promising colorfastness to sublimation, washing, and light, thus revealing the potential of such material (which is eco-friendly, cost-effective, novel) for future textile and fashion industry [75]. Genetically modified cotton have resulted in the reduction in pesticides as compared to conventional cotton. This was one important initiative taken by agricultural research institutes to solve the problem related to cotton damage during cultivation.

Another important initiative is taken by WTO in 2019 who have declared and celebrated October 7th as the "World Cotton Day" in collaboration and support of FAO, UNCTAD, ITC, and ICAC on global platform. The initiatives targeted the dissemination of benefits of cotton to the users and to form the economic stability worldwide [96]. Another important production modification is the organic cotton which is in line with sustainable development. Studies suggest that the consumers are inclined toward organic cotton and preference is increasing with every passing day. Organic cotton is another important production modification in cotton industry which has managed to reduce the harmful effect of conventional cotton manufacturing process, increasing its consumption among masses [66]. It aims at stabilizing agroecosystem and involves crop rotation and biological means for crop protection. Organic farming reduces the soil, water, and air contamination which is seen in conventional agricultural production [27]. Keeping the eco-friendly nature of natural fibers into consideration, the "International Year of Natural Fibers" (IYNF) was announced in 2009. As the natural material like cotton, silk, and wool (abundantly used in textile production) is limited, therefore the use of new alternatives can definitely reduce the dreadful effects on agriculture and people associated with it as well as deforestation. The wastage of agricultural products is a potential resource for the production of many useful and valuable products.

8 Conclusion

It is true that the quantity of agro waste is not enough to meet the demand of the growing population all around the world, but converting waste into treasure is moving toward a sustainable and ethical development. Fibers from waste of plants like bamboo, pineapple, lotus, and banana can be converted into textile and products that will contribute in the sustainable goals in different ways like providing variety to consumers, providing designers opportunities to play with new material, supporting/providing safety from occupational hazards as these materials are natural and their production involves minimum or no use of hazardous materials, providing biodegradability, etc. As these materials involve manual techniques and are time-consuming, therefore they can find their future in the luxury industry. High end consumers are the ones who are in search of new and innovative products which are comfortable and aesthetically pleasing for which they are willing to pay the amount it deserves. So for this sector, the less quantity of such products can be utilized to its maximum potential, leaving other natural fibers available for mass consumption. This will boast the market of such important and eco-friendly fibers and will help in maintaining the eco-balance. The white gold of India has potential to be converted into sustainable fiber and products, if the full supply chain works in collaboration. Sustainable in true sense means nature loving and nature friendly; not only these new fibers but cotton as well is one of the best natural fibers and should remain part of textile and allied industries.

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Ancient Natural Colors from Chinchero

Jiayue Chen, Jiani Huang, Chandrakala Choppala, and Ivan Coste-Manière

Abstract Chinchero, located in southern Peru, is not only the birthplace of the rainbow but also the birthplace of Peruvian weaving, with some of the best textiles in the Cusco region. Communities of Chinchero still retain the process of dyeing with pure natural materials. The dyeing process in the Chinchero region is usually derived from animals, plants, and minerals. Therefore, these dyes are renewable and sustainable by essence. Not only that, their extraction technology and dye application process are all natural. In other words, the production technology in the Chinchero region is characterized by sustainability. As we all know, the textile industry pollutes the environment a lot, especially when dealing with the pollution of water resources. If this time-honored traditional dyeing process could be applied to commercial production, it will have a huge impact on the future textile industry and even the entire fashion and luxury industry, such as sustainable technology and process implementations, reducing environmental pollution, forming a green production model; handmade, which requires a large number of technical personnel, creating employment opportunities for the society; and unique culture and pattern identification or uniqueness, the transmission of Chinchero traditional culture, etc. The best publicity for Chinchero's branding lies on cultural affinity itself. Especially under the establishment of CTTC, more people are willing to join this activity. Plus, influenced by local tourism, Chinchero is a brand in its own. But these advantages do not mean that we in the mighty luxury industry can ignore some of its limitations, such as high production costs, excess capacity, and poor team awareness among artists.

Keywords Chinchero · Natural dyes · Luxury industry · CTTC · Natural colors · Sustainable colors

J. Chen · J. Huang · C. Choppala · I. Coste-Manière (✉)
SKEMA Business School, MSc. Luxury and Fashion Management, Sophia Antipolis, France
e-mail: ivan.costemaniere@skema.edu

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1 Introduction

Chinchero is a town in South America, capital of the province of the same name in the Apurímac region, located in southern Peru. This town is not only the birthplace of the rainbow but also the birthplace of Peruvian weaving, with some of the best textiles in the Cusco region. There is an ancient natural dyeing and textile craft, which will be our core topic for this coming chapter. The locals live on this craft, and the traditional craft plays an important role in the local tourism industry. Natural materials were used for dyeing in the area very early, and the exact time is difficult to trace because the historical old textiles are perishable.

Communities of Chinchero still retain the process of dyeing with pure natural materials. Although the application of synthetic dyes in modern times has had some impact on natural dyes, as discussions on social issues such as environmental protection and life and health become more and more popular, people pay more attention to sustainable development, and pure natural pollution-free dyeing technology has been revived. Thanks to the people involved and organizations like CTTC (Centro de Textiles Tradicionales del Cusco), this staining technique is becoming well known again and attracting many tourists.

Compared to synthetic chemical dyes, fuels derived from nature are much less harmful to the environment and human health. Natural dyeing aims to be an added value in artisanal products, and there is a need to generate markets, through natural procedures, that help keep our environment healthy and with less pollution [5].

This dyeing process is usually derived from animals, plants, and minerals; therefore, these dyes are renewable. Plant roots, stems, leaves, and fruits can be turned to dyes, and animal dyes are extracted from insects, snails and fish, and minerals such as volcanic rock and alum stone. The application process of these dyes is also all natural, even when dealing with detergent and fabric sources. The textile industry pollutes the environment a lot, especially the pollution of water resources. Applying this traditional dyeing process with a long history to commercial production can not only promote the sustainable development of the textile industry but also promote and protect the minority culture, provide local employment, and devote itself to the development of harmless production.

In the following chapter, we will introduce and analyze the ancient colors of Chinchero through three parts: dyeing process, sustainable development value, and commercial application.

1.1 The Process of Ancient Color

The process of ancient colors in Chinchero is divided into four steps: cleaning the wool, winding wool into thread, dyeing, and weaving fabric on the loom. Next, we will describe this process in detail so that readers could understand the whole pathway.

A. **Washing**

In this process, they will use the tubercle called "saqta" which is for washing the wool. "Saqta" is a plant that grows in the Cusco region, and the locals use its roots to wash all kinds of wool, such as alpaca, goat, sheep, etc. The root of this plant can also be used to cleanse the hair, so it is also known as "Inca shampoo." The method of using this cleaner is very simple; just put it on rough rocks and rub the debris out, then add hot water, and then wash the wool in it to achieve a good cleaning effect. The whole process does not use any synthetic product but the cleaning effect is remarkable.

B. **Yarning**

The second step is to spin the natural wool and turn it to thread, which is the most complicated part. But it's easy for local women, who often spin threads while doing other things. They need to dry the wools first for yarning. For this, they use a famous drop spindle, called a "pushqa." It is a wooden instrument like a top with a long stick attached. Then attach the wool to it and drop it while giving it a twist. The "pushqa" pulls the wool through their fingers to thin it out. This makes it even and gives it a good twist [4].

C. **Dyeing**

We will focus on the coloring part. Unlike the synthetic dyes used in most modern factories, Chinchero dyes are all sourced from nature, and no chemicals are added to the production and use process. Although there are no synthetic substances, the materials from nature are still very colorful and can be dyed in a variety of colors. The three primary colors (red, yellow, and blue) are extracted from cochineal, ccollo flower, and quinsa K'ucho leaves. For pink color, they use the motemote seed. For orange tones, they use a moss called musgo de roca. Chilca leaves are used for green. Purple corns and awaypili leaves are both used for purple tones. Gray color can be obtained from tara fruits.

In addition to dyes, there is another very important thing called "mordant" in the dyeing process. The principle of the application is called "pre-mordentation"; it occurs when the wool is subjected to the mordant before dyeing and "post-etching," when this is done after dyeing. The "pre-etching" facilitates the capture and fixation of the dissolved dyes. Industrial mordants often contain a lot of chemicals, but everything is natural in Chinchero, and people often use lemonade, alum, or plant ash as mordants.

Compared with the previous step, the dyeing process is relatively simple. Select the dye and mordant, add it to the hot water, and then put the spun wool thread for soaking and cooking. This process usually does not take too long.

D. **Winding**

This step is the last and easiest step throughout the entire dyeing process. Usually those dyed yarns are rinsed with clean water first and then hung up to air-dry. The whole drying process usually takes a day.

2 The Value/Sustainability of Natural Colors from Chinchero

Nowadays, it seems that we can find clothing in any kind of color we choose, from gowns dyed a deep shade of ruby red to sweaters decorated with every vivid tint of the rainbow. But because toxic dyes are so widely used in the textile business, our love for deep hues and vibrant vivid colors is now turning lethal.

Chemical dyes used in the textile business are one of the most negative aspects of the fashion industry, since they have a variety of harmful effects on the environment and human health.

Bright colors are something we've always loved. The history of dyeing textiles began as early as 2600 BC. Of course, in those early days, plants and animals' natural pigments only could be used to color fabrics. As societies could only dye textiles using what was locally available or through limited trading, the variety of colors available would likewise have been more regionally confined. "Rare" colors were devoted to Gods … and nobles, which could be considered as the nascent beginning of luxury.

Colored clothing was costly and frequently used as a status symbol or to denote rank or class throughout history. Tyrian purple, for instance, was exclusively worn by the very affluent and privileged in ancient Rome. Tyrian purple is a color obtained using dye manufactured from shellfish through a complex procedure.

Everything changed in the middle of the 1800s when the first synthetic dye was developed. Petrochemicals were used to generate a "coal tar" or aniline dye in 1856 that produced a vibrant, long-lasting color. Just 10% of the textiles that are colored now use the natural dyes that predominated for most of history.

Particularly in this era of social media influence, fashion trends are subject to quick change. Large companies need to stay up with these rapid changing trends. This frequently entails providing fresh color combinations and a wide range of hues at lightning speed.

Chemically creating new colors for each season is made simple by synthetic dyes, and unsustainable coloring techniques enable businesses to adapt quickly to shifting consumer trends.

2.1 Environment

The negative environmental effects of synthetic dyes are quite well known. Synthetic dyes severely harm the environment. This is particularly true when textile industries discharge toxic chemicals into surrounding waterways without first treating the wastewater.

Increased health effects reported by persons working in the garment dyeing sector are caused by synthetic dyes. Even people who wear apparel colored with synthetic materials may experience negative health effects.

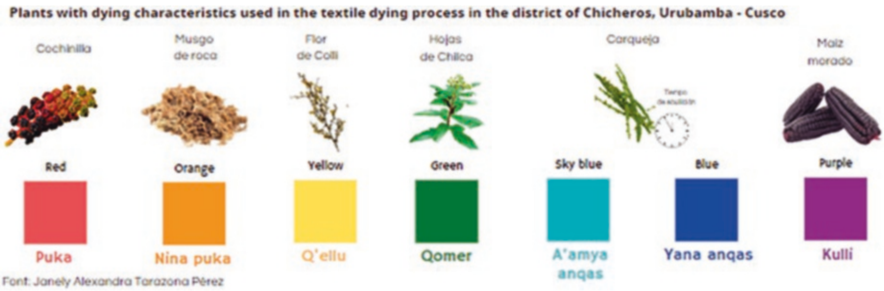

Fig. 1 Plants with dying characteristics used in Chinchero

On the other hand, natural dyes, which are made from natural materials, don't contain the same hazardous substances as synthetically produced poisonous colors used in the textile industry. This implies that they are less likely to seriously endanger employees' health. Also, they are less likely to result in dermatitis or allergic responses among wearers.

Natural dyes are particularly suitable for children's apparel or items for persons with sensitive skin because of these qualities.

Natural colors are biodegradable since they aren't produced from petrochemicals. When used without synthetic mordants, which help in binding the dye to the cloth, they don't produce chemical waste and come from natural, renewable sources. Nontoxic, non-synthetic natural colors offer a distinct advantage when it comes to protecting the environment.

From natural dyes like the ones from Chinchero to new technologies, there are solutions to make colorful dyes part of a sustainable future (Good maker tales).

In contrast to its counterpart, the shades are obtained in an environmentally and socially responsible way: they represent a sustainable source from their composition and production, unlike the synthetic ones, whose origin is petroleum and which, in its composition, contains toxic mordants such as chromium, tin, and copper (Fig. 1).

2.2 *Society*

Chinchero, one of the most well-known cities in the Sacred Valley of the Inca, was a predominately Inca city that the Spanish attempted to civilize in order to establish their culture. However, they were unable to fully succeed because the people of this city are still unwilling to give up their culture and traditions. They continue to live inside the constructions, exactly where their ancient ancestors lived and built the biggest and wealthiest civilization in North America.

They also preserve textile culture. It may be argued that the residents of this lovely city preserve all the historic methods used to create clothing as well as their uses and ornamentations. It was handed down from one generation to the next. The clothing is made by Chinchero artisans using age-old methods like the “away” and “loom.” Their attire is made from materials like wool from sheep and alpacas.

The ladies of Chinchero are known for their exquisite artistry, which transcends local boundaries. Thousands of visitors visit each year because of their high quality, and none of them leave without bringing one of the bright, beautiful, and elaborately designed outfits on exhibit. Manufacturing is their trade secret.

Since the last century, the Inca’s knowledge of extracting natural dyes has been disappearing. Marketing of crafts may be the only way these arts can survive. The product, being generated through workshop production and ancestral techniques, would promote culture and work in vulnerable communities.

2.3 Corporates

Despite being chemical-free, natural colors are sometimes more expensive than synthetic dyes. Because of this, most of the textile industry has switched to chemical dyes. However, the purity of natural dyes still makes them valuable.

Commercializing different types of products from these vicuña textiles would be a novel and differentiating idea as a luxury brand for the following reasons: from its manufacturing process, it is innovative and contains unique characteristics – such as historical references and a sustainable character – that could be valued for many markets.

The Environmental Benefits and Impacts of Natural Dyes

A. *Biodegradable, Nontoxic, and Hypoallergenic*

Some of the key benefits of natural dyes for the environment are as follows:

- They are fully biodegradable, which means that they will eventually degrade naturally when your use with them has finished, without releasing any nasty toxins into the soil/environment.
- They are made without any nasty toxins. Natural dyes are made fully from sources such as plants and insects, which makes them nontoxic to those who are exposed, and they don’t release harmful by-products into the environment like other dyes.
- They are hypoallergenic, which means they are less likely to cause any allergic reactions when the skin is exposed to them. This is ideal for those with sensitive skin conditions such as eczema, as well as babies and children (Fig. 2).

B. *Lowering our Dependence on Harmful Synthetics*

- If natural dyes are embraced by a larger part of the textile industry, fewer companies will be so heavily reliant upon harmful synthetically dyed fabrics.
- If consumers become acquainted with them and accept the different sort of tones and shades of color they can create, there will be less global demand for harmful synthetic dye.

Fig. 2 Advantages of natural dyes

- The fashion industry could become less dependent on this method of textile production and instead embrace more sustainable methods of clothing production.

C. *Lower Carbon Footprint*

- Another benefit of embracing plant-dyed clothing is that it helps to reduce your own carbon footprint. This is because many natural dyes tend to be made from fully renewable materials – plants or insects are good examples.
- Plants bypass the entire production process it takes to create synthetic colors, and the communities that farm these materials use the plants for a range of different uses other than just dye. Also, because they need less rinsing, they require a lot less water to produce. The water used can also be recycled back

into the next crop, as the water is hazardous, chemical-free, and low in toxins (Rare and fair).

3 Ancient Products in Business

Nowadays, handicrafts are positioned as one of the important export business activities worldwide, and commercializing these vicuña textiles with Peruvian cultural characteristics as luxury brands appearing all over the world will be a novel and differentiated idea. It is innovative and incorporates uniqueness such as historical references and sustainable features from its manufacturing process, which are valuable in many markets. In addition, the establishment of a local handicraft luxury brand expressing the local culture will aim to improve quality, cost, and variety, in order to enhance the local economic strength, compared to the current regional economy mainly driven by tourism. A proper "bespoke" and underground diffusion for a better penetration of an affinity driven segment…

3.1 Local Business Activities in Chinchero

Before the advent of commercial crafting events, most Chinchero women were limited to resale of handicrafts purchased at Cocus, and they would entrust merchants to lend them the handicrafts after a period of time. Over the years, these Chinchero women have gradually learned to weave and make handicrafts based on the knowledge of weaving inherited from their ancestors as the local tourism industry has gradually expanded. They learn how to do this work routinely, mostly from their own mothers and grandmothers, mostly from childhood perceptions. This also explains why these women weavers were able to incorporate their knowledge into a commodification of life, something called traditional fashion, a concept that they continued to endure, that continued to exist. Ethnofashion could be the key…

For the Aboriginal people of the Chinchero community, textile production complements agricultural activities, using clothing as a household item and generating economic income. This is especially true in weaving and making handicrafts, as they believe that the commercial activities of tourism require less physical effort and are more profitable than working on farms or herding animals.

The rise of tourism led Chinchero to decide to turn this into a new experiential tourism, one of which was Nilda Callañaupa, who realized the interest of tourists in textiles and led to the creation of the Cocus Centre for Traditional Textiles (CTTC).

3.2 *How Chinchero Became a Luxury Brand*

The Establishment of a Luxury Brand

For a luxury brand, regardless of its nature and price, all products sold under the same brand name have a symbolic meaning and a core of value that expresses the "essence" of the brand. In other words, no matter what type of product it is, all products express the core values of the same brand and are clearly identified [2].

If Chinchero want to be a luxury brand, it needs to follow the above principles. Fortunately, every handicraft of Chinchero represents the unique local culture of Peru, which is irreplaceable and unique. The reason why most consumers choose to buy local textiles and handicrafts when they travel to Peru is largely because of what these products may represent: cultural characteristics of the Chinchero community; pure handmade, Peruvian tourist souvenirs; sustainable production process; etc. These meanings go beyond the product itself and will become a multifaceted belief. This is the basis of Chinchero's strategy to become a luxury brand and its brand extension.

Moreover, analyzing the "old" RISC International image chart, to be considered a luxury, the product should be commercialized in countries where factors such as the high quality of the products and manual labor are highly valued by its buyers, like Japan, the United States, and Great Britain; and to be a luxury brand, factors of this new company of Peruvian vicuña handmade textiles should be marketed in countries where factors such as good quality products, unique style, long story, and traditional know-how are highly valued, like Japan, Germany, and the United States. As a result, it will be convenient to launch in Japan, the United States, and Great Britain. As part of the campaign, the history behind the garment and its production process would have to be highlighted due to its differentiating potential in the market (Janely Alexandra Tarazona Pérez).

Textiles from the Chinchero region maintain their own characteristics during the production process, such as dyeing characteristic colors, images, and representative fabrics [3]. For example, the artistic richness of the fabrics that form an important part of traditional clothing, especially in the lliklla blankets, ponchos, and chumpis belts, which have been representing the textile identity of the Chinchero region since the 1960s, has been influenced by the transition process in the design, color, quality, and use, due to ideology, education, local and regional infrastructure changes, and different and constant situations of synthetic materials (book by Nilda Callañaupa).

Not only that, but the Chinchero region has another, better well-known textile product – "Ñawiawapa," the iconic pattern of the finish that gives it its uniqueness by distinguishing it from other textile products in the region. At present, the artisans of Chinchero do not use traditional production processes to make fabrics, because there are industrial companies that provide wholesale and large quantities of raw materials that have been spun and dyed, also guaranteeing the duration of the color [3].

3.3 Marketing of Chincheros

Luxury marketing is a paradox. Managers want their brand to have a certain level of dissemination in order to be successful in the market. However, if their brand spreads excessively, it loses its luxurious character [2]. Therefore, the best marketing method for Chinchero to become a luxury brand is to rely on the local tourism industry, compared with the marketing methods of most luxury brands, in order to expand the popularity of its products and promote the unique local history and culture, so as to attract more consumers to buy its products.

Marketing ideas for Chinchero could include shooting related videos, showing how the product is made through using the strap loom technology to show the tradition and produce small garments with short production times, patent the dyeing technology, etc. The reason for this is that local artisans, through tourism, have direct contact with tourists and learn about their tastes and preferences, whether it is products, shades of color, or designs.

3.4 Profit Reference for Chinchero

There is no doubt that their labor costs must not be low and may even be high since Chinchero are handcrafted products. According to relevant studies, the cost of producing local textiles is greater than the cost of purchasing foreign products. The main reasons why producers acquire foreign products to replace their original products are that production capacity is related to time and the material premium that producers need to obtain products available for sale [3]. This is as pointed out in the report: artisans have gained greater utility by distributing foreign handicrafts (19.56% annual profit from local products and 80.44% annual profit from foreign products), which is the main reason for the replacement of original textiles, which is also the main reason why the image of textile tourism is affected.

Certainly, the significant impact of tourism on the Chinchero region cannot be overlooked in this section. Combining the above and the analysis of the report, the excellent markets for Chinchero to enter as a luxury brand are the United States, Chile, Spain, Germany, France, and Japan. It can be seen that people in a few EU countries are influenced by tourism propaganda and are very interested in the Chinchero region (According to the information provided by the Ministry of Foreign Trade and Tourism through the export and tourism promotion office PROMPERU, the region receives the highest income from tourism. The five main markets are the United States, Chile, Colombia, Spain, and France.).

3.5 Limitations of Chinchero

I. *The Emergence of Imitations and Their Impact on the Original*

Artisans at Chinchero provide visitors with textiles from Chinchero with images and textile finishing features, which are sold at high prices due to high production costs, in addition to low demand and low perceived utility by producers. As a result, large quantities of foreign textiles from other provinces of Cocus, as well as from the cities of Juliaca, Puno, De Sabadero, Bolivia's neighbors, etc., are bought and sold here. When these textiles enter the local market of Chinchero, it will replace and reduce the popularity of the original products, resulting in buyers being deceived and not carrying the original products as souvenirs, symbolizing the representativeness of Chinchero as a textile town. Even so, the advantages of Chinchero's handmade products cannot be ignored. We will show the difference between Chinchero's textiles and foreign textiles through Table 1 [3].

II. *Handmade Clothing Has a Negative Impact on Identity*

Wollum is pointing out that the women at Chinchero are not the ones who make the clothes, but the men in the machines elsewhere, and emphasizes that the clothes are presented for show. Weaving work has nothing to do with clothing; it is separate, while the work "like a weaver" is related to clothing. Thus, the clothing reflects the Indian character of women compared to men and their racial identity [3]. Goffman states that Chincheros inhabitants use "frontal" and manipulate their identity (exaggeration) to present themselves, which ultimately affects their self-perception.

Table 1 The difference between Chinchero's textiles and foreign textiles

Textiles by Chinchero	Foreign textiles
Made by Chinchero	Produced in Sicuani, Puno, Arequipa, Ayacucho, etc.
Handicrafts (handmade)	Industrial products, foreign handicrafts
Unique work	Continuous production
Technology: quadruped loom and strap loom	Using local typical industrial machinery and technology
Using traditional materials such as wool and alpaca fibers	Use of industrial and synthetic materials
High production cost	Low production cost
Natural dyeing (using dye plants)	Industrial dyeing or using aniline
Natural color	Bright colors
Featured portraits: The Eye of Loraypo and Awapa	Iconography is copied and innovated
Maintain cultural identity	Does not promote cultural identity
Provide quality assurance	No guarantee of the final product

III. *Risk of Overcapacity*

Today, the world is using the label of "sustainable development," and there are many shops selling their own products under the banner of handmade. Foreign products from the industrial sector and other sectors intensified the speed of competition. And in this highly competitive handicraft market, where little is known about the ingenuity of Chinchero textiles, due to the surge in demand, it is very easy to drive overproduction, resulting in lower prices and the risk of sluggish sales.

IV. *Others*

A. Little coordination between artisans and public institutions involved in tourism and crafts
B. The individualistic and distrustful qualities of artisans who do not allow the development of handicrafts (one of the problems that handicrafts men suffer from and hinder development is the lack of cooperative spirit, which is rooted in a poor business mentality)
C. Insufficient labor for local production, leading to outsourcing
D. Difficulty in obtaining raw materials and supplies at the regional and local level
E. Bargaining power in a competitive market

4 Conclusion

Natural dyeing work is mainly artisanal. There is therefore a strong need for labor, thus providing employment opportunities for all those involved in the cultivation, extraction, and work of these dyes.

Natural dyes and handwoven fabrics have given the locals of Chinchero jobs and employment prospects, which has helped to stabilize the finances of many people in the area and grow the local economy. In addition to offering workers safe working conditions, this way of producing clothing prevents workers from being exposed to hazardous chemicals in facilities with inadequate ventilation or safety measures. Since there is no water pollution due to the usage of dangerous pollutants, it also helps to safeguard the local ecosystem. A definitely successful global sustainable CSR…

Natural dyes are an economically and environmentally relevant solution for textile design in the future. Compared with natural and synthetic dyes, it is clear that the former are far better for the environment. The textile industry, especially in the luxury fashion industry where sustainability is the main trend now, must actively choose eco-friendly, nontoxic natural dyes over chemically produced synthetic dyes and textiles like the ones from Chinchero in order to take advantage of the environmental advantages of natural dyes [1].

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Eco-Pots: An Alternative to Plastic Sapling Bags

S. Amsamani, V. J. Aneetta, and C. Naveena Shri

Abstract Eco-pots are made from *up to 80% recycled plastic and natural stone*, giving their plant pots their unique look and characteristics. But here, *100% biodegradable* jute packaging waste and coconut leaf sheath have been used. It is a cost-effective method and environmentally safe. Jute is a sturdy and long-lasting material, and it also possesses absorbent and ventilating qualities. Due to their exceptional features, jute bags are still widely used today in packaging. After packing, the package material is leftover which is reused in some cases but at particular point it is discarded. These waste jute package can be an alternative to plastic pots, growbags, etc. The applications of jute material are vast, and it can be used for home textiles as mats, geotextile applications, mulch mats for agro tech, etc. Sustainable jute eco-pots are the best option for growing sapling as they can be directly introduced to soil because the plant roots can easily penetrate and these will biodegrade and form a part of the soil. The jute fabric also absorbs and retains water well, to help conserve water compared to thin plastic pots. These can also replace the plastic or ceramic pots used for home interiors by doing surface enrichment. Coconut leaf sheath can also be used to make eco-pots as they have naturally woven structure. Due to this, they are used as reinforcement material in composites.

Keywords Eco-pots · Biodegradability · Jute · Packaging · Leaf sheath · Sustainability

S. Amsamani (✉) · V. J. Aneetta · C. Naveena Shri
Department of Textiles and Clothing, Avinashilingam Institute for Home Science and Higher Education for Women, Coimbatore, Tamilnadu, India
e-mail: amsamani_tc@avinuty.ac.in

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1 Introduction

Environmental protection and waste reduction are areas of high interest. The existing production systems in agriculture and nurseries heavily rely on plastic pots, and "green" consumer behaviors fuel a market trend that is oriented toward improving pot sustainability. Use of biodegradable containers or biopots, which are created with natural raw materials that can disintegrate naturally, eliminating or reducing landfill trash, is a green alternative to encourage this behavior shift. Biodegradable containers are made from materials that come from renewable resources or from leftovers from farming, raising animals, fishing, tanning, etc. It is important to consider that plantable pots may act as fertilizers in the growth of plants. They deteriorate and decay, producing various materials close to the plant roots. Plantable pots would have two advantages over conventional plastic pots at the same time: they would not need to be removed during transplantation, and they would boost the fertilization of the surrounding soil if their materials broke down, releasing nitrogen, carbon, and other soil nutrients [1].

Concern for the climatic change opened a new path in developing eco-friendly and degradable products. Use of sustainable products has gained enormous importance and is substituting the plastic products. The field of agriculture, known to provide employment to half of the population, generates large number of landfills. Almost all the waste from agriculture is eco-friendly and can degrade itself into the soil. Efforts have been made by many researchers to convert the biodegradable wastes into useful products that can replace the plastics.

Conventional planting pots are made from clay, wood, and metals. Though they are sustainable, they have certain drawbacks such as they are heavy to lift, crack often, and are costly too. To overcome these drawbacks, plastic pots were developed, which met the disadvantages of conventional pots but failed to overcome the sustainability issue. Attempts have been made to replace the conventional pots and plastic pots meeting the disadvantages of both. Eco-friendly, strong, and pocket friendly pots are in need of the world today.

Plastics are widely employed in agriculture, from mulch film to seeds coated in plastic. All of these items have contributed to higher agricultural yields, but there is significant evidence that soil contamination from decomposed plastics is harming biodiversity and soil quality. These pots' excellent mechanical qualities, lightweight, chemical stability, longevity, and affordability are all benefits of using them. Additionally, mechanized devices can handle plastic containers to fill, seed, and transport crops. Every year, over 500 million plant trays and seed trays are produced. The vast majority are either burned uncontrollably or dumped in landfills. Plastic pots require a significant amount of fossil fuel to create, and it takes them 500 years to degrade. As a result, during nursery and greenhouse procedures, an excess of used and discarded pots is generated. Reuse and recycling are seen to be potential remedies for reducing these plastic wastes.

Biodegradable pots, also known as biocontainers or biopots, could be a practical replacement for plastic containers. Peat, paper, coconut fiber, rice hulls, chicken feathers, rice straw, dairy manure, and bioplastics are just a few of the materials that can be used to make biopots [2]. Currently, the two primary types of bioplastics used in the production of nursery containers are (1) plastics made of starch and (2) polylactic acid (PLA). Starch blends are created by combining 20–80% of starch with either bio-based or fossil fuel-based polymers to enhance the physical and chemical properties of starch-based plastics, which are water-soluble. Due to starch blends' sluggish soil biodegradability, polylactic acid is primarily employed with them. Polylactic acid is created by anaerobic fermentation of feedstock [3].

Jute is compostable and biodegradable, unlike plastic. Jute's relevance has increased over time as a result of its durability, porosity, low cost, and capacity to be reused. Jute is a typical lignocellulosic biomass material composed of cellulose, hemicellulose, and lignin. Due to its poor spinnability and rough touch, it is widely used as a low-valued industrial textile in the form of packaging bags and ropes. The increased usage makes waste management difficult, prompting us to seek green and efficient methods of converting these massive wasted jute fabrics into value-added bioproducts [4, 5]. Used jute packaging materials can be converted into jute planters and used as sapling bags or eco-pots. Upcycling waste fabrics has been a promising research because it can reduce textile pollution while also providing a solution to waste disposal.

2 Classification and Characteristics of Eco-Pots

Eco-pots are classified into two, based on the material used for preparation and according to their form of use. Jute bags collected from vegetable vendors and jute sacks from industries are recycled to make eco-pots which are 100% biodegradable and sustainable. Coconut leaf sheaths are the best alternative to plastic sapling bags. Naturally woven coconut sheath in the form of woven mat is extracted from outer basks of the coconut tree. The sheath consists of a mat of fine fibers placed between two layers of coarse fibers. They are usually burned to remove the waste from farms. These generally belong to plantable eco-pots, where the pots are directly introduced to the soil without causing any damage to the plant roots making the transplantation easier and zero waste. Plantable biopots undergo biodegradation; after being buried, they change to produce inorganic and biomass products.

Compostable eco-pots cannot be directly introduced to soil; after the plant has sprouted, these are removed from the pot and planted to soil. The compostable pots are disposed into a compost where it will biodegrade. The pot's lifetime can vary from few months to years depending on the application [6] (Fig. 1).

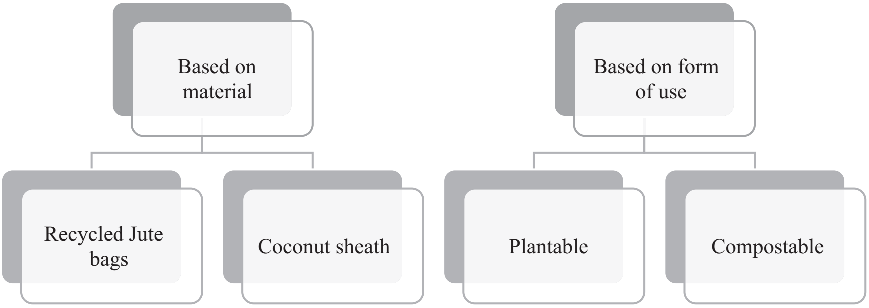

Fig. 1 Classification of eco-pots

3 Need for Jute Eco-Pots

Recently, the primary forms of bioplastics employed in biocontainers can decrease the amount of waste that ends up in landfills, but that is only one of many economic and environmental factors that may change as a producer switches from traditional plastic pots to alternative containers. Research from the past and present has identified both parallels and variations in plant growth, quality, water requirements, mechanized production success, transplant shock, and a number of physical characteristics associated to containers. This section provides a summary of the present state of knowledge and any potential problems related to the usage of biocontainers during production and afterward [7].

- Jute is a product that is both cheap and widely available on the market. Jute is a natural fiber that is both biodegradable and extremely strong. Plastics are nonbiodegradable materials that degrade over 400 years.
- Plastic bags are made from petroleum, a nonrenewable natural resource that is being depleted. In comparison, jute bag production requires only naturally grown jute. As a result, jute bags are more environmentally friendly than plastic bags in terms of preventing natural resource depletion.
- Jute bags outlast plastic bags because they are reusable, durable, and long-lasting. Polybags and plastic bags, on the other hand, have a shorter shelf life and lose their luster faster. Because of their shorter life spans, more waste plastic ends up in landfills, harming the environment and the health of living beings.

4 Eco-Friendly Pots in Current Market

The eco-pots mentioned here are created using organic materials like bamboo and man-made materials like newspaper.

- Cardboard and Recycled Paper Pots
  Paper or cardboard plant pots are ideal for starting seeds and growing seedlings. Every day, we manufacture a large amount of paper and cardboard. Since recycling initiatives do not always succeed, a large portion of it ends up in landfills. Paper or cardboard pots are not strong and will begin to fall apart as soon as they get wet. They are therefore not suitable for long-term or bigger plant growth. For seedling development, cardboard tubes from paper towels or toilet papers are being used.
- Clay Pots
  Plastic pots can also be substituted with clay pots, such as ceramic and terra cotta ones. They offer some advantages over plastic, such as making it easier for water to enter and exit the soil, and they also offer protection from sudden temperature changes. Clay pots are strong enough to support larger plants and additional soil. Because of this, they are beneficial beyond the seed-starting and seedling phases of plant development. The drawbacks of clay pots are they are very heavy to carry and it is even harder to drill drainage holes for plants.
- Coir Pots
  Coconut hull, a fibrous mass found between the coconut and its husk, is used to make coir pots. The roots of the plant can breathe easily in coir pots, which keeps the plant fresh and promotes greater growth, and can be kept inside any pots, allowing the soil to breathe and the roots to have sufficient airflow.
- Rice Hull Pots
  Rice hull pots are manufactured from rice hulls and natural binding agents, which are starch-based, water-soluble, and biodegradable. At no point during the manufacturing process are pollutants used or created. The pot maintains its shape and smooth surface until it reaches the end of its useful life. Decomposition won't begin until the waste is disposed of in a municipal compost or landfill. They will decompose into pH 7.0 organic debris that is rich in nutrients [8].
- Peat Pots
  All kinds of vegetables and flowers can be started in peat pots, which are constructed from a compostable blend of peat and wood. They are perfect for tiny seedlings with delicate roots, like cucumber and okra plants, which can be challenging to transplant.
- Cow Pots
  A seed-starting container constructed in the United States utilizing composted cow manure is called a "cow pot." Once planted, cow pots decompose more quickly than peat pots and have shown to have better root penetration than other biodegradable pots [9].
- Wood Fiber Pots
  Fiber pots are biodegradable and constructed from recycled materials. By encouraging airflow around plant roots and preventing plants from becoming root-bound, they increase aeration. Fiber pots protect the roots and keep them safe from sudden changes in temperature. Additionally, they prevent decay by draining extra water.

- Biodegradable Plastic Pots
  Pots made of biodegradable plastic granules entirely break down in the soil to produce biomass, CO_2, and water. It can survive up to 18–24 months, but when composted, they decompose in less than 6 months.
- Feather Pots
  Another agricultural waste item is feather pots. Each year, US poultry growers produce around 4 billion pounds of chicken feathers. The feathers can be ground into light, strong pots that can be composted after use and are a clean, sustainable supply of the protein keratin.
- EnviroArc
  It is manufactured from organically cultivated materials including bamboo pulp, rice hulls, wheat straw, and corn stalks. These pots survive 18–24 months, but when composted, they decompose in less than 6 months. They have a huge selection of sizes and colors [10].

5 Benefits of Eco-Pots

- Sustainable alternatives to plastic pots.
  The plastic planters we purchase for our plants are frequently disposed away in landfills since many of them cannot or will not be recycled. Biodegradable plant containers decompose over time and may even replenish the soil with nutrients. As a result, less waste will end up in landfills, saving the environment.
- Eco-pots are plant friendly.
  Plant pots made of biodegradable materials may encourage strong root development in plants. Since the plant pots are directly introduced to soil, the transplantation procedure is much easier and no damage is caused to the plant roots.
- Cost-effective
  Eco-pots are more affordable than plastic pots. One can create eco-pots with any waste material like paper, leaves, upcycled textile materials, etc. According to one's creativity, eco-friendly pots can be made and used indoors as well as outdoors (Fig. 2).

6 Plastic Usage in Agriculture

Plastics have expanded throughout the world since their introduction in the 1950s. The broad definition of agriculture includes the development and production of plants and animals for human consumption, whether as food to support a growing world population or as fibers, fuels, or medicines. To increase production, modern agricultural operations use a variety of plastic goods, including the following:

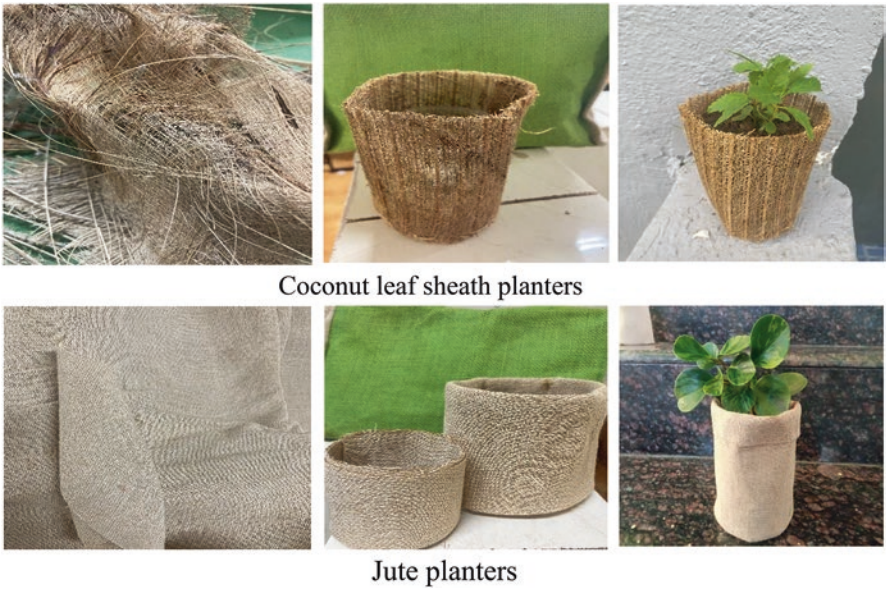

Fig. 2 Eco-planters

- Plant protectors: to prevent animals from harming young seedlings or saplings and to create a microclimate that promotes growth (such as tree guards in forestry)
- Fruit covers and protectors: nets, sacks, and sheaths that are occasionally infused with insecticides to shield fruit from weather and insect harm
- Mulch films: to promote plant development while reducing weed growth, evaporative water losses, pesticide, fertilizer, and irrigation needs
- Nonwoven fabric for protection, such as “fleece,” to shield crops from intense heat or cold
- Tunnel and greenhouse films and nets: to protect and promote plant growth, lengthen the growing season, and boost yields

When plastics near the end of their intended life span, the qualities that make them so helpful also cause issues. Plastic sorting and recycling are made more challenging by the variety of polymers and additives integrated into them to achieve optimal characteristics. Since plastics are man-made polymers, only few microbes can effectively degrade them [11].

7 Eco-Pots as a Plastic Substitute: A Realistic Alternative?

Although some of the more well-known peat and paper pots have been available for more than 50 years, the greenhouse and nursery industries have not yet adopted eco-pots in their entirety. The world is realizing that plastic should not be used. Plastic bags continue to clog landfills and cause contamination issues in many countries, so many have banned them for the sake of public health and the environment.

Because of their hazardous nature, more and more cities and countries around the world are substituting eco-friendly alternatives for plastic bags. Jute is one such material. Jute is biodegradable and compostable, unlike plastic. Jute has gained popularity over the years due to its reusability, low cost, durability, and porosity. It has natural UV protection and grows without the use of fertilizers or pesticides. The pots are biodegradable and recyclable. Jute is a renewable material and matures within 4 to 6 months which therefore makes it sustainable.

8 Future Trends and Challenges

Massive volumes of nonrenewable, petroleum-based polymers that are rarely recycled are used in modern agriculture. These materials must be replaced with environmentally friendly, biodegradable ones that can lessen the harmful effects. In particular, pots, containers, and seed trays make up a large portion of the plastic materials used in agriculture, and biodegradable substitutes are rapidly gaining market share. Eco-pots have various benefits for the manufacturer, including minimal cost, less effort on the farm, and no waste because they are planted with the seedling or young plant and immediately biodegrade in the soil.

One of the challenges of eco-pots is its esthetics when they are in the hands of the consumer. According to research, some eco-pots are more prone to algae and fungus growth, which may have a significant impact on consumer demand for these goods.

Genuinely sustainable products must also be commercially viable, socially acceptable, and environmentally sustainable. Eco-pot feasibility from an economic and environmental standpoint has not yet been thoroughly determined. The green marketing appeal of eco-pots will essentially turn into greenwashing or the false depiction of a product as being environmentally beneficial, if it is discovered that they are less environmentally benign than their traditional plastic equivalents [12].

Prices for greenhouse and nursery containers will continue to be determined by the constrained availability of petrochemicals for traditional plastic containers and the growing demand for petroleum globally (U.S. Energy Information Administration, 2013). Consumer interest in and awareness of the environmental impact of the green industry are also rising. Pressure from the economy and society to use less plastic and adopt more sustainable production methods will thus only grow. To meet the demands of their businesses and customers, the green industry must take into account increased reuse and recycling of plastic items as well as containers made of alternative materials [13].

We still don't completely understand the economic and environmental sustainability of alternate containers, including the carbon and water footprints connected to their production, transportation, and use. Alternative container uses should be considered against prospective difficulties, related losses brought on by the deterioration of container integrity over time, as well as other higher expenditures (e.g., increased water usage and energy requirements of industrial composting). Alternative containers that are impregnated with various ingredients, such as natural color, slow-release fertilizers, fungicides, insecticides, and plant growth regulators that are released during plant growth, are recently entering the market and may improve the effectiveness of production systems. Researchers, companies in related industries, and members of the green industry must continue to collaborate to create and perfect environmentally friendly alternatives to present manufacturing methods that are also commercially viable.

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An Alternative Fiber Source in Sustainable Textile and Fashion Design: Cellulosic Akund Fibers

Ece Kalayci, Ozan Avinc, and Arzu Yavas

Abstract Akund fibers are natural cellulosic fibers classified as seed fibers such as cotton, kapok, and milkweed. Akund fibers, which have structural and physical properties very similar to fibers such as kapok and milkweed, are a commercially widespread type. It stands out among natural fibers with its hollow fiber structure and low fiber density. It is accepted as a sustainable raw material source with features such as renewability, biodegradability, eco-friendly, nontoxicity, and similar features. The hollow structure of akund fibers, whose spinnability is weak as experienced in kapok and milkweed fibers, makes these fibers an important fiber source for advanced materials such as home textiles, composite textiles, and technical textiles. At the same time, studies on the development of the spinning properties of these fibers can be considered as an evidence of the potentiality of these fibers to be used as raw materials for the garment industry shortly. In this chapter, it is aimed to benefit future studies by summarizing the structure, properties, and utilization areas of akund fibers.

Keywords Akund fiber · Akund floss · *Calotropis gigantea* · *Calotropis procera* · Natural fiber · Sustainable textile · Hollow fiber

1 Introduction

Textile and fashion design often evoke the characteristics of visual concerns, such as the shape, color, or pattern of a product. Although visuality plays an important role in designing a product, designing a product also includes environmental and social responsibilities. Especially with the introduction of the sustainability concept into our lives, this concept has become a parameter as important as visuality in

E. Kalayci · O. Avinc (✉) · A. Yavas
Textile Engineering Department, Faculty of Engineering, Pamukkale University, Denizli, Turkiye
e-mail: oavinc@pau.edu.tr

S. S. Muthu (ed.), *Novel Sustainable Raw Material Alternatives for the Textiles and Fashion Industry*, Sustainable Textiles: Production, Processing, Manufacturing & Chemistry, https://doi.org/10.1007/978-3-031-37323-7_10

many areas. Sustainability is based on the necessity of today's generation to meet the requirements of future generations without compromising the requirements in a system that includes the efficient use of natural resources, environmental order protection, and economic growth [1–5].

The textile industry, which is one of the largest industrial areas in our planet, has a huge responsibility for creating a sustainable future. Many small and large companies seek to develop different solutions to raise awareness about sustainability and contribute to sustainable production. Bringing sustainable technology and methods to the textile industry, reducing the environmental burden of existing technologies and methods, using clean energy sources, etc. are among the studies carried out to make the textile industry more ecological [6–14].

Although most of the textile industry's raw material needs are met with petroleum-based synthetic fibers, the number of efforts to enhance the utilization of natural fibers or biodegradable synthetic fibers is increasing day by day [15–24]. The use of recyclable, reusable raw material sources that do not harm nature can be considered as one of the most basic methods that can be applied in sustainable textile and fashion design [1, 4, 5].

With increasing awareness in the society about environment-friendly production and sustainability concepts, it is observed that demand from the society is shifting toward products that use more natural materials, are exposed to fewer chemicals, and even harm the environment during production. Just for this reason, it is observed that the demand for products produced from organic cotton, in which chemical pesticides are not used, instead of cotton fibers, which are the most broadly used natural fiber type in textile, has increased significantly [2, 25].

As an outcome of the fast-changing fashion, growing world population, consumption habits, and limited efficiency in recycling, etc. methods, fiber demand in the world is increasing every year [26–28]. It seems possible that the demand, which is 100 million tons today, will reach 140 million tons in 2030 if the current rapid increase continues [29].

According to the recorded data, 100 million tons of fiber were used in 2018. Fifty-five million tons of this consumption is polyester, 26 million tons of cotton, six million tons of cellulosic, five million tons of nylon, two million tons of acrylic, and one million tons of wool [29].

Synthetic fibers constitute the fiber group with the highest usage rate in the textile industry. Recycling or recycling these fibers is very important in terms of reducing the environmental burden in textile production [26–28]. Otherwise, it creates an ever-increasing environmental burden and harms nature globally. Unfortunately, according to 2018 global fiber consumption figures, the share of recycled polyester among 55 tons of polyester consumption remains at 20,000–30,000 tons [29]. Tons of textile waste mountains have already been formed, and this situation will inevitably bring sad results if permanent solutions are not developed.

In addition, when we look at the total fiber consumption figures in the world, it is observed that the amount of natural fiber production is at very low levels next to the raw material need of the textile industry. Dissemination of natural fiber types that could be an alternative to synthetic fibers according to their usage areas is of great importance in environmentally friendly textile production.

The amount of natural fiber production carried out today is very low in addition to the raw material need of the textile industry. For this reason, natural fiber types that could be an alternative to existing raw material sources and the dissemination of production of these fibers are investigated.

Textile fibers obtained from agricultural wastes such as pineapple, banana, coconut, and raffia fibers can be evaluated as alternative textile fiber sources [30–32]. However, the majority of fiber sources obtained from agricultural wastes are included in the lignocellulosic fiber class. These fiber types, whose cellulose ratios are generally not very high, can be widely preferred especially as composite reinforcement fibers [33–35].

Akund fibers are a type of natural cellulosic fiber [36–40]. Akund fiber, which belongs to the class of seed fibers such as cotton and kapok fibers, exhibits very similar characteristics to kapok fibers in terms of both fiber structure and fiber characteristics [36, 40–46]. For this reason, it is possible to mix it with kapok fibers from time to time [41]. Akund fibers do not need any fertilizers and pesticides that may harm the environment during fiber production, unlike cotton fibers, and can be grown even in arid environments [47]. Therefore, they are nontoxic and abundant [35]. Akund fibers, which have a shiny appearance like silk and touch like cotton, are accepted as an alternative natural fiber type. In this study, detailed research on the structure, properties, and end-use areas of akund fibers is included.

To minimize energy and water consumption in the process steps of textile and fashion design, both textile industry employees and scientists devote significant time and budget to research. Since seed fibers such as akund, kapok, and milkweed are obtained from plants that grow naturally in nature and can be easily grown without the need for any pesticides, fertilizers, or even irrigation, they have become a promising textile material in regions with suitable climates for agriculture, especially in Asian countries. In some studies, akund fibers are described as a new ecological and cellulosic textile material with a great development potential [48]. In this chapter, it is aimed to benefit future studies by summarizing the structure, properties, and utilization areas of akund fibers. The next part of this book chapter will give information about the akund plant.

2 Akund Plant

Akund fibers are found in *Calotropis procera*, a member of the Asclepiadaceae botanical family [38, 41, 42, 49–52], and *Calotropis gigantea* [37, 38, 42, 47, 49, 51–56] plants. Akund fibers are fixed to the seed at one end and to the inside of a capsule-shaped fruit that surrounds the fibers at the other end [37, 52, 53, 57]. When the fruit is fully ripe, the capsule opens, and the aquatic fibers surrounding the seeds in the capsule are easily dispersed by the effect of the wind, as in dandelion flowers [36–38]. The average length of the capsule before opening is 6 cm and its weight is around 0.04–0.10 g [52, 53]. A single seed in the capsule weighs approximately 4 mg and is 6 mm long [53].

Akund fibers can be easily grown in poor soil without the need for fertilizers and pesticides, especially in countries such as China (Guangdong, Guangxi, Hainan, Sichuan, Yunnan regions), India, Indonesia, Lagos, Malaysia, Nepal, Burma, Pakistan, Bangladesh, Senegal, Mauritania, Sri Lanka, Thailand, Brazil, Vietnam, Iran, and other countries with subtropical climates [37, 38, 40, 41, 47, 49, 53, 54, 56, 58, 59]. Its natural plantation is in regions up to 1300 m above sea level, in semiarid conditions with annual precipitation between 150 and 1000 mm [58]. Akund plant grows in sandy and heavily drained soils and is resistant to climatic changes and various soil textures [55, 58, 59].

It is stated that the akund fibers grown in India begin to bloom in January–March, and the harvest is carried out in April–May [54, 56]. Harvesting is mostly done manually several times depending on the maturation of the fibers [54]. Akund fibers are obtained as a result of drying and opening the capsules, provided that they are constantly turned upside down in the sun for about 3 days. Akund fibers obtained are known as cotton-like fibers with their white and shiny appearance [55, 56]. The quality of akund fibers is determined depending on the color, smell, moisture of the fibers obtained, and foreign materials such as seeds, dust, and soil mixed between the fibers [54, 55].

Akund plant (*Calotropis procera*) is a multipurpose plant species that are frequently used by traditional healers and the public in medicines prepared for the treatment of many diseases and disorders [55, 58, 60]. Both *Calotropis procera* and *Calotropis gigantea* species belonging to the Asclepiadaceae family have enormous disease prevention potential against various infectious agents such as bacteria, viruses, fungi, protozoa, and worms, as well as being widely used in the treatment of different diseases and psychological disorders [58]. In the next section, information about akund fibers and their structure are given.

3 Akund Fibers and Their Structure

Akund fibers, also known by different names such as “akund silk,” “akund floss,” or “calotropis” [42, 49, 55, 56], are a single cell fiber [36, 42, 53, 54, 57]. These fibers, which have a thin wall, have a large space in the form of a long tube filled with air [38, 39, 61]. Akund fibers can be identified with large internal cavities and surface hydrophobicity [62]. This gap in the fiber structure constitutes 80% of the fiber [36, 38, 57]. The fibers are untwisted and in the form of straight strips [54]. The fiber cross section of akund fibers varies between 12 and 42 microns whose fiber length varies between 2 and 4.5 cm [42, 54, 57, 61, 63]. The linear density of the fibers is around 1 dtex [57]. The wall thickness of the fibers is 1.4–4.2 microns [54]. Akund fibers have good biocompatibility [39].

In proportion to the similarity between the kapok plant and akund plant, there are also great structural similarities between akund fibers and kapok fibers [56, 64]. Both fiber types are hollow, thin cell-walled, soft, shiny, warm feeling, light, and weak-strength fibers [65–67]. Their images under the microscope are also quite

Table 1 Comparison of akund fibers with similar seed fibers [35, 53, 61, 63, 64, 68–70]

	Akund	Kapok	Milkweed
Cellulose	55.45	35–65	52–55
Hemicellulose	21.91	22–45	24
Lignin	16.15	13–22	18–21
Pectin	0.32	0–23	0–4
Wax	4	2–3	1–2

Table 2 Comparison of akund fibers with similar seed fibers [38, 57, 69–71]

	Akund fiber	Kapok fiber	Milkweed fiber
The breaking strength (cN/dtex)	3.42	1.4–1.7	3.3
Elongation at break (%)	2.6	1.8–4	3
Moisture regain (%)	13.5–13.8	0–11	9.6–11.1
Density (g/cm^3)	0.9–1.1	0.4	0.97

similar to each other. However, the netlike thickening mainly observed in kapok fibers is not visible in akund fibers [42, 56, 65, 66].

The amount of crystalline region contained in akund fibers, which contain more lignin compared to kapok fibers, is around 28.92%. Akund fibers, which have a nice touch like cotton, also have a nice shine like silk fibers [38, 61, 63]. The majority of studies show that akund fibers exhibit better mechanical properties than kapok fibers [57].

In Table 1, the structural characteristics of akund fibers and cotton fibers and kapok fibers are compared. Akund fibers can be accepted as one of the lightest known natural fibers with a density of 0.90–1.14 g/cm^3 [29, 53, 57] (Table 2).

4 Properties of Akund Fibers

4.1 Mechanical Properties

The breaking strength and elongation at break of akund fibers are higher than kapok fibers, but these values are lower when compared to cotton fibers [57, 71]. The breaking strength of the akund fibers (dry form) was reported as approximately 3.42 cN/dtex [57, 71] (Table 2). With the enhancement in the amount of relative humidity in the air, an increase is observed in the breaking strength of the akund fibers [57]. This can be attributed to probable alterations in the interaction between large molecular chains as an outcome of water molecules penetrating the fiber structure. The water absorbed by the akund fibers causes the unevenness of the macromolecules to increase. It has been observed that the elongation percentage at break of dry form akund fibers was recorded as 2.6 on average [71]. The compressive-resilient property of akund fiber as wadding fiber exhibits satisfactory values [71].

4.2 Moisture Regain

The moisture regain of akund fibers is around 13.5–13.8% [38, 57, 71], which is higher than that of cotton fibers [38]. While akund fibers exhibit a quick moisture release feature, the moisture absorption performance of these fibers is slow [38]. The initial rate of moisture release of akund fibers is higher than that of cotton fibers, akin to that of kapok fibers. However, the initial rate of moisture absorption is quite low [71].

In addition to exhibiting structural similarities with kapok fibers, there are also similarities in their moisture absorption properties. Their ability to absorb and release moisture is similar to that of akund fibers and kapok fibers. Under standard conditions, the moisture content of akund fibers is slightly higher than that of kapok fibers [61].

4.3 Antibacterial Activity of Akund Fibers

It was determined that Li et al. 2019 [71] evaluated the antibacterial activity of akund fibers; however, akund fibers did not exhibit any antibacterial properties against *Staphylococcus Aureus* [71].

4.4 Spinnability of Akund Fibers

Owing to the low cellulose content of akund fibers, the spinnability (ability to be spun into yarn) is low [40, 42, 72]. In addition, the hollow structure of the fibers and the fact that this hollow structure is 80% make the fibers lighter and brittle, which negatively affects the spinnability of the fibers [72]. However, during the formation of yarn, there must be sufficient frictional force between the fibers forming the yarn so that the strength of the formed structure should be sufficient to maintain the yarn structure. However, it is very difficult to provide sufficient friction force within the yarn structure due to the smooth fiber surface of akund fibers [47, 72]. For this reason, it is preferred that these fibers are spun as a mixture rather than spun alone. It is also possible to increase the friction force between the fibers by treating them with $CaCl_2$ or glycerol before the spinning process [47].

Moreover, it has been noted that sizing agents such as polyvinyl alcohol (PVA) and acrylate and their mixtures at different rates can be used to enhance the spinnability of akund/cotton blended yarns and to prevent loss of strength, breakage, and similar physical damages that may occur during spinning [73].

Separation of akund fibers from the capsule can be performed using the airflow method [72]. It is probable to obtain high-quality fibers from these fibers by using new carding wires. To reduce the number of short fibers and neps, the combing length (width) during combing should be longer than the length of the akund fibers. Cotton/akund fiber blended yarns can be successfully spun at 18.45 tex fineness at 40/60 or 33/67 blend ratios [74, 75]. Cotton/akund blended compact yarn shows less hairiness and more advanced mechanical characteristics. However, there are some difficulties while weaving these blended yarns, and there is no model developed to solve these difficulties [47, 74, 75, 76]. The difficulties experienced during the weaving process are generally due to the low strength, high hairiness, and poor abrasion resistance of the yarns. To alleviate the effects of these weak features on the weaving process, it is necessary to develop an appropriate sizing process [47].

4.5 Pretreatment Processes of Akund Fibers

Akund fibers are fibers with high potential for use both in textile products and as fiber reinforcement in composite structures. During their use in these application areas, various pretreatments or treatments with chemicals may occur. Changes in fiber structure, fiber content, and fiber performance properties as an outcome of pretreatment processes of akund fibers are of great importance. For example, in a study examining the change in fiber characteristics as a result of pretreatment of akund fibers with sodium carbonate, as a result of the process, it was noted that the amount of noncellulosic material in the fiber structure decreased, but no significant change was observed in the chemical content. In addition, it was reported that the roughness on the fiber surface increased, and the fiber strength and fiber weight were lost, while the elongation values at the break of the fiber enhanced slightly [37].

In a study investigating the usability of akund fibers in the composite structure, akund fibers were pretreated with 15% NaOH solution for 1 h. It has been reported that mechanical characteristics such as flexural strength and tensile strength of the composite structure were improved after alkali treatment and akund fibers can be an economical and environmentally friendly alternative to synthetic fiber composite structures [35]. In the next section, information about the utilizations of akund fibers are given.

5 Uses of Akund Fibers

The usage areas of akund fibers are mostly common with kapok and milkweed fibers, where they exhibit similar properties. However, its commercial use in textile products is not very common. As a result of research on sustainable testis products and production methods, akund fibers can be accepted as an ecological, renewable, biodegradable raw material source [77]. Many products match the fiber structure and performance characteristics of akund fibers and can be designed by benefiting from the characteristics of these fibers. The current and potential uses of akund fibers are summarized in Table 3.

Table 3 Current and potential uses of akund fibers

Uses	References
As for filling material	[42, 50, 60, 78]
As insulation material	[42, 79]
As fiber reinforcement in composite materials	[33–35, 39, 51, 80–83]
Biological templates for advanced materials	[62, 79]
Home textiles and clothing in blended yarns	[54, 57, 75]
Fishing nets and ropes	[63, 78]
Oil sorbent materials	[62, 84–87]
Supercapacitors	[88]

Various information is available in the literature for the ability of akund fibers to float in water and their water resistance [42, 57, 70]. It was stated that although akund fibers exhibit similar properties with kapok fibers, it is not possible to use these fibers as fillers in materials such as life vests, since the ability to float on and resist water is low [42]. However, in different sources, it is stated that akund fibers can be used as fillers in glass rescue vests and life buoyans, and even in India, these fibers are used in fishing nets and fishing line threads [54, 89]. It has been noted that in Rajasthan and its environs in India, akund fibers are utilized in the manufacturing of ropes and similar materials and that it is stronger than hemp (sun hemp) and can replace it (more on that in the source) [49].

Akund fibers can be used in the production of thick yarns in a mixture of cotton fibers [54, 74, 75]. Studies conducted in recent years have proven that yarns that can meet the basic properties of akund/cotton fiber blend yarns that can be used in home textiles and clothing can be developed. In addition, studies to improve the usability of these fibers continue [57].

There are also studies aimed at improving the spinnability of akund fibers [90]. In these studies, it was aimed to improve the spinnability of the fibers and to expand their usage as yarn or fabric both in the textile industry and in other industries [90].

The usage of natural fibers in fiber-reinforced composite materials has become widespread in recent years, and various natural fiber types are being researched especially to produce composite structures with improved economic and performance properties [33, 83]. For the composite structure to be strong and durable, the moisture-absorbing properties of the fibers to be used in the structure should generally be good. Akund fibers have a very high ability to absorb moisture [81, 82]. In this context, the utilization of akund fibers as fiber reinforcement in composite structures is among the current research [33, 34, 82, 83].

In addition, the hollow structure, biocompatible character, and very lightness of akund fibers make these fibers a very important fibrous material option for many industrial areas, especially the defense industry. They are suitable for use as a template that can carry various nanomaterials to perform special functions [62]. For example, the development of conductive biocomposites has been made possible with the help of various metal particles [zirconia (ZrO_2)] or conductive chemicals such as polypyrrole [39, 79]. As a result of impregnation with zirconia (ZrO_2) by using akund fibers as a template, fibers that provide thermal barrier can be obtained with the highest thermal stability and the lowest thermal conductivity properties of zirconia [79]. In another study, carbon dot (CD) loading was applied in the inner cavity and fiber surface of the akund fibers to gain fluorescence properties. At the same time, it is aimed to gain antibacterial properties by synthesizing silver nanoparticles in the fiber [62].

Many studies describe akund fibers as materials with superior oil absorbing performance [62, 84–87]. It has been noted that various chemicals can be loaded on the fiber surfaces of akund fibers as catalysts and water treatment agents. However, in these studies, since the chemical loading is only on the fiber surface, it shows easy shedding and weak stability. Therefore, the resistance to washing (washability) is very limited [62].

6 Sustainability Potential of Akund Fibers

Since akund fibers are not a commercially common fiber type, detailed life cycle analysis, carbon footprints, water footprints, CO_2 emissions, and similar studies have not yet been conducted for sustainable analysis of these fibers, both in industry and academia. Akund fibers are believed to have very similar structures in both their chemical and physical properties and are very similar to kapok and milkweed fibers in their effect on the environment [36, 40–46]. The natural, nontoxic cellulose structure of these fibers, their renewable and biodegradable nature [77], and the fact that no fertilizers or pesticides are required for their cultivation [2, 25] and that they can be easily grown even in dry soils [91] support the potential of sustainable natural resources. It is believed that it can be an alternative to kapok and milkweed fibers, which are often preferred as sustainable natural fiber sources and have gained popularity among natural fiber sources in recent years.

7 Conclusion

With the introduction of the concept of sustainability into our lives, there are great changes like reform both in our daily consumption habits and in the decisions taken on an industrial scale. Considering the depleted and polluted resources, these changes, which have become mandatory, reveal the necessity of considering every step to be taken industrially, every decision to be made, and the results to be calculated in detail. In industrial production, especially in sectors with a high environmental burden such as textiles, from raw material selection to methods and technologies, energy consumption, and water consumption values, features such as post-use recyclability or biodegradability are of great importance.

In the textile industry, which is dominated by synthetic fibers, recycling rates are unfortunately very low when compared to fiber consumption rates, and this causes increasing garbage mountains and serious pollution every year. For this reason, the utilization of natural fibers and the use of biodegradable, renewable, environmentally friendly fiber types are preferred, especially in production areas where sustainability is at the forefront. New generation natural fiber sources have an important potential at this point. Akund fibers have become an important fiber type for both daily textile products and advanced technical textiles, which have come to the fore in recent years. They are considered as ecological fibers with features such as renewability, biodegradability, nontoxicity, not needing any pesticides, etc. during production. With its hollow fiber structure and low density, it creates an important potential for advanced materials. Akund fibers, which we do not encounter very often in textile structures due to their low spinnability, are thought to be used in much wider areas soon, with research aiming to improve their spinning properties. Considering the recent development in the use of kapok and milkweed fibers, which are very similar both in structure and properties, it is anticipated that akund fibers will undergo a similar popularity process. The use of fibers as a template, especially in the design of materials with an advanced hollow structure, and their utilization as natural fiber reinforcement in composite materials have as much potential as the textile fashion industry and home textile products.

This study was aimed to shed light on future studies by summarizing the structure, properties, usage areas, and potentials of akund fibers obtained from the literature. Considering the research, akund fibers create an important raw material potential for technical textiles, the garment industry, and home textile. One of the most important reasons for the spread of these fibers is that the natural structure and eco-friendly properties of these fibers support sustainable textile production.

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