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Cotton in the new millennium: Advances, Economics, Perceptions and Problems

Muhammad Tausif^{1*}, Abdul Jabbar², Muhammad Salman Naeem², Abdul Basit², Faheem Ahmad², Thomas Cassidy^{1#}

¹School of Design, University of Leeds, Leeds, UK

²Faculty of Engineering & Technology, National Textile University, Faisalabad, Pakistan.

Corresponding authors: *M.Tausif@leeds.ac.uk, #T.Cassidy@leeds.ac.uk

ABSTRACT

Cotton is the most significant natural fibre and has been a preferred choice of the textile industry and consumers since the industrial revolution began. The share of man-made fibres, both regenerated and synthetic fibres, has grown considerably in recent times but cotton production has also been on the rise and accounts for about half of the fibres used for apparel and textile goods. To cotton's advantage, the premium attached to the presence of cotton fibre and the general positive consumer perception is well established, however, compared to commodity man-made fibres and high performance fibres, cotton has limitations in terms of its mechanical properties but can help to overcome moisture management issues that arise with performance apparel during active wear.

This issue of Textile Progress is structured into four sections in line with following objectives:

- i) To focus attention on the advances in cotton cultivation and processing as well as improvements to conventional cotton cultivation and ginning. The processing of cotton in the textile industry from fibre to finished fabric, cotton and its blends, and their applications in technical textiles are also covered. (The review will not, however, focus great attention on nep reduction apart from reference to the recent Textile Progress about this issue [12] and advances in testing methods will not be covered in any detail).
- ii) To explore the economic impact of cotton in different parts of the world including an overview of global cotton trade and key economies.

- iii) To examine the environmental perception of cotton fibre and efforts in organic and genetically-modified cotton production. The topic of naturally-coloured cotton, post-consumer waste is covered and the environmental impact of cotton cultivation and processing are synthesised.
- iv) To critically analyse the problems associated with textiles containing the cotton fibre; for example, improving wrinkle recovery and reducing the flammability of cotton fibre requires additional finishing of the cotton products. Hazardous effects of cultivation, such as the extensive use of pesticides, insecticides and irrigation with fresh water, and consequences of the use of genetically-modified cotton and cotton fibres in general on the climate are summarised and the effects of cotton processing on workers are addressed. The potential hazards during cotton cultivation, processing and in use are also included.

KEYWORDS: Cotton fibre, cultivation, cotton processing, cotton trade, economic impact, environmental perception, post-consumer waste, genetic modification, naturally-coloured cotton, hazards.

1 Introduction

There have been many reviews produced in previous years that have focussed on particular aspects of cotton production and end-use, but this review takes a holistic approach rather than a specialised or particularised approach. To achieve this aim we have used a wider choice of contributors and referred the reader to previous Textile Progress reviews that have focused on specific areas. We have tried to cover the literature published since the year 2000 though the reader might find a small number important or seminal papers from before that date. Students, researchers and producers should therefore be able to identify the state of the art regarding cotton fibre, yarn and fabric production and its effects on the social and economic issues across the globe and perhaps identify gaps in the research which should be filled.

The geographic shift in cotton growing and the impact of cotton on economies around the globe are covered. One such example is Australia, which now has a 4% share in world cotton fibre production and is the third largest exporter of cotton fibre. By contrast, in Bangladesh, which does not grow cotton, the value-added industry has been established making it the world's largest

cotton importer and the world's second largest exporter of ready-made garments. A similar approach is taken by Vietnam, which, like Bangladesh, is one of the leading exporters of textile and apparel and one of the key importers of cotton.

1.1 *Cotton spinning's comeback to UK*

Historically, it was the UK that was home to cotton spinning on an industrial scale with the first mills being established in the 1740s. The dominant global position held by the UK as a cotton-producing nation started to fall after the turn of the 20th century and its decline became almost complete by the 1970s.

There is, however, growing interest in bringing production back (re-shoring) to developed countries for both economic and sustainability reasons, although it remains to be seen whether much significant reshoring will take place in the near future. Even so, such interest as there is has recently been put into practice through the commissioning of a new cotton spinning mill in the UK to produce fine cotton counts at English Fine Cottons (EFC) (Figure 1). Their state-of-the-art cotton spinning began as a commercial entity in October 2016 within a refurbished Victorian cotton mill in Dukinfield near Manchester at a cost £5.8 million. The financial package provides an indication of the range of support behind this particular reshoring venture: EFC invested £4.8 million including a loan of £2 million from Greater Manchester Combined Authority and £1 million was awarded by the N Brown Textile Growth Programme. The programme was driven by Lord Alliance and was funded from the UK Government's regional growth fund. It is important to mention that this was the first cotton spinning to be established in the UK for more than 50 years, and in a building that was first used for cotton spinning in 1886 when it was home to around 44,000 spindles. The current capacity is 7,200 spindles with plans to expand to 12,000 spindles (Figure 2) supported by demand for the mill's products from its customers.



Figure 1. The English Fine Cottons Mill

Beyond the commercial aspects, the mill has had strong social impact by reviving the traditional industry and causing emotional pride in the people, reshoring manufacturing and creating jobs (including opportunities for highly skilled professionals). The impact has already been evident by the extensive media coverage and letters of support by the general public and dignitaries including member of the royal family. The mill aims to provide value to the local textile supply chain and provide customised cotton yarn products to local industry and entrepreneurs. Having being planned to produce high-quality compact-spun combed yarns in the count range of 60 Ne to 150 Ne (10 Tex to 4 Tex), the mill now makes luxury grade yarns spun from extra-long staple (ELS) cottons including Californian Supima®, Indian Suvin Gold and West Indies Sea Island Cotton. American Pima is the most commonly cultivated ELS cotton, grown in large-scale plantations in California and the southern US states where it is usually machine harvested, and because supplies of the most luxurious, hand-picked varieties are limited, the bulk of the raw material at EFC is American Pima (Supima®). In 2017, English Fine Cottons relinked the local cotton supply chain to produce a shirt from their cotton yarns in partnership with Blackburn Yarn Dyers (BYD), John Spencer Textiles Ltd and Private White VC. Its small size and lack of organisation in the UK textile industry poses challenges to further growth of the UK's textile manufacturing in this manner. Championing by Lord Alliance and local government officials has been most helpful but the emergence of new champions, who will be listened to by the UK

government, is not clearly evident, but English Fine Cottons have now demonstrated that producing a high quality product with focus on responsible sourcing and adding value to the existing supply chain can begin to revive cotton spinning in the UK.



Figure 2. Compact Spinning Ring Frames at English Fine Cottons

2 Economics of cotton industry

2.1 Global Cotton Trade

2.1.1 Historical data on cotton production and consumption

Despite a trend towards increasing the use of man-made fibres in an ever widening range of applications since the 1960s and 1970s, cotton is still the most important natural fibre around the globe. More than 100 countries are growing cotton, of which China, India, the US, Pakistan and Brazil are the leading cotton producers of the world. The world's cotton production and consumption from 2009 to 2017 are given in Tables 1 and 2 respectively [1,2]. The percentage share of major countries in the world's cotton production and cotton consumption is shown in Figure 3 and Figure 4 for 2017/18 [3].

Table 1. World Cotton Production (Million Bales)

County	2009	2010	2011	2012	2013	2014	2015	2016	2017
China	32.0	30.0	33.5	30.5	32.8	30	22	22.8	27.5
India	23.2	26.0	27.5	26.5	31	29.5	25.9	27	28.5
USA	12.2	18.1	15.6	17.3	12.9	16.3	12.9	17.2	21.3
Pakistan	9.6	8.8	10.6	9.3	9.5	10.6	7.0	7.7	8.2
Brazil	5.4	8.2	8.6	6.0	8.0	7.0	5.9	7.0	8.0
Uzbekistan	3.9	4.8	4.0	4.6	4.1	3.9	3.8	3.7	3.7
Australia	1.8	4.0	5.5	4.6	4.1	2.3	2.9	4.1	4.4
Tajikistan	0.38	0.41	0.58	0.56	0.45	0.49	0.41	0.55	0.53
Kazakhstan	0.34	0.27	0.37	0.41	0.34	0.24	0.20	0.30	0.29
Turkmenistan	0.15	0.17	0.15	0.17	0.15	0.15	0.14	0.13	0.14

Table 2. World Cotton Consumption (Million metric tons)

County	2009	2010	2011	2012	2013	2014	2015	2016	2017
China	9.6	10.9	10.2	8.3	7.5	7.4	7.6	8.2	7.7
India	3.9	4.2	4.5	4.2	5.1	5.3	5.4	5.2	5.2
Pakistan	2.4	2.4	2.4	2.2	2.3	2.3	2.2	2.2	2.2
Turkey	1.1	1.3	1.3	1.2	1.3	1.4	1.5	1.4	1.4
Bangladesh	0.8	0.8	0.8	0.8	1.2	1.3	1.4	1.5	1.5
Vietnam	0.4	0.3	0.3	0.5	0.70	0.9	1.0	1.2	1.38
United States	0.8	0.8	0.8	0.7	0.8	0.8	0.8	0.7	0.6

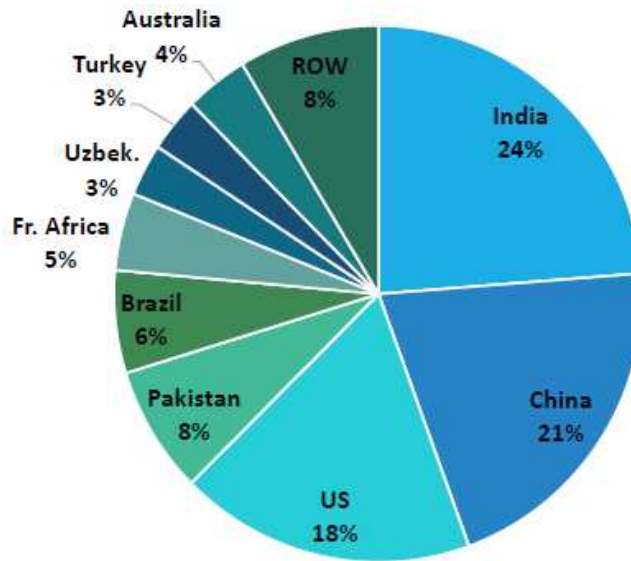


Figure 3. World Cotton Production % in 2017/18

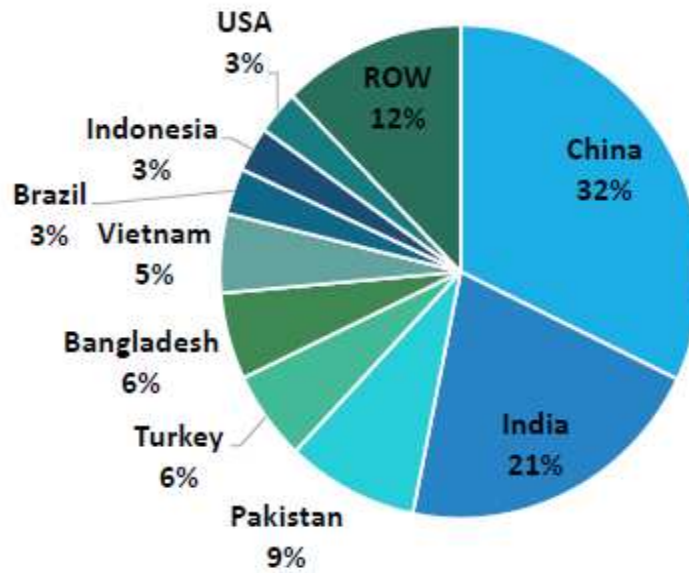


Figure 4. World Cotton Consumption % in 2017/18

2.1.2 Cotton pricing strategies

Real cotton prices, taking inflation into account, fell by 45 percent over a period of around 50 years – from more than \$3.00/kg in the 1960s to \$1.73 in 2014 [4]. Cotton price mainly depends upon the cultivated area on which cotton is grown. One can say that if a farmer is not getting the

right price for his crop then the cultivation of cotton in his area may have been poorer than in the previous year and consequently the price of cotton will fluctuate. Taking a slightly different perspective, cotton production decreased in 2016 by 19% which was the lowest since 2002. The low price of cotton was the major reason behind it and there was a consequent decline of 9% in cotton cultivation area in 2016. Also, the available varieties of cotton, demand and consumption of cotton by textile mills, the quality of lint and accurate information on the price of cotton set the price in the world market [5].

Of the above factors the demand of cotton from textile mills is the most crucial one because it decides how much cotton and of what type is required for certain textile products; such demand mostly brings about variations in the price of cotton in a specific region. For different types of textiles, mills require different varieties of cotton, so the quality and price of a specific textile product determine the price to be paid for the raw cotton.

The different varieties and qualities of cotton also help to determine their prices as the variety and quality of fibres play a vital role for the end product with desired functions and properties. The grade of cotton, which mainly represents the mean staple length of cotton fibres, their fineness, moisture content and the strength of the fibres plays a major role in determining the market price of the cotton. Ginning of cotton also plays a vital role in pricing. Over-ginning detrimentally effects the quality of cotton lint by damaging the cotton fibres, reducing the fibre length and potentially the efficiency of a textile mill, which ultimately causes a lowering of the cotton price.

The fall or rise in cotton price is directly linked with the availability of cotton in a specific region. If the cotton crop yield remains constant in a cotton season, then prices will also be constant. Sometimes stocking of the cotton on a large scale creates uncertainty in specific areas which ultimately effects the cotton price. For example, due to increased world cotton stock outside of China, prices declined by up to 33% in the last four months of the 2016 season as compared to the first eight months; cotton pricing/buying strategy must therefore be developed by taking account of these aspects as well.

Another important factor which determines the price of cotton is the availability of true information on the price of raw cotton around the world. Many analytical techniques are used to

report the true price of cotton and satellite communication has significantly improved the level of information available for prices of cotton [6-8].

2.1.3 Key cotton economies

China, India, USA and Pakistan produce close to three quarters of the world’s cotton and China, India and Pakistan are responsible for consuming more than 60% of the world’s cotton (Figure 3 and 4) showing only slight changes from 1989 to 2010 (9). The global area of cotton planting is divided usually into two regions, the Northern Hemisphere and the Southern Hemisphere [8]. From 2000 onward, 85 to 89% of world cotton was produced in the Northern Hemisphere and the rest was grown in the Southern Hemisphere. The share of the Southern Hemisphere had been 6% to 8% up until 2009 but the prices were then adjusted which caused an increase in planting of cotton in the south and consequently the share of the Southern Hemisphere rose to reach 11%. Figure 5 represents the world cotton area by hemisphere and yield to date. China was the world’s largest grower of cotton until 2015/16 but India became the leader in 2016/17 [10,11].

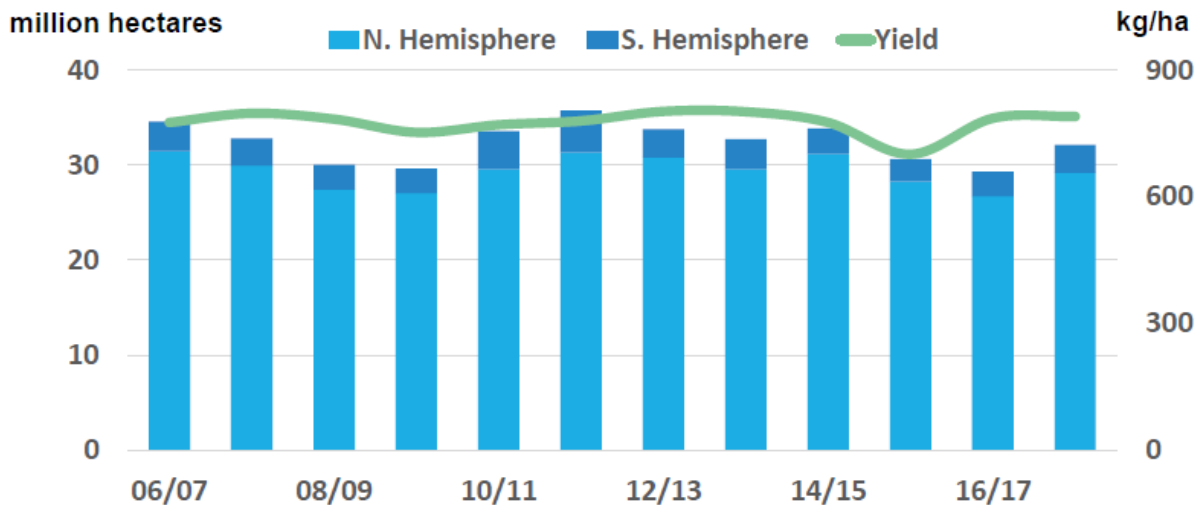


Figure 5. World Cotton Area and Yield

It is estimated that India will produce 25% of the world’s cotton in 2018 whilst China will continue to produce 21% and the US share will fall to 16% of world cotton in 2018 [12]. After

joining the WTO, the agricultural sector has faced lot of challenges in China which resulted in a decline in the cotton sector. Policies were therefore developed for increasing the output of value-added products to earn more in exports. More recently, the prices of raw cotton decreased 2015/16 which affected the farmers and ultimately the planting area in China was reduced [13-15].

Australia is another important cotton producer on the world map. More than 800 cotton farms exist in New South Wales and Queensland in Australia and the contribution of cotton exports to the Australian economy is currently \$ 1.7 billion; of the cotton grown in Australia, 98% is exported, the major part to Asian countries. Cotton production in Australia was affected by environmental conditions as well as by decline in global cotton pricing in the past few years (as was production elsewhere) but better farming practices including the implementation of efficient water irrigation system enabled increase in the cotton yield [16,17].

2.1.4 Emerging cotton economies

The role of developing countries has increased in world cotton trade over the last 10 to 15 years. In addition to countries in Africa, Brazil has emerged as a significant cotton producer and these sit alongside Australia in terms of their levels of production. The share of Brazil has grown because of increasing the cotton planting area in the last few years. For example, the cotton harvesting area was increased in 2016/17 by 2.1% as compared to the previous year in Brazil and it is estimated that the increase will be five times higher for 2018/19 compared with 2017/18. The increase in cotton production in Brazil is linked with good cotton prices and the overall economic condition of the country. Similarly, growth in the cotton share of Australia has been growing in the past few years with the Cotton Yield increased by 38% in Australia in the last 20 years through improving the seed technology; an increase in cotton production area is also a major reason behind its growth (18).

2.2 Cotton varieties

2.2.1 Desired cotton varieties

The selection of the variety of cotton means a lot to the farmer as it can lead towards benefits such as flexibility in time of planting, less use of pesticides, higher resistance against insects and environment impacts and high yield as well as processing performance during textile manufacturing. The different countries and their regions all have different varieties of cotton that they are able to grow. Therefore, the range from which to select the right or desired cotton variety for planting is quite wide. Other than yield and environmental factors, the properties of the cotton fibre itself are very important in the final selection of a specific variety of cotton.

There are more than 100 countries which produce cotton and almost every country has a bank of data related to cotton types and varieties. The research centres in these countries market the desired cotton varieties to farmers based on the above-mentioned factors. Mostly the High Volume Instrument (HVI) is considered as a most efficient test for the purpose of informing selection. This instrument measures the final properties of cotton fibre of a specific cotton variety then these results are evaluated by a group of researchers. HVI reports the length, strength, fineness, colour and moisture content of the cotton fibres. The information based on these parameters can be helpful in selecting the cotton variety for a region (19, 20).

2.2.2 Geographic distribution of key cotton varieties

Different cotton varieties are grown in cotton-producing countries depending upon the climatic conditions of that region. China, India and Pakistan and USA are the top four cotton producers of world cotton. Bt cotton is a genetically-transformed variety of cotton which produces toxins against insects as the plant grows that are intended to reduce or eliminate the need for the application of pesticides to the cotton crop. Bt cotton has remained one the most desired cotton varieties in the recent past in the above mentioned countries. The major advantage with Bt cotton is its resistance against cotton pests which ultimately increases the yield and lowers the production cost and that is why Bt cottons have been grown on more than 732 million hectares in the world since 1996. The yield comparison of Bt cotton with non-Bt cotton varieties in different regions of China in 2001 is given in Table 3. It was observed that the yield of non-Bt cotton was

6% lower than Bt cotton. There is a gradual increase in the yield of Bt cotton from 1999 to 2001 which showed that farmers adapted well to Bt cotton (21, 22).

Table 3. Yield comparison of Bt cotton with non-Bt cotton varieties

Location/type	Number of plots			Yield (kg ha ⁻¹)		
	1999	2000	2001	1999	2000	2001
Hebei						
Bt	124	120	91	3197	3244	3510
Non-Bt	0	0	0	na	na	na
Shandong						
Bt	213	238	114	3472	3191	3842
Non-Bt	45	0	0	3186	na	na
Henan						
Bt		136	116		2237	2811
Non-Bt		122	42		1901	2634
Anhui						
Bt			130			3380
Non-Bt			105			3151
Jiangsu						
Bt			91			4051
Non-Bt			29			3820
All samples						
Bt	337	494	542	3371	2941	3481
Non-Bt	45	122	176	3186	1901	3138

Along with Bt cotton, hybrid varieties of Bt cotton are also very famous and are grown in top cotton-producing countries of the world; details of the further varieties have been published (23-26).

2.2.3 Declining cotton varieties

Cotton varieties can be divided into three major classes in the current era which are Non-Bt cotton, Bt cotton and hybrid cotton. Due to higher yields and lower production costs, both Bt cotton and hybrid Bt cotton varieties have become the most popular in the last 25 years compared to conventional cotton varieties. Bt cotton has high resistance against pest attack but

this advantage has been challenged by evaluation of growing resistance in pests in recent years. Therefore not only have non-Bt cotton varieties declined over the previous few years in terms of their planting in different regions of the world but also some of the Bt cotton varieties (27, 28).

2.3 Cotton support programmes

2.3.1 Key organisations for cotton promotion and research

A number of organisations are operating for the sake of research and development of cotton and to provide information to farmers about cotton planting and cotton growing. The International Cotton Advisory Committee (ICAC) was formed in 1939 to address the issues faced by cotton-producing countries. With the exception of China, the larger cotton-producing countries are full members of ICAC. ICAC is operating to improve the quality and yield of cotton by focusing on research-based activities in different countries. They publish a variety of monthly and annual reports, statistics and scientific studies on the different aspects of the cotton industry to act as a help to the cotton growers. ICAC is also working on cotton testing standards and instruments and they have produced many key standards which are routinely implemented in the cotton industry. ICAC formed an international forum in the year 2000 called the International Forum for Cotton Promotion (IFCP) by making a partnership with various private organizations. IFCP acts as a clearinghouse which permutes the information and available technology for improving the yield and quality of cotton so as to be of most use to cotton growers. ICAC also represents the cotton industry on world forums like the United Nations to discuss the different issues which farmers are facing at domestic level [29].

The Asian Cotton Research and Development Network was formed in 1999 under the umbrella of ICAC to benefit the Asian cotton growers and similar organisations are working regionally like the National Cotton Council of America, the China Cotton Association, the Central Institute for Cotton Research India and the Pakistan Central Cotton Committee. These are providing a platform for farmers, ginner and traders to gain valuable information and to communicate about different issues regarding cotton.

2.3.2 Governmental and Non-Governmental Organisations role in cotton production

Governmental and non-governmental organisations are playing key roles in research and development of cotton in cotton growing countries. These organisations conduct scientific research and also collect novel information from farmers through their surveys. The organisations are fully active at the local level and are also coordinating internationally. They are focusing on improvement of cotton yield as well as the quality of cotton fibre. They also introduce new varieties of cotton in specific regions and also address problems related to existing cotton varieties. Another important job which these organisations have done very well is to set the true price of cotton crops. With the coordination of textile mills, these organisations have also adjusted and reported the demand and supply of raw cotton in producing countries [31].

2.3.3 Controlled cotton production and incentives for cotton growers

Certain principles and criteria can be applied relating to the use of seed technology, irrigation systems, cotton variety and reduction of the use and types of pesticides for the production of cotton to achieve what may be described as ‘controlled cotton production’.

The Better Cotton Initiative (BCI) was introduced, in their own words, ‘to make global cotton production better for the people who produce it, the environment it grows in and the sector's future’. Widely supported by a large number of well-known retailers and brands, BCI is providing funds to different organisations and farmers to enable them to adapt certain standards and principles for better cotton production and is working in more than 20 cotton-producing countries. Generally, BCI introduced six basic requirements for the farmers which need to be implemented in order to produce better cotton. These consist of minimizing the use of harmful pesticides, better water management for crops, care of soil, natural habits of farmers, quality of fibre and decent work of farmers. The farmers are given a minimum set criteria to achieve by BCI to obtain a license to grow ‘better cotton’. The minimum requirement criteria consists of production criteria, management criteria and reporting.

Organic Cotton, established by the Soil Association in collaboration with Global Organic Textile Standards is supported by retailers and brands alongside organisations committed to organic farming practices and the fair treatment of small farmers such as Fairtrade, Textile Exchange and

Cotton Connect. Organic Cotton is concerned with growing cotton using methods and materials with a low impact on the environment. Their aim is to reduce the use of toxic and persistent pesticides and fertilisers, maintain soil fertility, and build biologically-diverse agriculture. The verification of organic production is carried out by third-party certification organisations.

The Cotton made in Africa (CimA) initiative was established in 2005 to sustainably improve the living conditions of cotton farmers in sub-Saharan Africa, where cotton growing plays a key role in fighting poverty and makes a major contribution to food security. Cotton is grown here by about 3.4 million smallholder farmers and more than 20 million people in the region are directly or indirectly living on the proceeds derived from growing cotton. CimA trains African smallholders about efficient and environmentally-friendly cultivation methods and has established an international alliance of textile companies who purchase the CimA raw material and pay a licensing fee to use the seal [32].

Fairtrade Cotton was launched in 2005 to offer cotton producers an alternative to the volatile conventional market which provides a safety net when prices fall below a sustainable level. The Fairtrade Standards include a guaranteed Fairtrade Minimum Price (from €0.66/kg in Kyrgyzstan to €0.39/kg in South Asia) for seed cotton. The additional Fairtrade Premium (€0.05/kg) for farmers is included to enable them to invest in improving the infrastructure of their communities, the strengthening of their support organisations and in developing their businesses [4].

Government support may be helpful to the country if the contribution of cotton to the economy of that country is significant, so it is not unusual for governments to provide incentives for farmers and support for research institutes. These incentives and support measures aim to promote the cultivation of cotton and increase the production of crops [33,34]. The New South Wales Department of Primary Industries (DPI) in Australia, for example, provided funds to the farmers to improve irrigation in 2014 which ultimately resulted in higher cotton yield. The Government of India has been offering a bonus price for the past few years to improve the cotton yield in the state of Gujarat. Similarly, the Credit Programme was launched in Brazil in 2005 which raised the value of cotton crop to 40 percent. The Government reduced the loan interest rates to 7.5 percent in 2010-11 through this Credit Programme to support the cotton producers in the country. In Africa, the Tanzanian Cotton Association helped the farmers in the past years in use of tractors for soil preparation which contributed to improvements in cotton production.

Other countries and regions often give different incentives some of which may include tax reductions for farmers, the provision of high-value seeds, supply of low-cost pesticides, better pricing of crops and easy loans to the farmers (35-38).

2.4 Cotton vs commodity man-made fibres

2.4.1 Comparison of fibre properties

By comparison with synthetic-polymer man-made fibres which arrive at the spinning mill in a clean condition, cotton fibres, depending upon the harvesting and ginning methods employed, can carry significant amounts of trash and contamination (foreign matter). Attempts are made to remove such trash and contamination during the yarn manufacturing process, steps which can, however, adversely affect both the cost and quality of the yarn. The continued presence of plastics contamination (especially polypropylene from bale wrappers) poses challenges, as such polymers are likely to be left undyed during further processing in the making fabrics from cotton and cotton blended yarns, and this will adversely affect the appearance of the finished fabric. The cotton fibre is considered to possess good tensile strength and elongation; it shows moderate moisture regain (8.5%) under standard conditions of temperature and relative humidity hence static electric charges are not produced on cotton fibres, an advantage compared to man-made fibres which is quite important in the context of its processability, though relative humidity and temperature do have to be carefully controlled in cotton yarn and fabric mills [39]. Normally the strength of cotton fibres is lower than that of a synthetic polymer man-made fibre of similar cross-sectional dimensions, but its strength depends upon the type and maturity of the cotton fibre. Cotton is attractive to touch and handle and the drape of cotton-based fabrics is also better than that of many man-made fibres and, being a natural cellulose fibre, possesses the potential to undergo biodegradability, as do other natural fibres, which should prove to be an advantage compared with synthetic-polymer man-made fibres at the end of its useful lifetime (unless this is adversely affected by dyeing and finishing treatments).

2.4.2 Life cycle assessment studies

Several studies have been conducted to quantify the relevant energy and cotton fibre inputs from its production to end use. These studies also describe the environmental emissions from cotton production to its end use. The life cycle assessment studies of cotton fibres have usually focused on planting of cotton, cotton based textiles and utilization of these textiles. So from these three processes, the life cycle assessment of cotton is determined. Cotton Incorporated, the organisation which conducts research on behalf of the Cotton Board (which represents upland cotton in the USA), conducted a study from 2005 to 2009, a project of The Cotton Foundation (a not-for-profit organisation that provides support to the US cotton industry) to assess the life cycle of cotton from fibres to fabric. They collected cotton fibre production data from China, India and the USA and then selected Turkey, India, China and Latin America for collecting data related to both knitted and woven cotton fabric production. The study concluded that certain processes in textile manufacturing and end use have the most significant effects on the life cycle assessment of cotton: - energy utilization was greatest in fibre processing, wet preparation and dyeing during manufacture and in the laundering of garments during end use as compared to other processes [40].

3 Advances in cotton cultivation and processing

3.1 Cultivation and lint production

3.1.1 Modern farming methods

The key issues arising in sustainable cotton farming are runoff water from fields, use of insecticides, depletion and pollution of water resources, contamination and degradation of water bodies. These issues can be addressed by sustainable practices of cotton-crop management including multi-cropping, minimal or no use of pesticides, soil management to enhance its fertility, choosing sustainable seed and plant varieties, water conservation and sustainable irrigation thus increasing crop water productivity [41]. Dong et al. [42] conducted two experiments to study the effect of integration of plastic mulching and seedling transplanting on plant growth, development and fibre yield in the case of Bt transgenic cotton in the northern part of Shandong Province, in Yellow River Valley of China from 2003 to 2005. In the first

experiment in 2003 and 2004, a hybrid Bt cotton cultivar SCRC 15 was planted in a greenhouse-like hut in early April, and the raised seedlings were subsequently transplanted to mulched or non-mulched field plots in early May. The cotton plants were evaluated for growth and development, yield and yield components, and earliness of cotton. In the second experiment in 2004 and 2005, three hybrid and three non-hybrid Bt cotton cultivars were examined for yield with the integrated system or with transplanting alone. Results from both experiments showed that an integration of plastic mulching and seedling transplanting can be a more-effective approach rather than individual use of transplanting to enhance cotton production in northern Shandong and other low average temperature areas.

Cotton is grown in more than 100 countries in the world on 30–35 million hectares and the production has exceeded 25 million tons of lint [43]. The harvest losses remain very high despite the continual improvement in the performance of chemical control strategies for crop protection. Deguine et al. [44] presented two sustainable models of the future of crop protection: total pest management which involves the abolition of pests and integrated pest management (IPM), which aims at the management of pest populations below economic thresholds by a combination of chemical control and a suite of alternative control measures. Integrated pest management (IPM) has been practiced in many countries to reduce the impact of highly toxic pesticides on people's health and the environment. However, the lack of farmers' knowledge of ecological principles and local ecological dynamics caused slow diffusion of IPM due to the inherent complexity of the approach based on farmers' decisions. Therefore, farmer field schools about IPM have proved to be very effective for building the essential knowledge and decision making skills among the cotton growers in Andhra Pradesh, India [45]. Lancon et al. [46] developed a prototype system (including new genotypes, increased plant stand, lower rates of fertilisers and the use of herbicides and growth regulators) to design and assess sustainable crop management. Fourteen indicators were selected to assess the economic, environmental and social performance of the prototype. The findings showed that the prototype had helped to improve farmers' incomes and labour productivity along with a satisfactory environmental performance.

China produces over 20 % of the world's cotton output with only 15 % of the world's cotton land allocation [13]. This high unit yield of cotton is mainly due to adoption of a series of intensive farming technologies for cotton production including seedling transplanting, plastic mulching,

double cropping, plant training and super-high plant density techniques. However, this high-yield cotton production is associated with great challenges such as soil pollution by plastic film and chemicals, labour shortages due to urbanization, global climate change and intense competition for land from food crops. Therefore, Dai and Dong [8, 13] recommended reformation of traditional intensive farming technologies to counter these challenges and to support sustainable cotton production by reducing soil pollution through the rational use of plastic film and chemicals, labour saving through simplifying field management and mechanization and increasing benefit through reforming the cropping system. Organic production of cotton could be an alternative solution for small scale cotton farmers in developing countries due to stagnating yields and high input costs. For example, a comparative two-year study was carried out in central India covering 170 cotton fields [47]. The results showed that the organic management of cotton fields has reduced the nutrient inputs and input costs per crop unit by half and cotton yields were on a par with those of conventional farms. Moreover, the average gross margins from organic cotton fields were 30 – 40 % higher than in the conventional system due to 10 – 20 % lower total production costs and a 20 % organic price premium. The organic farming system also does not pollute the soil and groundwater with synthetic fertilizers and pesticides in addition to producing economic benefits. In a similar study, the effect of organic cotton cultivation on the yield and fibre quality was compared with other modern methods of cultivation during three years (2002 - 2005) of an eleven-year study (1994 - 2005) [48]. The results demonstrated that cotton grown under organic conditions had significantly better fibre length and strength compared with cotton raised using modern methods of cultivation. Additionally, soil samples of the organic fields had significantly greater carbon content, water-stable aggregates and mean weight diameter than modern methods of cultivating fields. In another project to study the effect of organic and modern methods of cotton cultivation on soil nutrient status, organic carbon and nutrients were significantly built up, except for iron (Fe) and magnesium (Mg), in the organic cultivation system as compared to the modern method of cultivation [49].

3.1.2 Cotton ginning

A recent issue of Textile Progress about nep formation [12] provides a great deal of detailed information on the ginning process. The purpose of this Section in the current issue is, therefore,

to focus more on providing the reader with an overview of the evolution of the ginning process and to point to key (post 2000) references which will inform the reader of the current and future direction of the process.

Ginning is a process of separating the cotton fibre from cotton seeds [50]. The harvested cotton that is transported to the gin for processing is called seed cotton. Cotton in its raw form consists of both lint and non-lint material. The lint refers to pure cotton fibres and all extraneous matter other than lint is called non-lint material or trash. At the start of ginning process, an effort is made to extract the maximum amount of extraneous material present in seed cotton in order to preserve lint quality. Therefore, cleaning equipment is used in combination with ginning machines to separate lint from the cotton seeds and trash [51].

Keeping in view the developments made till now in cotton ginning, there are mainly two types namely saw and roller ginning. Saw ginning is generally preferred to process Upland cottons (*Gossypium hirsutum* L.) with short to medium staple length in the range of less than 25 mm to 30 mm (1" - 1" 7/32'), while roller gins are used to process ELS cottons (*Gossypium barbadense* L.) with staple length equal to or greater than 35 mm (1" 3/8') [55,56]. Roller ginning results in a better fibre quality with longer and more uniform staple length, fewer neps and short fibres and higher lint turn out as compared to more aggressive saw ginning process [57]. Efforts have been made since 2005 to convert the conventional rotary knife roller gin to a high-speed rotary knife roller gin with the aim to process upland cottons and to increase the ginning rate without compromising the fibre quality [59,60]. The decrease in service life of the ginning roller due to high-speed ginning was tackled and improved in 2007 with the use of variable frequency drives [59].

Advancements in gin technologies to preserve the fibre quality and its utilization potential as well as to reduce manpower, energy, and fibre loss have made the modern ginning operation very sophisticated. Recent developments in the gin process control include the Uster IntelliGin™ that utilizes colour, trash and moisture sensing to automatically optimize ginning operations such as cleaning, drying and moisture restoration. Thanks to this innovative technology the results to expect, according to Uster, are improved fibre length, strength and uniformity, less short fibre content and less nep formation with consistent fibre quality [24]. The process control system brings direct benefits to the gins using fewer cleanings and lower dryer temperatures resulting in

saving of fuel and electricity. Another important benefit is the 10% increase in cotton yield which simply means there will be 10% more finished ginned bales each year, hence increasing the annual revenues [25]. Other developments include:

The Schaffner IsoTester™/GinWizard™ systems (Schaffner Technologies, Inc. Knoxville, Tennessee, USA; the equipment is no longer available but some machines are still in operation) measured the fibre length, strength, colour, trash, moisture, neps, seed-coat fragments, stickiness, and micronaire values from the bale sample to provide the ginner with timely data to modify the gin processing [61].

The Lummus Sentinel™ saw-type lint cleaner (Lummus Corporation, Savannah, Georgia, USA) feeds individual tufts of fibre directly to the saw through the use of a high speed perforated air and dust separator cylinder, rather than feeding tufts in the form of a batt on a low-speed revolving condenser drum, thus reducing the risk of fibre damage [62]. Another device, the Continental LouverMax™ lint cleaner (Continental Eagle Corporation, Prattville, Alabama, USA), adjusts the number of grid bars to reduce the amount of good fibre loss by the lint cleaner and hence improves the fibre turnout [63].

The automation of the ginning process using soft computing techniques such as a fuzzy clustering technique, a backpropagation neural network and adaptive network-based fuzzy inference system (ANFIS) can help for on-line identification of trash objects into individual categories for defining the optimal settings of cotton cleaning and extraction equipment before and after ginning. This can result in the production of high-quality lint in a modern gin (51). The revolution in technology has helped to produce more energy-efficient ginning machines. Despite that, a survey conducted in 2013 revealed that the energy cost is still 25 % of the total variable ginning cost (29). The electricity consumed per unit of processed cotton decreased by 19 to 34% during the past 50 years due to three- to six-fold increases in ginning rates and from automation utilising labour more efficiently (30). Saving of electricity can also be made possible by reducing air volume and friction losses during material handling and pneumatic conveying as this accounts for more than half of the electricity consumed at gins [65]. Good business management practices, optimized machinery operation procedures and adoption of new technology have the potential to shape the future of the cotton ginning industry.

3.2 Processing and performance

3.2.1 Cotton and its blends

The term 'blend' in textiles, refers to an intimate mixture of different fibre species used to produce a textile product [65]. The purpose of blending is to get a better combination of performance characteristics of different fibres in a single textile product. The ultimate garment can have better durability, handle, colour effects, fabric appearance and/or aesthetics. Blending is also done to reduce a garment's cost effective by mixing cheaper fibres with more expensive ones [66]. Cotton is mostly blended with man-made fibres to achieve required characteristics in the end product, amongst which polyester/cotton blends are usually good in performance terms and hence are a popular and an important well-known blend. The reason for the popularity of this blend arises from the close matching initial moduli of both cotton and polyester fibres along with better performance and durability characteristics conferred by the polyester fibres to the blend coupled with the good comfort characteristics of cotton fibres [35]. Apart from the combined durability and comfort benefits, studies about improving the antibacterial, antistatic, easy-care and ultraviolet-radiation blocking properties of cotton/polyester blends using different multifunctional finishes have been reported [67-69]. Cotton is also blended with nylon [70], various types of viscose rayon such as that derived from bamboo [71-74], Tencel[®] (Lenzing AG, Austria) [75,76], modal [77] and Viloft[®] (Kelheim Fibres GmbH, Kelheim, Germany) [78], wool [79], acrylic [80-82] and angora rabbit fibres [83] to enhance comfort properties in the corresponding blend fabrics. A cost-effective Nomex[®] (Du Pont Wilmington, USA)/cotton blend fabric was developed for fire-retardant applications using a multifunctional non-formaldehyde flame retardant finish [84]. Table 1 presents the blending of cotton (which is mainly aimed at contributing to the comfort aspect) not only with conventional man-made and natural fibres but also with the new/improved forms of viscose rayon fibres, such as lyocell, modal and bamboo viscose rayon.

In addition to the summary of cotton blends shown in Table 4, studies on blending cotton with polylactic acid (PLA) ([85], soybean protein fibres, Seacell[®] (Developed and marketed by Smartfiber AG, Rudolstadt, Germany and produced by Lenzing AG, Austria) and silver fibres [86] have shown the potential of utilizing the specific properties of these novel fibres in cotton blends for specific end products. However, the development of new generation regenerated

cellulose fibres has created a major challenge to the cotton fibre, not only by being a constituent replacing some of the cotton in a fibre blend. These fibres from sustainable sources, being cellulosic in nature with comparable comfort, moisture management and durability characteristics, can pose a threat to the cotton fibre, as the availability of these fibres is not so readily affected by the decisions of growers or by the vagaries of nature. Moreover, their production demands significantly less water and has lower global warming potential as compared to cotton and traditional viscose rayon fibres [87].

Table 4: Cotton blends with man-made and natural fibres [66, 87, 88]

Sr. No.	Cotton and blend	End uses	Contribution of fibres in the blend to end use
1	Polyester	Shirting fabrics, suiting, dress wear, casual wear, household textiles	Polyester contributes to wrinkle recovery, mechanical performance and durability.
2	Nylon	Dress wear, light weight suiting, sportswear, swimwear, leisure shirts, socks and stretch wear	Nylon contributes to mechanical performance, durability and smoothness.
3	Acrylic	Bulky woven and knitted dresses, vests, socks, warm up fabrics, sports, leisure wear and knitted under wear	Acrylic contributes to bulk, warmth and durability.
4	Modacrylic	Dress wear, night wear, under garments	Modacrylic contributes to bulk and durability.
5	Spandex	Stretch garments, sportswear, under garments, leisure wear, jeans, skirts	Spandex contributes to extensibility and elasticity.
6	Polypropylene	Dress wear, casual wear, household textiles	Polypropylene contributes to low cost and durability, performance.
7	Kevlar®	High performance apparels	Kevlar® contributes to tensile and tear strength.
8	Viscose	Knitted apparels, leisure wear, ladies tops and trousers, children clothing, T-shirts, blouses, towels, curtains, furnishings	Viscose contributes to lustre and softness.
9	Wool	Knitwear, dresses, ladies inner wear, sweaters, blankets, shirtings, gabardine	Wool contributes to bulk, wrinkle recovery, resilience and warmth.

10	Silk	Ladies dresses, scarfs, ties, shirts	Silk contributes to lustre, softness, strength and durability.
11	Linen	Men's shirts, trousers, household textiles	Linen contributes strength, smoothness and comfort.
12	Lyocell	Shirting fabrics, denim, towels, hospital textiles, bed linen	Lyocell contributes to strength, lustre, breathability and comfort.
13	Modal viscose rayon	Clothing, outerwear, towels and household textiles	Modal contributes to softness, lustre, smoothness, more moisture absorption and crease recovery
14	Bamboo viscose	T-shirts, socks, underwear, nightwear, bath suits, blankets, towels, hospital textiles, home textiles	Bamboo viscose rayon contributes to lustre, breathability and softness.
15	Poly (lactic acid)	Sportswear, under garments, active wear	PLA fibre contributes to moisture wicking, resilience and crease resistance.

3.2.2 Cotton yarn and fabric manufacturing

Cotton Yarn Manufacture

Yarn manufacturing refers to the process of converting textile fibres into yarns by binding fibres together either by twisting or some other means (89). The conversion of cotton fibre and its blends into yarn is key to the subsequent production of woven, braided and knitted textile products. Different techniques for conversion of textile fibres into yarns include ring spinning, rotor spinning, air vortex spinning, air jet spinning, friction spinning and wrap spinning [90]. Among them, ring spinning is the oldest, versatile and dominant technique, used today in the cotton spinning industry. Following the preparatory processes, the basic principle of this technology consists of continuous and stable drafting, twisting and winding operations in sequence. However, since the invention of ring spinning in 1832, this technology has undergone a lot of developments from the era of the industrial revolution to the digital age. These developments mainly include improvements in design and components of drafting arrangements, design aspects of the ring and traveller, productivity, machine monitoring, drive systems, increase in the number of spindles per machine and automation that includes roving stop motions, roving bobbin transfer from the fibre preparatory section, doffing and automatic cop

transfer to winding section. Other developments include compact, solo, Siro, core-sheath, slub and fancy-yarn spinning, achievable without changing the basic principle of ring spinning thus making it a very flexible and versatile technology [91]. The main reasons of flexibility and versatility are its ability to process a range of fibre types, produce coarser to finer yarn counts and most importantly, the unique structure and properties of its spun yarns [92]. Among the various technological developments which have taken place over the years in ring spinning, compact spinning has gained much commercial interest since its first commercial introduction at ITMA-99 in Paris. After a few years, Marzoli, Toyota and Lakshmi also introduced pneumatic compact systems in their ring spinning machines. A mechanical compact spinning system developed by Hans Stahlecker with the trade name of RoCoS[®] was introduced by Rotorcraft Maschinenfabrik Switzerland. The RoCoS[®] system condenses the fibres purely by mechanical means thus eliminating the need of any pneumatic system and saving energy cost. This system was claimed to process 100 % cotton, cotton blends and 100 % synthetic fibres. However, the market acceptability of RoCoS system has remained under pressure as compared to pneumatic compacting systems due to limitations in the degree of fibre compactness for a wide range of yarn counts and subsequent yarn properties. A comparative study also proved that a pneumatic compacting system produces superior quality yarns than mechanical compact spinning system. Compact spun yarns offer many advantages over conventional ring spun yarns such as reduced yarn hairiness, superior yarn strength and elongation and less generation of fibre fly during processing; a comparison of the structure and properties of the two yarn types has been reported [95]. Compact spinning was initially used to produce fine yarn counts from combed roving. However, a new design having a D-type slot in a Suessen compact spinning system (Spindelfabrik Suessen, Sussen, Germany), is claimed to maintain appropriate control over short fibres during condensation and was evaluated for spinning compact yarns from carded roving [96,97]. Similarly, other compact spinning systems available in the market have undergone many physical modifications and design changes since their introduction, to enable the processing of a wide range of both carded and combed yarn counts and to improve the degree of compactness of staple fibres from carded and combed rovings without any change in the basic principle of fibre condensation. For example, Rieter GmbH+Co.KG, Winnenden, Germany, claims to produce compact yarns in the count range Ne 10 – 160 on its latest K46 compact spinning machine [98].

In the fibre preparatory sections before spinning, the main advances in the last two decades have involve the increase in carding [99] and combing speeds, machine productivities, online monitoring and optimization of machine settings/operations using the latest technologies, energy efficient drives, flexible drafting operations at the draw frame, automation in combing lap transfer and batt feeding [100]. Some of the recent research and developments in ring spinning technology are summarized below.

In staple spun yarns, hairiness is an important parameter which not only affects yarn quality and causes an influence on air drag especially at higher spindle speeds [101] but also affects the downstream processes and quality of resultant fabrics. Apart from the available compact spinning systems which considerably reduce yarn hairiness by eliminating spinning triangle during yarn formation, many researchers have made efforts to reduce hairiness of cotton yarns by modifications to conventional spinning machines. Mirzaei et al. [102] suggested a new and simple method for reduction of yarn hairiness by attaching an air-suction system to the web-detaching zone of a conventional carding machine immediately behind the crushing rollers. The ring-spun yarn produced using this system was called vacuum-cleaned carded (VCC) yarn and showed a 20% improvement in yarn hairiness along with improvement in yarn evenness, tenacity and elongation at break. However, this system was not utilized to produce combed cotton yarns. Studies also reported reduced yarn hairiness by modifying the yarn path in the right and left diagonals (Figure 6) [103], using various offset left diagonal paths (Figure 6a) [104] and spinning with adjacent spindles. The results showed 50% reduction in hairiness in the left diagonal path [103] and a 40% reduction in hairiness at 60mm offset left diagonal path [104] with slight increase in yarn strength. Another approach employed a special iron-heating apparatus attached to the exit of front drafting roller in the spinning triangle area in an attempt to replace compact spinning and proved to be effective in reducing yarn hairiness [105]. Yilmaz and Mustafa [106] studied a comparison of the properties of compact-jet, compact and conventional ring-spun cotton yarns. The compact-jet yarn was produced using a combination of a compact and a jet-ring spinning system. An air-jet nozzle was placed at the exit of compact unit and the yarn guide, thereby forming a jet-ring spinning system. The results revealed 40 – 50% decrease in hairiness of the compact-jet yarn compared with the conventional ring-spun cotton yarns. The air-jet nozzle attached to the Siro spinning system is called the Siro-jet system. The use of a Siro-jet system was also found effective to reduce hairiness of Siro-spun yarns [107-

109]. A special designed air-jet nozzle attached to a conventional ring spinning system was also found useful to reduce yarn hairiness [110]. Xia et al. [111] introduced a contact surface next to the front roller exit at a distance of 20mm to rewrap the protruding fibres and ultimately to reduce yarn hairiness. However, yarn evenness and strength deteriorated as a result of using the contact apparatus during the spinning.

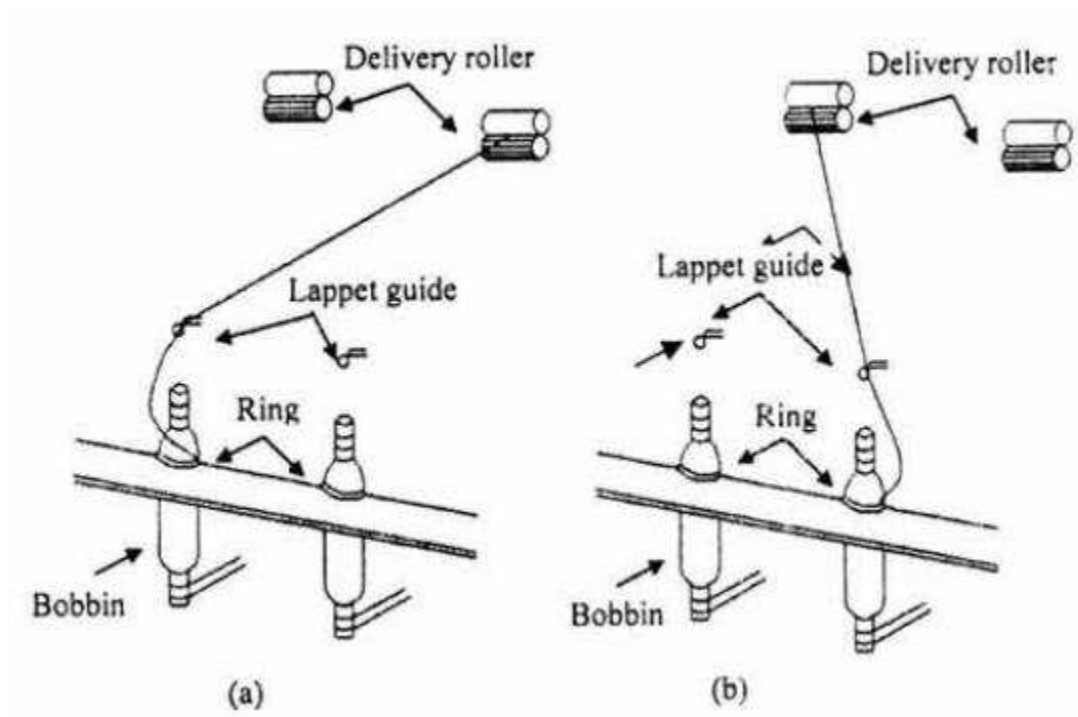


Figure 6. Diagram of ring spinning with (a) left diagonal and (b) right diagonal yarn path (103).

A modification to a conventional ring spinning system with an optional fibre separation device and a false twist device to produce a torque free cotton ring spun yarn has been reported, as shown in Figure 7 (112). The modified ring-spinning system developed by HKRITA, a research unit at the Hong Kong Polytechnic University, altered the yarn cross-sectional structure and fibre path resulting in a modified low-twist yarn with a low residual torque and relatively high strength, thus combatting the issue of spirality in knitted fabrics, which arises owing to residual torque in the yarn (113). This technology is known as Nu-torque™ yarn spinning. During Nu-torque™ spinning, most fibres come close to the yarn centre due to higher twisting density in the spinning triangle zone and alter their radial position in a yarn to a higher amplitude which is beneficial for improving yarn strength and hairiness with low residual torque (114).

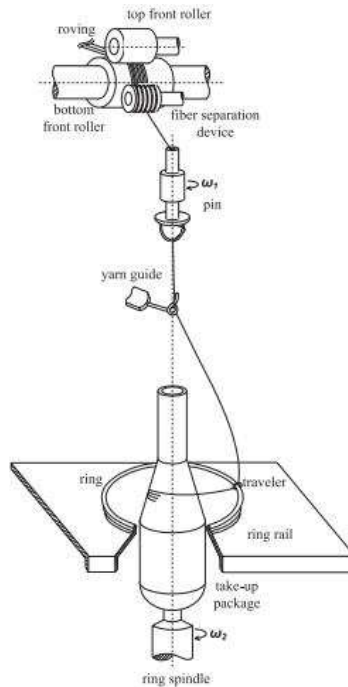


Figure 7. Modified ring spinning system to produce torque free yarns [112]

Another modification made to the ring spinning system produces a “cluster-spun yarn”. This recently-devised method was developed to overcome the problem of staple sheath fibre slippage from the core filaments in core-spun yarns. A detailed description of this modification has been reported and the structure and properties of cluster-spun yarns were compared with conventional core-spun yarns [115]. The results demonstrated a significant increase in tenacity and breaking elongation for the cluster-spun yarn.

Liu et al. [116] developed a bobbin-tracing system based on radio frequency identification (RFID) technology to overcome the problem of quality control for each spindle on a ring-spinning frame. The existing twisting mechanism, consisting of a combination of ring and traveller, limits the productivity of ring spinning due to friction and generation of heat at higher traveller speed. Researchers have tried to overcome this limitation by completely replacing the existing ring/traveller system of the ring-spinning machine with a rotating magnetic ring suspended in space by magnetic levitation [117], and with a magnetic bearing system based on superconducting technology (as shown in Figure 8) [118]. In laboratory-scale studies, the magnetic bearing system based on superconducting technology did not show any negative

influence on yarn properties and indicated the possibility to increase productivity up to three times as compared to a conventional ring/traveller spinning system [119]. Further research is under way to check the feasibility for industrial use, including cost factors.

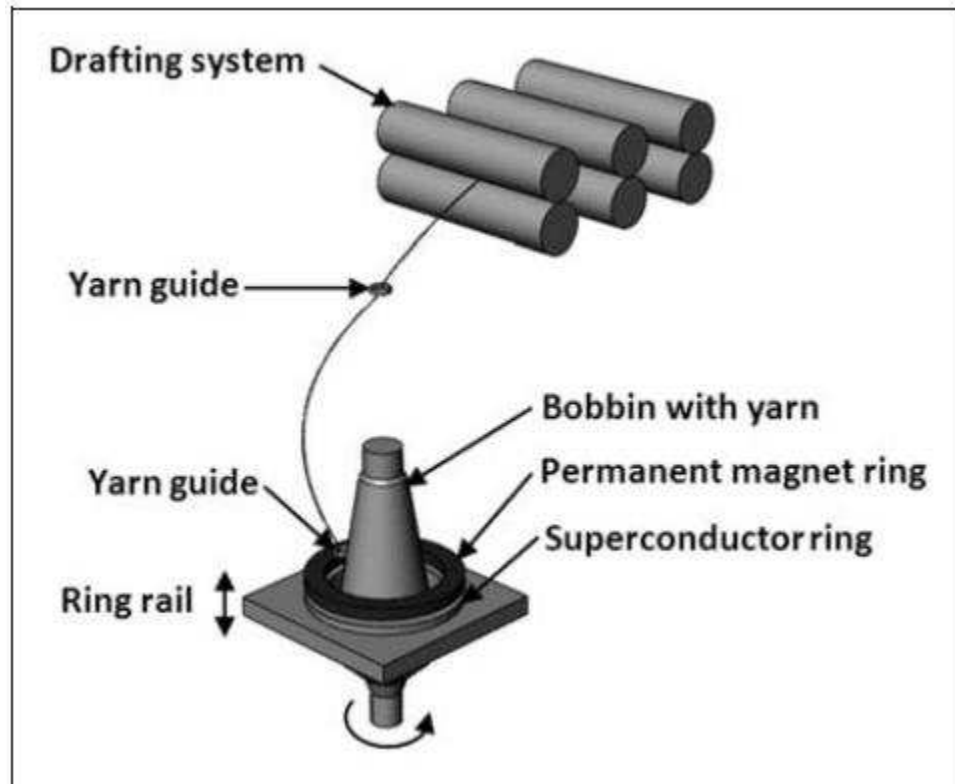


Figure 8. New concept of ring-spinning using superconducting magnetic bearing [118].

Rotor and air-vortex spinning are the commercially the more-successful techniques amongst the newly-developed spinning systems to produce cotton spun yarns due to the unique yarn characteristics created and their higher productivity over ring spinning. The yarn formation principles of both spinning systems are well explained in the literature [90, 120-122]. Recent developments in rotor spinning have concentrated on improving yarn quality and productivity through design modifications of machine components. For example, modification in the feeding unit by using two feeding rollers rather than one was done with an objective to improve fibre opening by gradual loading of the opening roller and to improve the fibre orientation and properties of the final rotor yarn [123.124]. Since its commercial introduction in ITMA-1967, the rotor speed in rotor spinning has been increased from 30,000 rpm to 200,000 rpm and

manufacturers have produced longer automated machines. The major limitations existing today are the inability to produce finer yarn counts and the poor yarn strength of rotor-spun yarns compared to ring-spun yarns due to the relatively random orientation of fibres (125). Despite the inherent advantages of rotor-spinning technology's productivity over ring spinning, the utilization of rotor spinning for a wide range of yarn counts and fibre types still poses challenges for researchers and machine manufacturers.

Air-vortex spinning is considered a modern alternative to both rotor and ring spinning, because of its ability to produce yarns at speeds significantly higher than both ring and rotor spinning (up to 500 m/min) and inherently less yarn hairiness. The particular characteristics of this technology though are that it is limited to the production of yarn in a specific medium count range, and the fabrics have high abrasion resistance but a harsh feel which limits the range of applications of air vortex fabrics. Although it is claimed that air-vortex spinning can be used to process 100% cotton, this technology is mainly used to produce cotton-rich blend yarns. The future challenge will be to overcome the harsh feel of vortex yarns and to bring about improvements in yarn quality together with the ability to process 100% cotton fibre (irrespective of selection of fibre and preparation) through suitable modifications to both process and design in order to make this technology a potential substitute for ring spinning for certain applications [126].

Ring spinning, together with its developments highlighted above, is expected to continue to dominate the cotton yarn market, at least in the near future, despite the difficulties that stand in the way of improving its productivity. This is because there are no acceptable developments in other spinning systems that can, as yet, match either its versatility to provide high-strength yarns, the flexibility to produce yarns in a wide range of counts or the ability to process a wide range of fibre types achievable with ring-spinning.

Woven Cotton Fabric Manufacture

Among fabric manufacturing processes, weaving is the main process used for converting cotton yarns into fabrics, in this case by the interlacement of two or more sets of yarns using a loom [89]. The technological developments that have taken place in the woven fabric manufacturing processes and weaving technology of the modern age, have been the subject of discussed in detail in the review articles [127-129]. The major developments highlighted included,

innovations in shuttleless machines, shedding and weft-insertion mechanisms, let-off and take-up mechanisms, multiphase weaving, applications of electronics and composite materials, automation in drawing-in and developments in weaving preparatory processes. Productivity is of the utmost importance in the manufacture of commodity cotton fabrics.

The common picking (weft insertion) systems available in the weaving industry are shuttle, rapier, projectile, air-jet and water-jet picking systems. Reducing energy consumption and noise pollution, whilst increasing productivity and flexibility are still the main challenges which are only partially fulfilled by the existing systems, so attempts have been made to explore new methods of weft insertion using electromagnetic force [130-132], to overcome the existing challenges. The efficiency of electromagnetic weft insertion mechanism has been improved by using a programmable logic control (PLC) system [133]. A new laboratory-scale method based on magnetic weft insertion via a magnetic timing belt, showed the potential for saving energy of about 60% in comparison with a conventional air jet weaving machine [132]. In a recent study, a coil electromagnetic launcher was employed as an accelerator for yarn attached to a ferromagnetic projectile intended to predict the strike of the projectile by optimizing the parameters of the weft-yarn accelerator for optimum tension and velocity of the weft yarn. A finite-element method was used to develop a 3-D imitating launching model. The experimental results were found to be in good agreement with the numerical model [134].

Among the shuttleless weaving machines, air-jet weaving is the most popular, highly productive and successful technology in the textile industry [136]. However, the manufacturing cost of air-jet weaving is higher than that of other shuttleless weaving technologies due to its requirement for supply of a large quantity of compressed air thus making it less preferable in countries where energy cost is high (despite its higher production speed) [137]. Researchers and machine manufacturers have made efforts to overcome this drawback by reducing air consumption in their new designs and by doing some modifications in existing designs. A study was conducted in a weaving mill having 202 air-jet looms with the objective of minimising air consumption. A 21% decrease in air consumption was achieved simply by decreasing the hole diameter of the single-holed relay nozzles and by optimizing the blowing time of the multi-holed relay nozzles which resulted in a decrease in electricity cost of approximately 240,000 € per year [138]. A similar study resulted in a decrease of air consumption of 11 cubic feet per minute in a weaving

mill by just adjusting the air pressure [139]. A new concept of relay nozzle design, called High-Volume-Low-Pressure (HVLP) geometry, based on convergent nozzle aerodynamic theory has been proposed. Computational Fluid Dynamics (CFD) simulation showed the nozzle potential to reduce energy consumption up to 30%. The proposed future work was the validation of this new concept within the weaving process and to study the interaction between the relay nozzle and the reed in the weaving process with a purpose to reduce the amount of wasted air through the dents of the reed [140]. In another recent study the airflow characteristics in the semi-closed irregular narrow flow channel in profiled dents were examined by numerical simulation in a study for optimizing the weft insertion process of an air-jet loom [141]; also, a numerical simulation was performed to analyse the influence of input air pressure, the structure of the main nozzle core and its internal diameter on the internal flow field of the main nozzle and an optimized nozzle core structure was proposed from the perspective of fluid dynamics to prevent unnecessary energy loss [142]. Air pressure of main and sub nozzles, blowing time, pick insertion and arrival time are considered to be important parameters affecting air consumption. Apart from these, some other parameters such as weft yarn count, loom speed, reed count, fabric width, pick insertion cycle, selvedge pattern and machine stop and running position also affect air consumption [143]. A mathematical model was proposed to calculate the minimum required air pressure of main and sub nozzles for different weft yarn counts to optimize the air consumption of weaving mills [144]. Statistical and adaptive neuro fuzzy models have been developed to predict the compressed-air consumption on air-jet looms. Fabric width was found to be the most prominent parameter affecting the air consumption followed by loom speed, reed count, and weft yarn count respectively [145,146]. The models that were developed could be helpful in estimating air consumption, air leakages and production planning of a weaving mill. Future developments in the woven fabric manufacturing processes will continue to enhance productivity of different operations by modification in the designs and, using advanced electronic devices with close and precise control and monitoring of various functions, reduce energy requirement, noise pollution and vibration of looms.

In the weaving industry, fabric inspection is usually done manually after weaving to detect fabric defects which contributes to an increase in production cost and wastage of time. An online monitoring system on the weaving machines during weaving was proposed by using the

principle of image-processing coupled with artificial neural network (ANN) techniques showing an ability to identify fabric defects with 92% accuracy [135].

Knitted Cotton Fabric Manufacture

Knitting is the second most-commonly used technology for cotton fabric manufacture, in this case by interlocking or intermeshing loops of a singles yarn, set of yarns or more groups of yarns [147]. Knitting technology can be classified into two types, weft knitting and warp knitting. In weft knitting the yarn forming each row of loops passes across the fabric, and it is the most popular method for producing fabrics suitable for apparel, fashion garments, underwear and sportswear. By contrast, in warp knitting, the yarn forming the loops follows a path which is (largely) along the length of the fabric (what would be the warp direction in a woven fabric) and this is mostly used to produce generally less-extensible fabrics such as nets or lace and/or specialist technical products employing synthetic fibres or, where controlled levels of extensibility are required, in power nets.

Most of the cotton and cotton-blend knitwear is produced by weft knitting [148]. Weft knitting can be further divided into circular knitting and flat-bed knitting on the basis of the geometry of the machinery from which the product is obtained [149]. The advancements that have taken place in the process and products of both circular and flat-bed knitting have been critically reviewed elsewhere [150]. Some of the key developments in weft knitting include seamless knitting technology, fine gauge circular knitting machines to process fine yarn counts (Ne 90 to 120), mechanisms to produce speciality fabrics (sliver, pile, fleece, plated and spacer knitted fabrics), energy efficient and variable speed drives, high productivity, automation, online quality control, and design facilities (tucking, floating, plating and loop transferring) using computer aided design (CAD)/computer aided manufacturing (CAM), multiple cam track arrangement or electronic jacquard [149].

Seamless knitting produces a garment to the required shape, rather than the more-usual knitting of the cloth and then cutting and reassembling the pattern pieces into a garment (cut and sew), with minimal or no cutting and sewing processes. Seamless garment production offers many advantages including production cost and waste reduction, lower lead time, good aesthetics, comfort, flexibility and durability. However, the disadvantages include costly knitting machines

and garments, product quality issues during production and the requirement for skilled labour (147, 151). From the view point of sustainability, knitting is a more-sustainable industrial fabric production process as compared to weaving because of the lower energy consumption and reduced related environmental load. Moreover, energy-intensive machinery is not required before and after the knitting process as it is the case for woven fabrics [147].

3.2.3 Cotton wet processing and finishing

The wet processing of cotton fibre usually involves different processing stages including scouring, bleaching, mercerizing, dyeing, printing, and finishing [152]. Scouring, bleaching and mercerizing are pre-treatment steps applied prior to dyeing or coloration. Pre-treatment processes help to remove natural contaminants, improve the degree of whiteness/brightness and the absorbance of cotton fibre for deep dyeing. Dyeing and finishing are important processes which impart colour, aesthetic properties and functionality to the final textile product. Numerous classes of dyes are used for cotton dyeing with sulphur, direct, vat and reactive dyes accounting for more than 85 % of the dyes used [154]. Among them, reactive dyes are widely used for cotton dyeing and printing [154] and more than 50 % of the cotton produced is dyed with reactive dyes [155]. However, common features are that all of these wet processes generate a substantial amount of chemical effluents [156], need substantial supplies of water and energy during processing and thus contribute to environment pollution and to making the production processes expensive. In recent years, research has been undertaken to develop cleaner, eco-friendly, cost-effective, and value-added textile products for a variety of applications without compromising issues related to the environment [152]. The developments that have taken place in sustainable reactive dyeing of cotton fabrics with reduced effluent pollution have been reviewed in detail [157]. The developments highlighted to improve the sustainability of the dyeing process include, the further development of reactive dyes, modification of dyeing machinery and processes, chemical modification of the cotton fibre prior to dyeing, use of biodegradable organic compounds in dye-bath formulation and the improvement of effluent-treatment processes. The paper also highlighted the significance and limitations of each approach to improve the sustainability in reactive cotton dyeing along with suggestions for further improvements. Similarly, the latest trends in sustainable cotton dyeing using so-called ‘green’ approaches have been discussed in detail [152, 158-161]. Zahid et al. [162] studied the potential

of utilizing gamma radiation, in comparison with the mercerization process, to enhance the colour strength of reactive-dyed cotton fabrics. The results revealed that dyed cotton fabric irradiated with gamma radiation has comparable colour-fastness properties to that of mercerized fabric. Moreover, the radiation technology is cost-effective in the long run, time-efficient and cleaner due to lower amounts of chemicals being involved.

Despite the wide usage of reactive dyes for cotton dyeing, the major limitation is the requirement of a high concentration of salt for dye exhaustion. Depending on the dye structure, shade depth and dyeing method, approximately 0.6-0.8 kg of salt per kg of fibre is required [157,163] for dye fixation. Even with the required amount of salt, 100 % exhaustion cannot be assured and only 65 – 70 % of reactive dyes are exhausted [164]. The remaining 30 – 35 % of dyes are removed as a highly saline, coloured effluent after dyeing, then additional wash liquor is generated during removal of the residual dye adhering to the fabric thus contributing to environment pollution. The treatment of this coloured, salt-laden effluent is not an economically viable proposition as it significantly increases the cost of dyed goods. Therefore, the achievement of salt-free reactive dyeing is now an important requirement for cotton industries. Cationisation of cotton is an effective alternative way to eliminate the need for salt in the reactive dyeing process [163,165,166]. Researchers have made efforts to achieve salt-free reactive dyeing through the cationisation of cotton fabrics on an industrial scale using 3-chloro-2-hydroxypropyl tri-methyl ammonium chloride (CHPTAC) as a cationic agent by an exhaust method followed by salt-free reactive dyeing with ultra-deep jet black dye of shade 9.95% using a combination of the dyes Black GDNN-8.2 % and Navy Blue-1.75 %. In addition to it being a salt-free dyeing process, the total dye fixation (%) of the cationised cotton dyed fabric was higher at 58.2 % whereas it was only 51.7 % for the conventionally-dyed cotton fabric. A comparison of effluent parameters of both routes revealed that the total dissolved solid (TDS) value for a salt-free reactive dyeing process was four times lower than for the conventional dyeing process [165]. The sequence of operations involved in conventional and salt-free dyeing processes are presented in Figure 9. In a similar study, the cationisation of cotton fabric on an industrial scale was done by an exhaust method using CHPTAC with concentration of 40 g/L and 80 g/L followed by dyeing with three different dye types [163]. The results showed that salt-free and alkali-free reactive dyeing is possible in producing medium to extra dark dye shades without affecting the dyeing time. Samanta et al. [167] proposed a method for the eco-friendly salt-free reactive dyeing of cotton

fabric after cationisation with amino acid from soya. It was discovered from the study that cotton treated with the soya extract provided a new route of eco-friendly salt-free reactive dyeing with high exhaustion-type reactive dyes showing much higher dye uptake than the control on the cotton fabric. Some more studies have also favoured using salt-free reactive dyeing through the cationisation of cotton textiles using CHPTAC as a cationic agent and Drimarene yellow HF-CD, Drimarene red HF-CD and Drimarene blue HF-CD reactive dyes [164], Navy Blue and Green reactive dyes [166] and CI Reactive Blue 235 (CI RB 235) and CI Reactive Blue 19 (CI RB 19) [168].

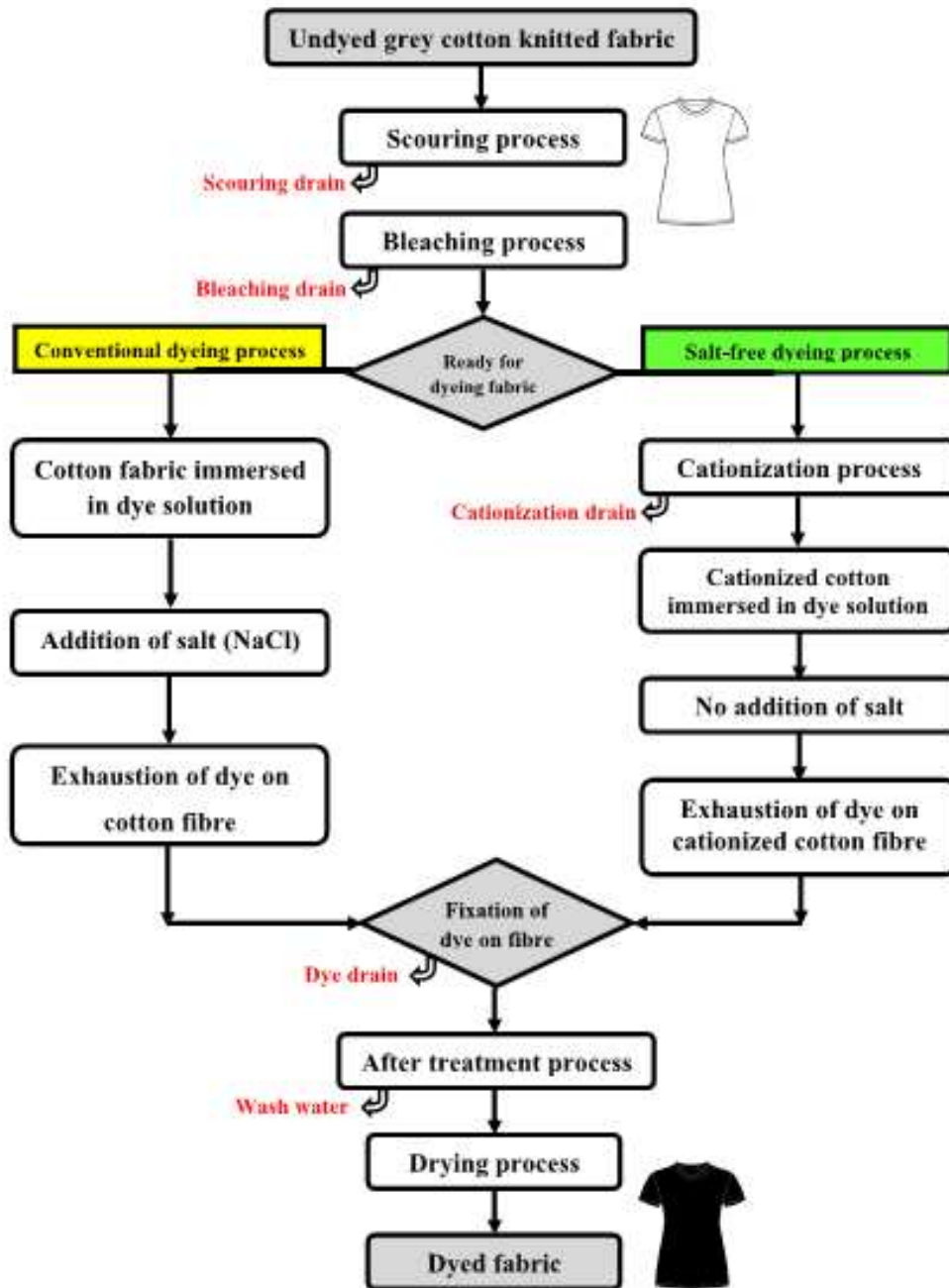


Figure 9. Schematic diagram depicting the sequence of operations involved in conventional and a salt-free dyeing process [165].

Recently researchers have explored different methods to make the cotton dyeing environment friendly. Khatri et al. [154] proposed an economical and convenient cold-pad method for reactive dyeing of cotton fabric using ultrasonic energy. This method is considered environment friendly due to its achievement of high dye fixation without the need for thermal energy. The results showed that the use of ultrasonic energy not only shortens the batching time but also the alkali concentrations can be considerably reduced along with improvements in colour strength and dye fixation %. The method is not only helpful to reduce auxiliary costs but it also reduced the subsequent environment impact. Another study revealed similar results using the same cold-pad method for natural dyeing of cotton fabric using *Uncaria gambir* bark with ultrasonic energy [169]. Chen et al. [170] investigated the reactive dyeing of cotton via nucleophilic substitution with monochlorotriazine (MCT) dyes in an inert media. The process is illustrated in detail in Figure 10. The undesirable hydrolysis associated with conventional aqueous dyeing was eliminated throughout the process. The solvent-based process required 30 - 40% less dye, up to 97.5% less base and no inorganic salts as compared to conventional aqueous dyeing. Recycling of all spent baths throughout the process was demonstrated with a 10-cycle repeated dyeing sequence, which showed consistently high shade build-up and colourfastness. The requirement for waste disposal was estimated to be reduced by over 99% for both organics and salts based on the 10-cycle sequence. The developed solvent-based dyeing method, proposed in this study, could be a solid step towards sustainable textile wet-processing due to a reduction in waste and the reuse and recycling of resources. The dyeing of cotton fabrics was carried out in a similar study using a polyfunctional reactive dye and a protic ionic liquid (PIL) as an alternative solvent to reduce the water consumption, chemical additives and hence the environmental impact [171]. The proposed procedure, as shown in Figure 11, using the PIL as a dyeing solvent in the absence of any auxiliary agent, showed exceptional results when compared with the conventional aqueous process under the same operational conditions. Xiao et al. [172] also presented eco-friendly approaches for dyeing different types of fabrics (including cotton) using cationic reactive dyes with an objective to reduce the consumption of water and salt in the dyeing process. In a different study, it was verified that microwave-irradiated reactive dyeing of cotton fabrics improved the dye up-take and percentage fixation along with a great reduction in the dosage of salt and alkali [173]. It is foreseen that the future of cotton wet processing will be focused on the development and implementation of sustainable and eco-friendly wet-processing

methods in order to reduce the burden on the environment. However, we should not leave this subject without a mention of a very different route taken by a research group at the University of Leeds, which used seawater with reactive dyes [174].

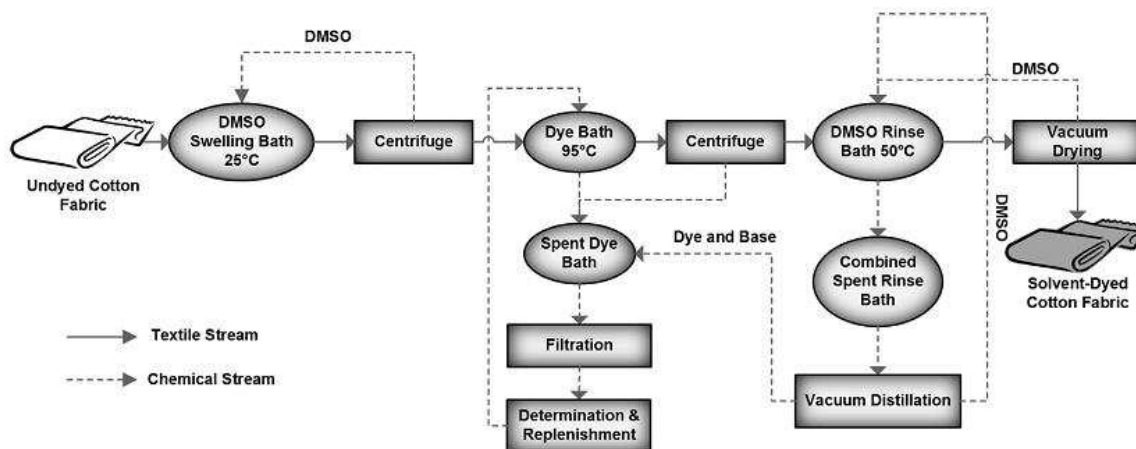


Figure 10. Schematic illustration of the fully recyclable reactive dyeing of cotton in non-nucleophilic solvents [170].

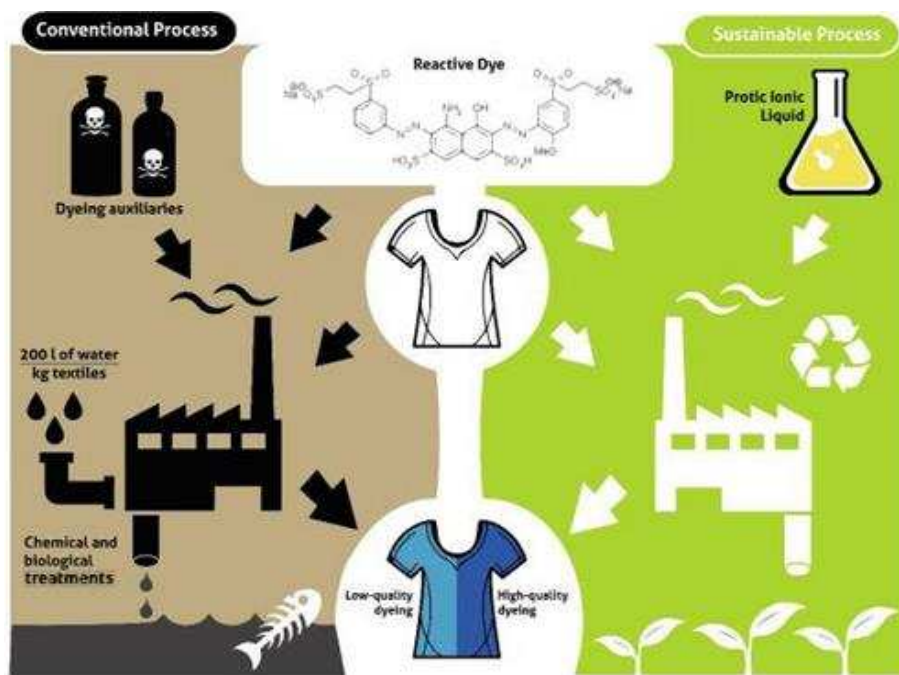


Figure 11. Comparison of conventional aqueous and proposed sustainable dyeing method using PIL as a dyeing solvent [171].

Finishing of cotton-based products is an important process after wet processing in order to achieve the required functional properties in the end product. Cotton fibres, yarns and fabrics can be treated with antimicrobial, flame-retardant, wrinkle-resistant, UV-resistant, self-cleaning, insect-resistant and water- and oil-repellent finishes according to performance requirements. The developments that have taken place in wrinkle-resistant, flame-retardant and antimicrobial finishing of cotton fibres were critically reviewed in an issue of *Textile Progress* in 2012 [175]. Similarly, reviews have been done in recent years on the latest advances in antimicrobial finishing based on sustainable green approaches [176] and flame retardant finishing based on the most significant scientific and technological results [177] and using phosphorus chemistry [178]. Moreover, the future prospective of cost-effective and environmentally-sustainable flame-retardant finishing of cotton using suitable phosphorus-containing biosources, possibly coming from a waste stream or byproducts from agriculture, have been highlighted by Alongi and Marcelli [177].

The demand for cotton fabrics with multifunctional properties is growing due to ever-increasing consumer demands for safe, healthy lifestyles. Different studies have been done in recent years to explore the possibilities of multifunctional finishing of cotton fibres. Shafei et al. [179] improved the flame-retardant and antimicrobial properties of cotton fabrics using an eco-friendly finishing agent (TiO₂ nanoparticles and chitosan phosphate). In another study, sustainable antibacterial and UV blocking properties of cotton fabrics, treated with date seed extract capped zinc oxide nanoparticles, were reported [180]. Similarly, studies on multifunctional finishing of cotton fabrics have been reported using, cyclotriphosphazene/polydopamine/silver nanoparticle hybrid coatings [181] and guanidyl- phosphorus containing polysiloxane to improve flame retardant and antibacterial properties [182], chitosan film containing metal-oxides hybrid coatings to improve antimicrobial, UV-protection properties [183], TiO₂ nanoparticles applied with different finishing formulations to improve anti-crease self-cleaning, UV protection and antibacterial properties [184], iodine butyl-N-sulfonate amino polysiloxane [(IB-N-SA) PDMS] treatment to improve water repellent and flame retardant properties [185], ZnO/SiO₂ core - shell nanorods coating to obtain super-hydrophobic and UV-blocking properties [186], and potassium alginate (a green polymeric material extracted from seaweed) coupled with an environmentally-friendly antimicrobial polyhexamethylene guanidine phosphate (PHMGP) coating to improve flame retardant and antimicrobial properties [187].

Antimicrobial finishing of cotton fabrics using some sustainable and eco-friendly options has reported in the past few years. Raza et al. [188] impregnated enzymatic pre-treated cotton fabric with silver nanoparticles (SNPs) by using starch as a reducing and stabilizing agent under controlled temperature and pressure in an autoclave, as illustrated in Figure 12. The results demonstrated good and durable antibacterial activity of impregnated cotton fabrics against *Escherichia coli* and *Staphylococcus aureus* strains. A sustainable antimicrobial finishing of cotton fabrics was achieved by ultraviolet grafting of a chitosan biopolymer. The results confirmed a strong antibacterial activity with good washing fastness of UV irradiated samples in both dry and wet conditions[189].

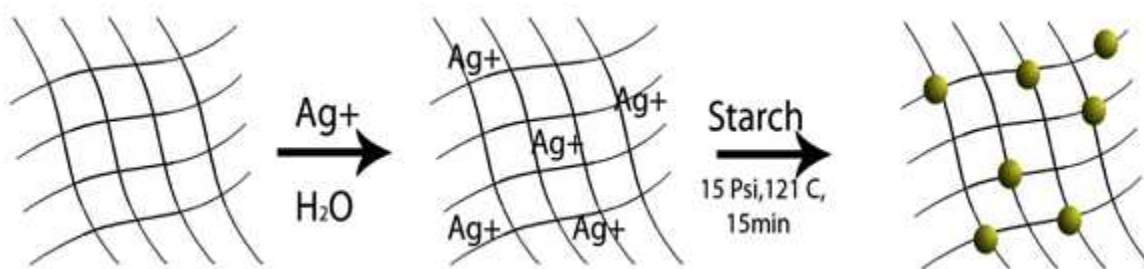


Figure 12. Illustration of impregnation of SNPs on cotton fabric (188).

In a recent study, a sustainable fragrance and antimicrobial finishing of cotton fabric was carried out through a pad-dry method by using lavender essential oil along with β -Cyclodextrin, Chitosan citrate and β -Cyclodextrin/Grafted Chitosan [190]. The results revealed improvements in fragrance durability and antimicrobial performance of cotton fabric treated with the β -Cyclodextrin/Grafted Chitosan and lavender oil. Similarly, Saif et al. [191] reported an eco-friendly, permanent, and non-leaching antimicrobial activity of cotton fabric coated with quaternary ammonium-modified triethoxysilane by a sol-gel process. The coating proved to provide very good wash fastness with no significant decrease in antibacterial properties even after 15 laboratory washing cycles. Another study showed improved antibacterial activity of cotton fabrics finished with a novel environment-friendly reactive siloxane sulfopropyl betaine (SSPB) [192]. The reaction of cotton cellulose with SSPB is presented in Figure 13 which shows that SSPB is covalently bonded to the cotton textile surface thus imparting durable antibacterial activity.

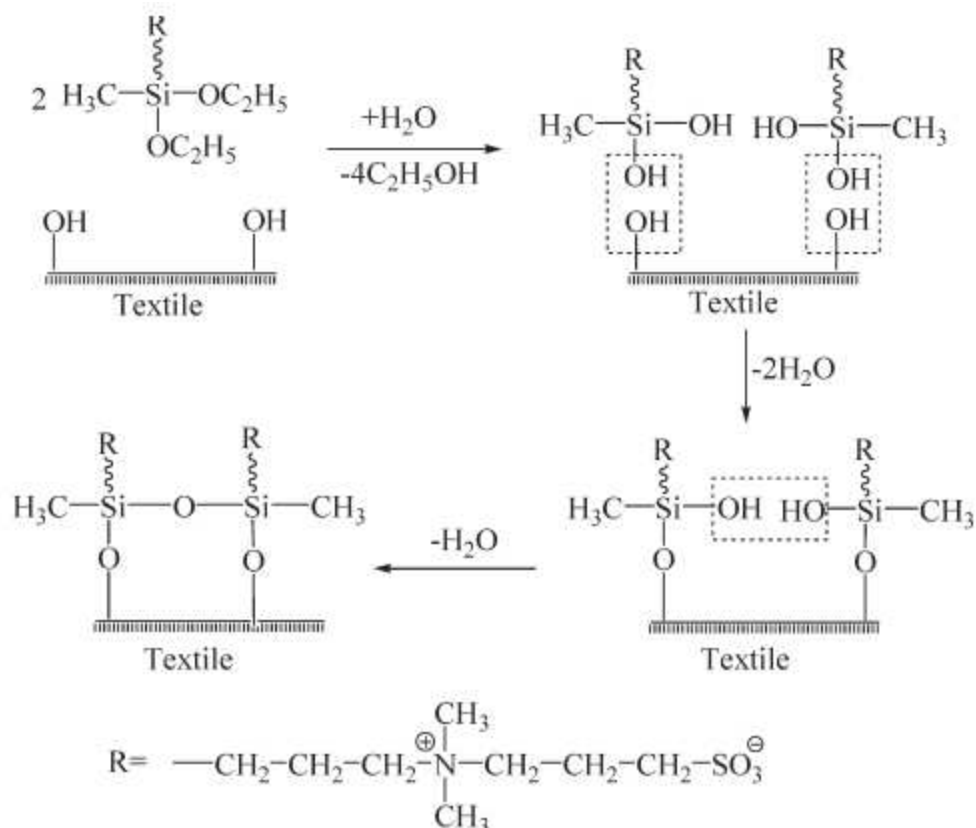


Figure 13. Reactive principle between cotton textile cellulose with SSPB [192].

Due to the flammability characteristics of cotton fibres, efforts are constantly being made to make cotton products flame retardant:

Mohsin et al. [193] applied N-ethyloldimethylphosphonopropionamide, commercially known as Pyrovatex® (Huntsman Corporation, Texas, USA), on cotton fabric using citric acid as a formaldehyde-free bio cross-linking agent and sodium hypophosphite (SHP) as catalyst for cross-linking of citric acid with cotton. The flame retardancy of the fabric was found to increase due to the presence of citric acid and the catalyst Pyrovatex® and the additional phosphorous based catalyst SHP. Finishing of cotton textiles using formaldehyde and halogen based flame retardants generates toxic and poisonous substances, when on fire, which are harmful to humans and to the environment. Therefore, researchers have tried to explore formaldehyde-free and halogen free flame retardants for cotton fabrics [194-197] thus offering environmentally-

friendly solutions to increase the fire resistance of cotton fibres. Similarly, a novel formaldehyde-free phosphorus-nitrogen flame retardant with multiple reactive groups, dioxo (3-triethylphosphite-5-chlorine-1-triazine) neopentyl glycol (DTCTNG), was applied to cotton fabric to enhance fire-retardant behaviour [170]. In different studies, organo-phosphorus compounds [methacryloyloxyethylorthophosphor tetraethyl diamidate (MPD)] [198] and hexamethylenediamine-*N, N, N', N'*-tetra (methylphosphonic acid) (AHDTMPA) [199] were applied to cotton fabric to improve its flame resistance. Carosio et al. [200] pre-activated cotton fabric with poly (acrylic acid) and then employed starch and poly (phosphoric acid) alternately via a layer by layer assembly method for efficient and sustainable bio-based coatings to improve the flame retardancy of cotton fabric. A detailed description of the process is presented in Figure 14. The results demonstrated highly-efficient and green fire protection solutions to be exploited for cotton substrates. Caseins and hydrophobins, which are phosphorus and sulphur rich proteins and considered green flame retardants, have been successfully applied on cotton fabrics starting from protein aqueous suspensions/solutions, resulting in enhanced flame resistance of treated fabrics [201]. Basak et al. [202] developed a flame-retardant cotton fabric using spinach leaves juice (an eco-friendly natural herbal extract). Similarly, a green finishing treatment, consisting of whey protein isolates, was performed on cotton fabric to enhance its thermal stability and flame resistance [203].

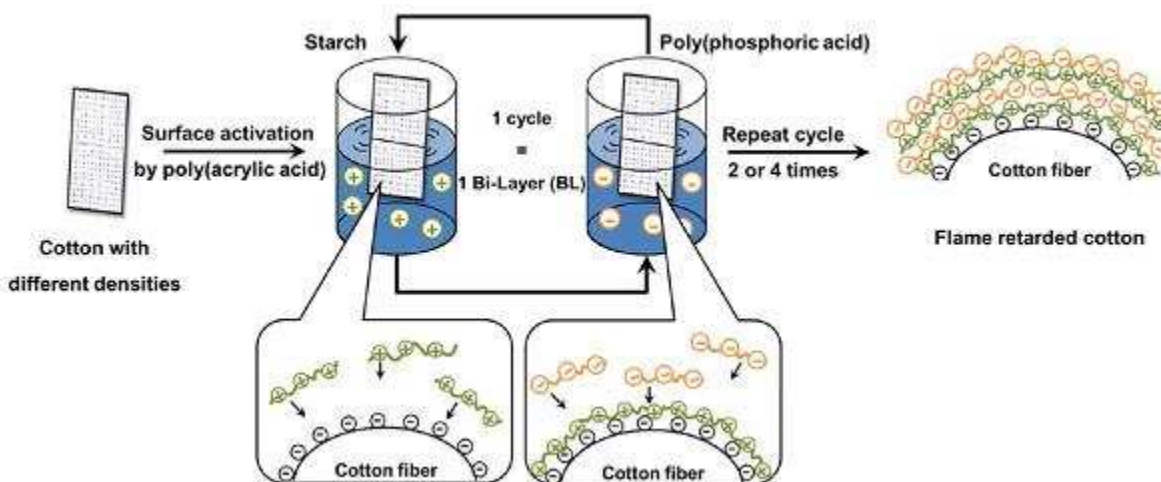


Figure 14. Schematic diagram of the adopted layer-by layer assembly [200]

Textiles with water and oil repellency have gained increasing interest in sports and outdoor applications. Only few studies based on environment-friendly approaches to increase the water and oil repellency of cotton fibres are cited here. Gao et al. [204] used polyhedral oligomeric silsesquioxane (POSS)-based hybrid nanomaterials to increase the hydrophobicity and oleophobicity of cotton fabrics. Mohsin et al. [206] applied fluorocarbon-based acrylate polymer (Genguard L-19296) on the surface of cotton fabric with the help of an eco-friendly formaldehyde-free cross-linker (citric acid) as a durable finish to improve the oil and water repellency of treated fabrics. In the same way, the surface of cotton substrate was made hydrophobic by using an environmentally-friendly and non-toxic polymer nanocomposite comprising a C-6 perfluorinated acrylic copolymer and silica nanoparticles and acetoxycure silicone (PDMS) resin [206] and a colloidal suspension of zinc hydroxide followed by subsequent hydrophobisation with stearic acid [207].

Mosquito-repellent finishing has a prime importance in the insect-repellent finishing of textiles because the bite of a mosquito can cause serious life-threatening diseases such as malaria, dengue and yellow fever etc. In a recent study, durable mosquito-repellent finishing of cotton fabrics was carried out with natural oils like tulsi, lemongrass and citronella keeping in mind the ecological and economical aspect and their performance was compared with a synthetic repellent diethyl metatoluamide (DEET) [208]. The mosquito repellents were applied using a microencapsulation technique. The results showed that the performance and washing durability of natural oils (especially lemongrass) was comparable with the synthetic repellent. Similarly, cotton fabric was finished with microencapsulated citronella essential oil and the insect repellency was assessed against *Aedes aegypti* mosquitoes (209). The results demonstrated a higher and longer-lasting protection from mosquitoes as compared to fabrics sprayed with an solution of the essential oil in ethanol.

3.2.4 Cotton in Technical Textiles

The use of textile fibres in new technical applications has substantially increased in the last decades. The high economic growth rate of the technical textiles market is demanding new or additional properties of textile fibres to meet the requirements of specific technical end products (210). Among the textile and technical fibres, the consumption of cotton fibre in this regard is under pressure due to its poor mechanical performance, variation in fibre properties and cost in

certain applications [211]. However, due to the global issues of sustainability, carbon footprint and disposability, the interest in the use of cotton fibre is increasing in many technical applications [212] including medical textiles, smart textiles, healthcare and hygiene and disposable nonwoven products. The good absorbance, softness, comfort, superior wet strength, breathability, biodegradability and natural feel make cotton a fibre of choice in disposable healthcare and hygiene applications [213]. Mostly bleached cotton is used in nonwoven products because it is cleaner and free of inherent impurities. Hydro-entanglement technology is usually used to produce cotton-based nonwovens because it not only allows the bonding of fibrous web but also helps the additional cleansing of cotton fibres. A recent study explored the potential of using comber noil (a by-product from the production of fine-quality combed-cotton yarns) to produce hydro-entangled nonwovens for hygiene and healthcare applications [214]. The results of this study showed that hydro-entangled nonwovens from comber noil can be potentially employed in disposable applications. The structure and properties of resulting cotton nonwovens can be engineered by changing the water-jet pressure and conveyor speed. Similarly, the feasibility of utilizing greige (non-bleached) cotton comber noils in the development of air-laid cotton batts bonded with hydro-entanglement technology for certain economical, environmentally-efficient and sustainable end-use products, have been explored [215]. The use of UltraClean[®] cotton (Barnhardt Manufacturing Company, Charlotte, North Carolina) as a valuable raw material for hydro-entangled nonwoven products was also presented in another study [212]. Sawhney et al. [212,216] used greige cotton (scoured/bleach-less) to produce hydro-entangled nonwovens at different water jet pressures. The results of their preliminary study revealed that, depending on the base material type, density and the various processing conditions, there are certain “threshold limits” of the water pressures at which the greige cotton nonwoven fabrics first become partly hydrophilic (from the original hydrophobic stage) and then at higher pressures, the fabrics become wickable and absorbent [212]. Furthermore, greige cotton is a viable and promising candidate for incorporation into existing and new nonwovens and related products for many end-use applications, such as disposable/reusable/recyclable/semi-durable and even durable wipes, uniforms, towels, sheeting, tablecloths, napkins, flushable articles and perhaps even sustainable “green” denims. Due to increasing attention to replace non-biodegradable synthetic-fibre-based nonwovens with biodegradable and disposable cotton-based nonwovens, research was conducted to find the effect of different biodegradable binder fibre

types and content and bonding temperature on the bond morphology and fracture and failure mechanisms of cotton-based nonwoven fabrics. The outcomes of this research exhibited the potential of using these nonwovens as absorbent materials due to low flexural rigidity and good absorbency [217]. Studies also exist on using cotton fibre, blended with flame retardants, as high-loft nonwoven for bedding products such as comforters, pillows, and mattress pads [218], perpendicular-laid high-loft nonwoven with better fire resistance and compression resilience [219], needle-punched nonwoven for absorbent products [220], absorbing material blended with bamboo fibre for baby diapers [221] and as nonwoven reinforcement for automotive composites [222].

Smart textiles are textiles that can sense and react to environmental conditions or stimuli from mechanical, chemical, thermal, electrical, magnetic or other sources. They are also able to sense and respond to external conditions (stimuli) in a predetermined way [223]. Smart textiles have gained considerable attention due to their essential features including weaveability, wearability, stretchability and sensing/response capability [224]. Cotton fibres, after making them conductive, can substantially be employed in smart clothing [225]. In different studies, cotton fabrics have been made conductive by coating with polypyrrole/multi-wall carbon nanotubes (MWCNT) [226], polypyrrole/CuO nanoparticles [227], polypyrrole/lignosulfonate [228], multi-wall carbon nanotubes [223] and carboxylated MWCNT [229] to make flexible electrodes for supercapacitors/energy storage materials. Zhang et al. [230] made a cotton yarn conductive by the self-assembly of single-walled carbon nanotubes (SWCNTs) through electrostatic forces. The yarn was subsequently used to make chemi-resistors which demonstrated electrical response to ammonia gas at room temperature due to the variation in hole density of SWCNTs. Due to the reinforcement and protection of carbon nanotubes (CNTs), the cotton textiles exhibit enhanced mechanical properties, extraordinary flame retardancy, improved UV-blocking and water-repellent properties. Therefore, CNT-coated cotton fibres can be used in the development of textiles for healthcare, sports, military applications, and fashion [211]. Azam et al. developed multifunctional and durable cotton fabrics by in-situ deposition of silver [231] and copper [232] nanoparticles for applications in different areas of smart textiles. The developed smart cotton fabrics were evaluated for electrical conductivity, electromagnetic shielding and durability to washing. The results confirmed improvement in these properties. A similar study compared the performance of silver and copper-coated stretchable cotton fabrics [233]. Azam et al. [234] also

investigated the utility of silver coated cotton blended fabrics as electrodes in electrotherapy applications. The unchanged electrical volume resistance over repeated extensions and insignificant change in electrical resistivity over prolonged time suggested potential usage of the developed fabrics as flexible textile electrodes in electrical-nerve-stimulation electrotherapy applications. The cotton fabric was functionalized with CNTs to produce a highly-efficient and flexible electro-thermal heater. The outcomes of the study revealed the efficiency of CNT-functionalized cotton fabrics as promising candidates for low-cost wearable fabrics, flexible heaters, bullet-proof vests, radiation-protection suits, and spacesuits (235).

The use of textiles in the medical and healthcare industry is mainly concerned with reducing exposure to, and transfer of, various micro-organisms that are commonly present in the atmosphere. Cotton fabrics have been coated with microencapsulated copper oxide nanoparticles to evaluate their antibacterial resistance. The results proved their efficacy against microbes supporting their use in the manufacture of medical apparel [236]. Budimir et al. [237] examined the antibacterial and antifungal activity of citric acid-treated cotton textiles. The performance of the treated cotton fabric was evaluated against gram-negative bacteria, gram-positive bacteria and yeasts. The results confirmed the possibility to substitute potentially-hazardous substances with eco-friendly citric acid for cotton medical textiles. The antimicrobial performance of cotton fabrics was enhanced using, core-shell nanoparticles consisting of silver nanoparticles as core and chitosan-O-methoxy polyethylene glycol (CTS-O-MPEG) as shell [238], methoxypolyethylene glycol-N-chitosan graft (MPEG-N-CTS) copolymer [239] and microwave radiation-cured alginate nano-capsules containing peppermint oil [240] for medical applications. Cotton fibres have also been functionalized to impart antibacterial activity by direct loading of silver nanoparticles [241] and by loading silver nanoparticles developed by a green approach using natural leaf extracts [242] for usage in medical and infection prevention applications. Cotton is commonly used in wound dressings owing to its inherent hydrophilicity and moisture and fluid retention properties. Cotton fabrics were modified with encapsulated Aloe Vera extract [243] and antimicrobial peptides [244,245] for wound-dressing applications. The results demonstrated the higher antimicrobial and wound-healing effects of the treated cotton fabrics.

4 Environmental perceptions

4.1 Genetically-modified cotton

Cotton yield and growth is frequently obstructed by means of a variety of abiotic and biotic stress factors (BSF). Considerable quantities of crop yield are endangered owing to the presence of different BSF, for instance pathogens (9%), weeds (36%) and insect pests (37%). Various traditional methods such as mutagenesis, somaclonal variation and conventional breeding were adopted and have upgraded the traits such as fibre quality, heat tolerance, photo-insensitivity and early maturity, but the integration of advantageous traits following these approaches is limited by diverse evolutionary constraints. Besides, employing intensive breeding has constrained the existing gene pool for enhancement of cotton. (246). A key problem in agriculture is insect pests [247]. Around 30% of cotton yield is attacked by pests in spite of the actions taken to control insect pests using chemical pesticides [246]. Moreover, their extensive use has caused many problems; several chemical insecticides contaminate the environment by killing beneficial insects along with insect pests and humans can also be severely affected by the insecticides and pesticides. Furthermore, the majority of insects have now developed chemical resistance resulting in increased use of pesticides [247].

Through genetic engineering, scientists are now able to alter plants without relying on any sexual compatibility among species but by using biotechnology tools instead. Consequently, scientists can establish new crop varieties having features beneficial not only for humans but the environment as well. Various plants have been altered effectively to get better herbicide tolerance, pest resistance, stress tolerance and quality of nutrition. The introduction of plant biotechnology has integrated genes into crop plants from different sources to make the crop plants pest resistive [248]. The cotton crop is prone to damage by 162 species of pests during the period from germination to the final picking [249]. Genetically-modified (GM) varieties of cotton can control some of the pest infestations. The only successful approach to genetically-modified cotton crops for insect resistance has been the *Bacillus thuringiensis* (Bt) cotton toxin, a soil bacterium discovered by a Japanese microbiologist (Ishiwata) in 1901 [250], which was developed by integrating Bt into the cotton tissue. Afterwards, some (highly toxic to larvae of certain insect species) Bt strains (Cry+) were found. In 1938, in France, Bt was initially sold as a spray formulation to treat an insect pest, the European corn borer [251]. Transgenic cotton is

distinguished from conventional cotton when DNA from another organism is inserted into the genome of transgenic cotton. The inserted DNA is usually comprised of three parts namely a gene of interest, a promoter and a marker gene:

- The gene of interest produces an insecticidal protein from *Bacillus thuringiensis*.
- The promoter enables the gene to express itself as required.
- The last part of the gene is the marker gene which introduces the required characteristic (e.g. resistance to insecticides) into the genome of the plant.

The gene of interest in this case produces Bt toxin throughout the cotton plant over its complete lifespan; the proteins produced from the Bt gene are prefixed with 'Cry', like Cry1Ab, Cry1Ac, and Cry9c are detrimental to the larvae of beetles, moths, butterflies, and flies, and the toxin kills the insect by piercing its small intestine when the insect eats any portion of plant.

Monsanto (a leading agricultural biotechnology company) has introduced genetically-modified cotton worldwide, starting from the US in 1996. A technology fee is paid at a specific rate per hectare to the owners of the gene for the commercial production of GM varieties. Different countries may buy the technology from the companies owning the genes so developing countries buy the technology from the gene owner as they are not capable of developing their own genes [252].

The major challenge in agriculture in the medium term is to ensure fibre availability while conserving the environment to support an estimated 9 billion human world population in 2050. Conventional cotton has a major impact on the environment whilst showing lower profitability than Bt cotton [253]. Farmers had two options before the invention of Bt cotton, either letting cotton bollworms damage their cotton or sacrificing their health by using larger quantities of sprays on their crops. It is scientifically established that Bt cotton is very much pest resistive in particular against bollworm infestations and thus can enhance profitability with a reduction in the environmental footprint [254, 255].

Bt cotton has not only increased crop productions but also provided a better environment by lowering the consumption of pesticides; reduction in CO₂ emissions comparable to the removal of millions of cars from the road and furthermore helped small farmers and their families to avoid poverty. The area on which cotton is cultivated has remained steady for the last five decades however its productivity has enormously increased thanks to insect-resistance from transgenic technology [253, 256]. Bt influences other important factors in addition to cost and

yield, the first two of which are the reduction in labour hours and better health. The reduction in number of sprays brought about a reduction in the work in Makhatini Flats (South Africa) by two days per hectare for Bt cotton growers as well as reducing the exposure to pesticide poisoning [257]. This reduction in work hours enabled them to devote more time to their family or generate the additional income. Similarly, in China, an extensive decline in the use of chemical sprays on Bt cotton has occurred giving healthy benefits to farmers. Likewise, in Pakistan, Bt cotton adoption has raised the requirement for hired labour by 55 % [258]. The third factor to show benefit is the environment. The decrease in bollworm sprays has reduced the effect on the environment. However, some studies have reported an increase in non-bollworm pesticides due to the increase in pest resistance against Bt toxin [255]. To avoid pest resistance, a resistance management tactic “high dose plus refugee strategy” has been recommended in which some refugee non-Bt cotton is grown near Bt cotton. The purpose of the refugee cotton is to maintain the level of Bt-susceptible insect populations rather than exerting pressure favouring the emergence of resistant insects.

4.2 Organic cotton

Organic agriculture is an environmental production management system based on management practices that are intended to restore, sustain and improve ecological harmony which may further support and boost biodiversity, soil biological activity and biological cycles [41]. Organic cotton is also known as green cotton, environmentally-friendly cotton or biological cotton [259].

Organic cotton must be grown without resort to harmful toxic chemicals such as insecticides and synthetic fertilizers (unlike conventional cotton where chemicals are used) [259], and use materials and methods that avoid negative impacts on the environment [260]; for example, plants get disease due to three reasons: pathogens are present, the environment is favourable and the host is sensitive to that disease; in part (at least) the problem can be avoided by removing one of these factors. Apart from the contamination to the soil and surroundings that may arise from the practices employed in conventional cotton growing, cattle feed and edible oil are extracted from cotton seed, therefore, cotton production comes into the human food chain. Moreover, organic cotton does not use genetically-modified seeds nor does it use, in the wet processing applied in the final stages of manufacturing cotton fabrics, any type of toxic bleaches, dyes or finishes [261]. Another issue with conventional cotton growing methods is that beneficial insects are

killed by the pesticides [262] and the insecticides and pesticides can runoff the treated areas to contaminate the surface water [263]. It is estimated that every year up to seventy-seven million non-organic cotton workers suffer poisoning from pesticides every year. In addition, non-organic cotton consumes worldwide US\$2 billion of chemical pesticides annually [264].

Organic cotton was started to grow as a rotational crop in US and Turkey for the first time in 1990. The first organic cotton was distinguished owing to ecological features rather than for fashionable appeal, quality or design. In late 1992, some textile and clothing companies and designers initiated the sale of extra ecological, fashionable textiles, afterwards branded as the 'eco-look'. The eco-look lasted till late 1994, when fashion turned towards the use of bright colours and synthetic fibres. The quality, colour-range and design of organic-cotton articles got notably better in late 1990s. In general, the worldwide requirement for organic cotton remained roughly steady till 2000. By 2000, multinational companies in US became more concerned about social issues like child labour and working conditions, and some brands became aware that involvement in organic cotton might help them to increase or restore their brand value and image. However, they were not eager to pay considerably more for organic cotton than for conventional cotton so they started to use yarns blended with organic cotton fibre sharing 3-5 % in their products. In this way, organic cotton entered in market whose share increased with time and now products are available of pure organic cotton [265].

Soil fertility, weed management and insect management practices are important for growing organic cotton. Soil fertility involves practices including crop rotation (a typical sequence of different crops on farm fields), cover cropping (other crops are grown for soil cover to avoid erosion), and adding animal manure as well as naturally occurring rock powders. Weed management practices include flame weeding and insect-management practices include trap cropping (a crop is planted particularly to attract pest insects which are then killed), strip cropping (two or three crops are planted in the same field in strips width-wise), and managing border vegetation (this strategy leads to planting plants that provide substitute food sources). Currently, there are 18 countries growing organic cotton of which India's share is 56 %, second being China with 14 % share. Other countries include Kyrgyzstan (7%), Turkey (7%), Tajikistan (6 %), US (4%), and Tanzania (3%). These seven countries account for 97 per cent of total organic cotton global production [266].

It is reported that the organically-grown cotton offers advantages over conventional cotton because it reduces global warming and soil acidification by up to 46 % and 70 % respectively. Moreover, it is claimed to reduce soil erosion, water consumption, and primary energy demand up to 26 %, 91 % and 62 % respectively [260, 266, 267] and that the use of organic cotton in textile products reduces the risk of skin irritation and allergies and protects the environment from toxic chemicals which ultimately supports sustainable agriculture [262].

Even though organic cotton is thought to be advantageous as it avoids the use of synthetic fertilizers and toxic chemicals that are detrimental to the environment, it cannot be thought of as a universal alternative to conventional cotton because the share of organic cotton continues to be less than 1% of total cotton production [268]. Furthermore, it has some limitations e.g. organic cotton cannot be grown where pest problems are not manageable so relying straight away on an organic system can be result in crop failure. A textile product made of organic cotton only becomes available for consumers after 18 months from the preparation of land (269) and this delay is no doubt one factor affecting a grower's willingness to change.

A premium price is needed, particularly in unfavourable years in order to compensate for yield gaps between organic and conventional cotton. In years with good yield and/or high price for commodities, it is claimed that premium prices are not required to achieve comparable economic returns in organic and conventional cotton [270]. Organic Content standards (OCS) and Global Organic Textile standards (GOTS) are the important standards. GOTS monitors the processing, manufacturing, packing, labelling, trading and distribution of all textile products made from not less than 70 % certified organic natural fibres. OCS covers third party certification to make sure that a final product contains an exact amount of organically-grown material (271). The organic certification is tedious as there is a land management requirement, which for USDA organic standards, for example, is to be managed organically for 3 years before certification which means that no forbidden substances (no pesticides, synthetic fertilizers, or GMOs) can be used to the land. So, for the farmers, the land transition is costly. Moreover, to buy land that has already gone through this transition is very expensive. As organic farming is often more labour intensive (because it requires more time to manage the weeds and monitor pests), so, it also raises its cost [272, 273].

The organic cotton farmers need to ensure that they get untreated seeds, preferably from organic multiplication. After procuring the organic seed, it is necessary to provide suitable doses of nutrients for growing organic cotton. Table 4.1 demonstrates the recommended nutrients required for a soil of average fertility for high-yield cotton varieties. The previous crop can play an important role by providing substantial amounts of nutrients through nitrogen fixation. Organic manures such as cattle dung and compost have a wide range of nutrients as well as micronutrients in a balanced composition. Thus, sufficient micronutrients are likely to be available where organic manures are used in adequate quantity [262].

Nutrient	Quantity per ha	Possible resources
Nitrogen (N)	100-120 kg/ha	Residues from previous crop, nitrogen fixation through pulses, compost, vermin-compost, liquid manures
Phosphorus (P ₂ O ₅)	50-60 kg/ha	Residues from previous crop, compost, rock phosphate, wood ash
Potassium (K ₂ O)	40-50 kg/ha	Residues from previous crop, compost, muriate of potash, wood ash

Table 4.1: Recommended nutrient doses in average organic cotton fields [262]

There is, and should be continuing debate about the relative value and benefits, environmentally and otherwise of, on the one hand, organic cotton, and on the other, genetically-modified cotton. The genetically-modified cotton has become costly due to the higher costs of seeds which has led to financial pressure to farmers (in India) contributing, it is said, to farmer suicide. Also, prolonged use has had long-term negative effects, and pests have developed resistance against genetically-modified cotton.

In spite of the above mentioned disadvantages, genetically-modified cotton occupies the dominant part of world cotton production [274] and there are good reasons for this, not least relating to reduced inputs of insecticides, and improved yields. In the case of organic cotton, typically, apart from significant delays encountered during the early stages of moving to organic production methods during which the product cannot be claimed to be organic and cannot attract

a premium, this type of farming is labour-intensive, requires significant non-chemical inputs and the yields are typically low at around 375kg per hectare. There is considerable risk associated with making such a change; farmers, processors and retailers cannot rely on growing numbers of consumers consistently being prepared to pay a premium for the organic product.

4.3 Naturally-coloured Cotton

Cotton with naturally-coloured lint is considered to be coloured cotton (Figure 15). The concept of coloured cotton is not new, however, it started to be used around 2700 B.C. although of white cotton preceded it at around 5000- 7000 B.C [275]. The use of coloured cotton started to decrease during the industrial revolution as its low levels of production were unable to meet the demands of large industrial scale. Moreover, its inferior quality [276] and the cost-effective use of synthetic dyes on white cotton replaced the use of naturally-coloured cotton in the textile sector. In addition, synthetic dyes such as the azo dyes give exceptional colour fastness properties having a broad range of colour shades [277]. With time, the use and discharge of synthetic dyes started to cause environmental problems e.g. polluted water. Polluted water enters the water system and can badly affect the quality of underground water and consumers are becoming worried for coming generations about the effects of such pollution some of which arises from the chemicals being used in the dyeing of fabrics. Naturally-coloured cotton started to become popular again when parts of the textile industry recognized its potential and started to focus on ecology and sustainability to conserve the environment [278] as it is an eco-friendly textile raw material.. Naturally-coloured cotton undergoes pigmentation through the synthesis and accumulation of natural pigments in developing fibres [279] and the natural colour is expressed by the coloured pigments present in the fibre cell . Green and brown colours are the most widely produced [280,281].



Figure 15 Naturally-coloured cotton

Naturally-coloured cotton is antibacterial [282, 283] and shows natural resistance against pest and insect attack so it can be grown according to the methods of organic cotton farming. It requires lower amounts of water as it is drought and salt-tolerant, hence, can be cultivated in salty water. Moreover, it is found to be less flammable due to its low oxygen index linked to the presence of tannins and sodium salts (284, 285). It has high wax content and so has resistance against mildew and the colour pigments present in coloured cotton absorb some UV rays, which may offer some protection to the wearer. Naturally-coloured cottons do not lose their colour in laundering contrary unlike some direct-dyed cottons, instead, the colour is said to become more intense and deep after the laundering process [286].

There are problems; the yield of coloured cotton is lower than that for white cotton [287, 288]. The fibre quality is inferior due to its shorter fibre length, lower micronaire value and lower strength which ultimately give yarn of lower quality, and the colour range is limited. Also, in processes ginning and yarn manufacturing cross-contamination can occur and higher levels of process waste is generated when dealing with different colours. Some of the limitations arising from poor fibre quality can be overcome by blending with white cotton, which can help to increase the spinnability and compensate to some extent for the inferior quality of the coloured fibres.

4.4 Environmental concerns

Difficult environmental sustainability problems are being faced by the textile industry. A large amount of man-made fibres (63 %) are being synthesised from non-renewable sources causing substantial CO₂ emissions. Cotton is an important natural fibre whose demand is increasing worldwide owing to the growth of world population and it accounts for 24% of the total share of the textile fibres but cotton is apparently considered to be one of the thirstiest crops consuming large amount of water and is causing severe pollution owing to the use of large amount of pesticides. The later stages of textile production have even larger environmental impacts. Similar to other textile fibres, the spinning of cotton yarns and subsequent knitting/ weaving of fabrics depend upon fossil energy use giving CO₂ emissions and particulates. Similarly, textile dyeing, printing and finishing also produce toxic emissions/effluent.

4.4.1 Cotton cultivation

Cotton is said to be one of the thirstiest, mono-cultured, and intensive pesticide crops. It is grown on only 2.5 % of global arable land but accounts for 6.8% of all herbicides and 16% of all the insecticides used worldwide [289]. Global freshwater resources (lakes, atmosphere, or glaciers) are not evenly distributed across different regions and lakes and river systems, the visible form of freshwater, comprise merely 0.65% of worldwide freshwater resources. China, USA, India Turkey, and Pakistan can get their water from their internal freshwater sources whereas Uzbekistan relies on freshwater sources from other countries. Worldwide, irrigated cotton is largely grown in regions with dry conditions (53 %): Uzbekistan, the province Xinjiang of China and Egypt are completely irrigated whereas in Pakistan and Northern India, not all but most of the crop water is supplied by irrigation; in China, the huge use of freshwater for irrigation has dropped the water tables [289].

Cotton production significantly changes the climate. The production of industrial fertilizers uses a large amount of energy (1.5 % of global annual energy consumption) and releases a huge quantity of CO₂ into the atmosphere. Moreover, the extreme use of nitrates produces nitrous oxide that is 300 times more detrimental than CO₂ regarding global warming. As soil is a major carbon sink, so soil degradation badly diminishes its carbon sequestration capacity, thereby contributing to the greenhouse effect [290] and chemical pesticides not only affect humans but also influence biological diversity as well as surface and groundwater quality. The World Health

Organization (WHO) has already mentioned that pesticides are seriously toxic as well as sources of carcinogens. Some pesticides are not easily removed and their residues seriously affect ground water, soil, and the food chain. Other pesticide sources which produce contamination are from the fine mist spray, residues in animal feed (seed cake) and contamination of running water, illegal disposal of unused or expired pesticides and the improper use/disposal of pesticide containers. Various symptoms relating to pesticide poisoning cause dizziness, stomach cramps, heavy sweating and vomiting. Pesticides also affect domestic animals and wildlife. The frequent use of pesticides produces a situation termed the “pesticide treadmill”. It is a situation in which large amounts of pesticides have to be used to control pests due to the development of pesticide resistance. In the 1940s and 1950s, organochlorides and DDT were used and they enormously improved the yields of cotton for around a decade. Later on, resistance developed in insect pests and farmers started to use more and more pesticides (which not only increased their cost but also severely damaged the eco system and also killed beneficial insects [263,291]).

4.4.2 Cotton processing

Today, awareness is growing about the damage caused to the environment due to the use of chemicals some of which are carcinogenic and others that are poisonous. The origins of such effluents is chiefly because of heavy alkali discharges, inorganic salts and other chemicals such as dyes and surfactants.. Worldwide, the textile dyeing industry is recognized as a notorious cause of environmental pollution [157], mainly due to its need for a huge amount of chemicals as well as water for fabric bleaching, dyeing and finishing. Even though fabric treatment causes water, air, and noise pollution at each and every step, it is the fabric wet processing that is more problematic in terms of the large volume of clean water and the considerable amount of chemicals used, and, when the processes are completed, effluents having high oxygen demand, salt load and colour, in the form of unexhausted dyes lubricants, defoamers and other chemicals together with water, are discharged [292].

The dust generated during cotton processing is a key pollutant in cotton spinning and poses the risk of chronic bronchitis. Long term inhalation of cotton dust may cause the respiratory disease byssinosis and many studies report health issues pertaining to cotton dust from spinning [293].

For preparing for the weaving of cotton, sizing is done in which yarn is treated with a sizing agent, typically an adhesive substance. Different sizing agents such as starches, gums, polyvinyl acetate, carboxymethyl cellulose and polyvinyl alcohol are utilized to enhance the warp yarns' weaving properties such as abrasion resistance and smoothness. In the knitting process, it is noise and solid waste that are the major problems [293]. In dyeing and printing, where dye fixing agents containing formaldehyde are utilized together with reactive or disperse dyes, they cause severe skin and eye irritation, hence, non-formaldehyde based chemicals should be used in their place.

It is crucial to avoid the use of chemicals which end up in hazardous wastes. Such harmful chemicals require to be recycled and reused when toxic chemical outputs are unavoidable from processing. Recently, there has been some emphasis given to sustainable textile materials developed in an economical manner to avoid such chemicals. So-called eco-friendly textile fibres (bamboo, hemp, corn, milk, tea, pineapple, organic cotton, jute, organic wool, organic silk, banana leaf) continue to be explored but it can be difficult to differentiate between helpful developments and those which offer little ecological advantage over existing commodity fibres. Sustainable textile processing may be an alternative in diverse areas of wet processing for instance: the use of enzymes, eco-friendly dyeing, plasma treatment and supercritical fluid technology, digital ink-jet printing, use of ultrasonic waves in place of thermal energy, recycling of process inputs, electrochemical dyeing, foam finishing, innovations in dyeing and printing machines. Concerning textile dyeing and printing, sustainable developments are and have been extensive in terms of improvements in economy, quality and energy conservation as well as in addressing environmental concerns [294].

4.4.3 Post-consumer waste

The definition of waste is “any object or substance, which the holder discards or intends or is required to discard” [295]. Post-consumer waste is produced by industry (e.g. hotels, restaurants), public (e.g. hospitals) and private household consumers. Commonly, most clothing disposal reasons are because of poor fit, wear and tear, boredom and most importantly, fashion. Worldwide, post-consumer fashion waste is considered to be a growing dilemma, meaning that more fabric composed of all types of fibre ends up in worldwide landfills in the form of used

clothing [296]. As cotton is the second fibre mostly consumed worldwide after polyester, so, cotton waste is produced in a massive amount. The US alone produces 12 million tons of cotton garments waste of worth \$350 billion [45]. Though cotton is a natural fibre which naturally decomposes, if it is recycled, it is more sustainable as the need for virgin cotton (which consumes large amounts of water, pesticides and insecticides) will be decreased [297]. Post-consumer cotton waste is collected in the form of textile products used in home textiles and apparel. Cotton waste can be reused after recycling. The first step in recycling is sorting according to type and colour. Sorted cotton waste is then passed through the machines which perform the equivalent of a severe carding action. This action breaks the yarns and fabrics into small pieces which are further pulled to convert them into fibres. These fibres are then passed through a carding machine several times to become cleaned and much better mixed fibres suitable to spin into new yarns. The resultant recycled cotton fibres, having lower staple length than virgin cotton, are difficult to spin, hence not more than 30 % of the recycled fibres are mixed with pure cotton fibres to produce yarns of good quality (45). As cotton-waste fibres are already sorted by colour, they may not be re-dyed. It is estimated that one tonne of reused cotton saves 765 m³ of water (around 98% of that which would be used in the processing of virgin cotton) [44].

Different textile companies (Recover, Evrnu, Renewcel, Lenzing, and Worngain) are working on sustainable regeneration of cellulosic fibres from cotton waste. For instance, the “Recover” company claims that, in 2017, it saved 43.1 billion litres of water, avoided 3.1 million kg of pollutants, saved 156 million kWh of energy, and removed 2.9 million kg of textile waste and 3.2 million kg of toxic chemicals as well as preventing 60.7 million kg of CO₂ emissions whilst saving an area of 7.2 million m² of landfill space [45].

5 Problems: cotton growth, processing and consumption

5.1 Wrinkle recovery

In the apparel industry, cotton is by far the most used natural material because of wickability and comfort especially wearing comfort due to which its share in the apparel industry is around 50%

as compared with the consumption of other fibres [298]. Cotton is able to absorb moisture quickly hence apparel using cotton fabric gives a comfortable feel on exposure to the skin [299,300]. However, this quality of cotton is the main reason for its failure as far as wrinkling and dimensional stability are concerned. Wrinkles are produced because of the viscoelastic characteristics of the fibre and they can be classified as desirable and undesirable wrinkles [301]. Dimensional stability is the ability of a textile material to resist changes in dimensions [302] and therefore indicates to what extent a material will retain the original dimensions either after the manufacturing process or during use by customers [303].

5.1.1 Mechanism of wrinkle formation

Different factors are involved in the dimensional stability of fibres and fabrics such as the type of raw material, yarn structure, woven fabric construction and different chemical finishes that are applied to the fabric. Good moisture absorption, which is the most advantageous characteristic of cotton, is also responsible for poor wrinkle resistance in cotton fabrics. Cotton fibres consist of the long polysaccharide strands of cellulose which are held together by hydrogen bonds in the both the crystalline and amorphous regions of the fibre as shown in Figure 16 [304]. Water molecules penetrate inside the amorphous regions, hence these strands can move relative to each other and form new associations in terms of hydrogen bonding with other partner strands [305], whilst on drying, water molecules leave these strands which have formed the new complexes and cause wrinkle formation as can be seen from Figure 16 [175]. Further, more-detailed mechanisms regarding wrinkle formation and other wrinkle-related models have been extensively described by researchers [175, 306].

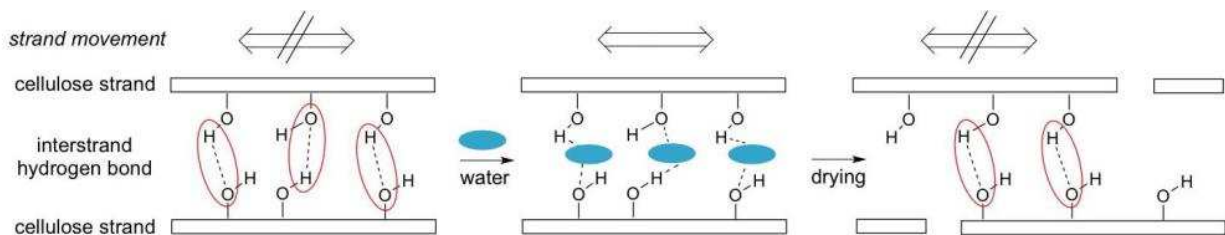


Figure 16: Development of wrinkles in cotton fabric [175]

5.1.2 Wrinkle resistance through finishes

5.1.2.1 Importance and limitations of chemical finishing

The use of chemical finishes in textile processing is important because it not only may improve aesthetics but also the functional characteristics of the fabric. Various groups of researchers have tried different methods, physical and chemical, in order to impart wrinkle resistance to cotton fabrics, for example, the use of formaldehyde-related products in wrinkle-resistant finishes [307] is long-standing. Both formaldehyde-based finishes, and non-formaldehyde finishes such as sodium hypophosphite with polycarboxylic acid act by cross-linking with the cellulose within cotton fibres [308]. Maleic acid also reacts through cross-linking with the cellulose in cotton fibres when applied along with NaH_2PO_2 [309]. Different formaldehyde-based thermosetting resins are employed for making cotton wrinkle resistant such as the urea/formaldehyde, phenol/formaldehyde and melamine/formaldehyde resins because of their ease in use but they cause adverse effects on the environment [302] and also to health [310, 311]. Melamine/formaldehyde derivatives do not have durability issues but they are more expensive and can cause the release of formaldehyde [312] and the cyclic urea methylol derivative is also one of them. Hence citric acid, maleic acid, tartaric acid and other organic acids have been tried in attempts to eliminate the use of formaldehyde, however their further use is limited because of the loss of strength in cotton fabric along with environmental issues caused by the presence of phosphorus [313] and much extensive work on glyoxal/urea-based derivatives and aldehyde-based derivatives has therefore been carried out [175].

5.1.2.2 New Trends in Wrinkle Resistance

Nowadays more attention has been paid to using alternative methods for achieving wrinkle resistance that are less toxic and not so damaging to the environment. The concept of using biopolymers for improving functional characteristics is gaining importance. Telhi [314] extracted chitosan from bio waste and used this along with dimethylol dihydroxy ethylene urea (DMDHEU) to improve crease recovery and flame-retardant properties, but the release of formaldehyde remains a major issue with this technique. In another study 3,3,4,4 benzophenone tetracarboxylic dianhydride (BPTCD) was effectively employed for the incorporation of wrinkle-resistance and antimicrobial performance [315,316]. BPTCD can be hydrolysed to 3,3,4,4 benzophenone tetracarboxylic acid (BPTCA), which can impart good wrinkle resistance along

with better mechanical properties. It is also able to provide ultra-violet protection. However, the major problem with BPTCA is its water solubility. Qi applied 5-(carboxyloxysuccinic)-benzene-1,2,4 tricarboxylic acid (BSTA) to cotton fabric in an attempt to confer wrinkle resistance. The succinic acid groups helped to dissolve the aromatic carboxylic acid. BSTA showed the same wrinkle-resistance behaviour as that of BTCA due to the high water-solubility of BSTA (317). For sustainable industrial chemistry, the formation of specific chemical compounds is necessary. In this regard the use of enzymes as a catalyst can be used for the replacement of conventional industrial chemistry [318,319]. On the other hand hydrophobic cotton fabrics are gaining interest because of additional characteristics like antifouling, friction reduction, self-cleaning and water repellence [320] hence, various surface modifications are already in use for making cotton fabric hydrophobic. In this regard Zhao [320] adopted an environmentally-friendly and cheap method, by coating cotton fabric with poly (ethylene glutarate) and the coated fabric showed improved hydrophobicity and wrinkle resistance. The wrinkle resistance was improved due to in situ enzymatic formation of monomers and oligomers of poly (ethylene glutarate) at the surface of cotton fabric.

Nowadays, the research is shifting towards nano-technology because the properties of substrates are changed when the size of particles are reduced to nano-scale ([321]. This concept has been effectively utilized for the development of innovative finishes for textiles. Nourbakhsh [322] deposited copper nanoparticles by two different methods using sodium hypophosphite as a catalyst and maleic acid as a cross-linking agent. The results showed that a higher concentration of copper nanoparticles caused an increase in the crease-recovery angle. Chemical finishes have been used for making cotton fabric wrinkle-resistant for some time, but now more-serious effort has been given to develop alternative, cheap and environmentally-friendly methods that use fewer resources in terms of processing, chemicals, energy and emit less toxic residues. For this purpose, enzyme coating or coating with biopolymers are interesting areas that need to be explored further.

5.2 Flammability

Cotton fabric has gained tremendous popularity both in military and civil applications because of good water absorbency, air permeability, mechanical properties and biodegradability [323-325]. However cotton fabric also possesses some drawbacks which limit its applications for example

poor water repellence, poor microbial resistance, weak wrinkle-resistance and both flammability and ease of ignition [326]. Flame retardancy of cotton fabric depends on several factors which can be summarized as the structure of the fibre, density of the yarn, construction of the fabric and the weave design, availability of oxygen and the prevailing humidity situation [175]. The process of burning in cellulose can be categorized as glowing followed by flaming. Glowing is actually direct oxidation of cellulose and is regarded as a slow combustion process. However, flaming combustion involves a solid as well as a gas phase and it can be considered as a cyclic process involving continuous supply of gaseous fuel that continues fire propagation [327].

5.2.1 Mechanism of flammability in cotton fibre

In textile fibres the process of ignition takes place when flammable gases released from the pyrolysis process combine with available oxygen below their flammability limit. The heat produced during the combustion process gives additional thermal energy required to further propagate the process of pyrolysis; it is the fibre that is the source of the fuel. Chemical investigation of the process of pyrolysis has revealed that branching of chains within the fibre takes place when oxygen reacts with gaseous products of the cellulose fibre during pyrolysis. For effective working of a flame retardant finish it must be able to disrupt chain branching [328]. Further detail about the mechanism of combustion, the different processes involved during pyrolysis, initiation and propagation of flame and char formation can be found in Issue 3/4 of Textile Progress published in 2012 [175].

5.2.2 Principles of flame retardant finishes

Most of the flame retardant agents work either by modifying or changing the mechanism of combustion and pyrolysis through physical or chemical means [175]. Physical effects through which flame retardancy can be achieved are dilution, coating and cooling mechanisms. Researchers have tried different techniques for achieving flame retardancy like forming a protective layer having lower thermal conductivity, or finishes that are able to decompose on heating and give off non-flammable gases like carbon dioxide, water vapours, ammonia and sulphur dioxide which can diffuse with available oxygen and protect the fibre from combustion, and some flame retardants work as heat sinks and cause cooling of the substrate [329]. However, the second category of flame retardant additives are able to interfere chemically through the formation of char and water during combustion.

5.2.3 Flame retardant additives

Different types and categories of flame-retardant finishes and treatment methods have already been in use to yield durable, semi-durable and non-durable flame retardant finishes. Mostly, the finishes are halogenated, nitrogen-based, phosphorus-based or incorporate different minerals [330] however, where non-durable flame retardant treatments are concerned they give temporary protection because they use water-soluble salts [331] such as inorganic bases and acids or inorganic salts [327]. Semi-durable finishes for flame retardancy can withstand from 1-20 washing cycles and are suited for textiles that are not washed on a very-frequent basis. These finishes can contain insoluble salts like borates of tin, phosphates, zinc, aluminates and tungstates. Aluminium phosphate can be effectively used because of the presence of the phosphorus, but it needs high loading that causes problems in fabric handling and mechanical properties [332]. Some inorganic salts can give good flame-retardant characteristics for durable finishes (1-50 washing cycles) and depend on halogens, phosphorus or nitrogen for their effectiveness as they form cross-linkages within the fibre structure [333]. During combustion flame-retardant polymers give denser smoke as compared with neat polymer (which could become a problem in itself but in this regard, using metal oxides for smoke reduction is an effective approach [334].

Metal ions of cobalt, phosphate, silver, chromium, mercury and cadmium react with cellulose ammonium phosphate and cellulose phosphate which are helpful in flame retardancy by causing smoke reduction [335] although for some of these, their toxicity could provide new problems. In general mechanical and flame-retardant properties of substrates are also related to the particle size of any metal hydroxides in the finish and their distribution [336], hence focus is now shifting towards the development of nano-sized particles from metal hydroxides. Further surface modification of metal hydroxides and encapsulation improve their miscibility and dispersion in the polymer causing higher flame retardancy. Further detail of flame-retardant characteristics of halogen compounds and phosphorous compounds have been provided in an earlier review [175].

5.2.4 New Trends in Flame retardant finishes

Flame-retardant fabrics can be achieved through different mechanisms from those described in the previous sections. Silica precursors, introduced by using a sol gel technique, form three-

dimensional nanostructures of polymers on fibres hence separating fibres from fire [337,338] and thereby making fabrics flame retardant; furthermore in this process, immobilization of inorganic and organic compounds like nitrogen and phosphorous compounds possessing flame-retardant characteristics is made possible [339-341]. Another option is to coat fabric with reactive phosphorus organo-silicon compounds [342]. In recent studies, cotton fabric was treated with guanidine carbonate and ammonium phosphate by using aminopropyltriethoxysilane (APS). Both compounds are rated as highly flame-retardant and because of their immobilization in APS they can be effectively attached to cotton fibre. Furthermore, as both compounds contain alkoxy groups they can form stable bonds with the hydroxyl groups on the cellulose molecules in cotton [343]. One method for applying flame-retardant coatings to a fabric is in the form of layer-by-layer assembly [344,345]. By using this technology a flame-retardant nano-coating can be applied to a variety of fibres like ramie, polyester and cotton [346, 347]. Recently a new method for depositing oppositely-charged polyelectrolytes by using a single solution has been proposed by Haile in order to minimize deposition steps [348]. Marcus developed a method for conferring flame retardancy on cotton-nylon blends using a halogen-free coating consisting of melamine phosphate and polyethylenimine along with 20% less deposition on fabric [346].

For 'coloured cotton' the brown colour is due to the presence of tannins, which is also linked to the higher thermal resistance of this fibre in comparison with white cotton. This natural flame retardant property has attracted attention towards the potential use of tannins in flame-retardant applications [284]. Sunghyun [349] produced cotton non-woven fabric and coated it with tannic acid and sodium hydroxide. Experimentally it was found that tannic acid was not effective in producing flame retardance in cotton, however the addition of sodium hydroxide in small concentrations improved the limiting of the oxygen index up to 30%.

Phosphorylated compounds are the predominant agents for bringing about flame retardant characteristics in cotton fabrics, however most of these compounds release formaldehyde during their service life. Many innovations in these compounds have been conducted by researchers [350]. However, growing unrest towards anti-environmental issues is pushing scientists to explore new directions for the development of eco-friendly flame-retardant finishes and chemicals. Linear polyamidoamines (PAAs) are amongst the family of synthetic polymers that have exceptional structural versatility and good potential for flame retardancy in cotton fabric

finishes [351]. They are also degradable to non-toxic products within a few months but the only drawback is that they are not very stable in wet conditions [352].

5.3 Impact of cotton cultivation on climate

Cotton cultivation is a broad concept that can be divided into land preparation, seeding, using pesticides and fertilizers, watering and harvesting. The environment is one of the most important aspects affecting not only human beings but also other living creatures as well as vegetation. The environment can be described as the circumstances taking place around an organism or group of animals. Connell [353] divided the environment into different levels:

- Immediate environment
- Local environment
- Regional environment
- Global environment

Generally, ozone layer depletion, climate change, terrestrial eco-toxicity and acidification, human toxicity, agricultural land occupation, freshwater eco-toxicity and eutrophication are important parameters while studying environmental aspects.

The increase in population and industrialization are the main reasons for the increase in demand for cotton fabric and this has pushed cotton-producing countries to meet the increased demand. The crop of cotton is mainly distributed in regions having dry areas where it is difficult to grow other commodities and approximately 270 million farmers worldwide dependent directly or indirectly on this crop [344,345]. There is no doubt that increased production of cotton is a contributing cause of severe adverse effects on the environment in the form of water pollution, air pollution, land contamination, depletion of ground water, global warming, climate changing etc. [356]. More than 50 cultivated and wild species of cotton exist worldwide, of which the four categories of cotton grown on a large scale are *Gossypium barbadense*, *Gossypium herbaceum*, *Gossypium arboretum* and *Gossypium hirsutum*; these categories of cotton meet 95% demand of cotton worldwide. Cotton fibres with extra-long staple length such as Sea Island cotton, occupy only 3% of world production; they belong to *Gossypium barbadense*. Overall production of cotton quadrupled in just over half a century from 7 million tonnes (1951) to 27 million tonnes (2007) but this had risen dramatically to 116.7 million tonnes by 2014 accounting for 5.1 million

hectares of cultivation land [357]. As stated earlier, the production of conventional cotton requires excessive use of inputs in the form of pesticides, fertilizers and irrigation [47, 358]. Pesticide is a general term that includes a broad range of compounds including fungicides, insecticides, herbicides, nematocides, molluscides and rodenticides and cotton cultivation is regarded as a pesticide-intensive process throughout the world [263]. Current research shows that excess use of chemicals, different kinds of toxic emissions, occupation of land and most importantly water consumption need to be focused on while studying cotton production [359]. Enormous use of pesticides is causing diverse adverse effects like increases in the price of cultivation, killing of beneficial microbes, environment pollution, residues of pesticides and insecticides in cotton and other value-added products from cotton endangering human health. The production of cotton uses around 25% of insecticides and 11% of pesticides worldwide with the proportion of pesticides being more in developing countries such as India where cotton farms constitute only 5% of cultivable land but the proportion of pesticides is around 50% of the total of the pesticides used in the country and in the case of Pakistan where 70 to 80% of its pesticides are used in cotton farming [255,360].

The biggest concern regarding cotton cultivation is the excessive usage of water. Throughout the world 53% of cotton cultivation is carried out using irrigation water and whilst different irrigation systems are used for cotton cultivation, around 95% of cotton cultivation is carried out by using a furrow irrigation system, a system which causes huge wastage of water in terms of evaporation and transpiration. More efficient systems should be adopted to avoid this excessive usage and wastage.

Several reports are available showing the impact of pesticides on humans, wildlife and on the environment. Skin, the largest organ of human body, takes up the traces of insecticides which are released from cotton during its life cycle which are then able to make their way into the blood stream from an individual's clothes. People using water near to cotton farms encounter more problems because they risk their lives because of seeped water into the ground.

Aerial spraying and over spraying of the cotton crop are amongst the most-significant factors affecting the environment in several ways and it is reported that the use of pesticides has adverse effects on the river ecosystem in Australia causing decreases in diversity of microorganisms [361].

One of the adverse effects of pesticides is contamination of the hydrologic system as it supports aquatic life, drinking water and many other purposes. Pesticides are transported by air, soil and water (primary mechanisms for pesticides transportation) into living creatures causing biological magnification [361] and deterioration of the ecosystem. Pesticides and different kinds of fertilizers are amongst the major pollutants of river systems. Although water treatment is done before supply, industrial pollutants and traces of pesticides are not removed by these techniques. To avoid the current prevailing situation of cultivation of cotton in terms of excessive use of water, pesticides and insecticides, cotton farmers, especially those in developing countries, need to be guided so they can change from traditional/conventional methods towards sustainable agricultural methods. Given that it occupies only 1% of total world cotton produced, the production of organic cotton has not yet convinced the world about its feasibility even though currently this seems to be the best solution for long term fertility of soil, helping to meet food scarcity by rotating crops which is also helpful for farmers to get better revenues with low incomes. In this regard maybe more farmers need to be supported and trained so they can effectively participate in the globalization of organic cotton production.

5.4 Concerns with genetically modified cotton

For a long time, farmers have been trying to change the genetic makeup of plants. Genetically-modified cotton was first grown in the USA on a large scale in 1996. Genetically-modified cotton is the result of such efforts in which characterized genes are incorporated in a conventional cotton plant through using recombinant-DNA technology. The required gene that is to be introduced is called a transgene and plants having a transgene are called transgenic plants. The statistics from the last 20 years showed that land under cultivation for the production of genetically-modified cotton is continuously increasing and reached around 18.5 million ha (hectare) in 2014 having a growth rate of 3-4% per annum [362]. As far as cotton is concerned crossbreeding between cotton plants having required characteristics, produces different varieties with improved fibre yield and quality and having better sustainability in temperate regions [363]. In spite of all these achievements the potential of yield increase via this traditional approach has reached a plateau that requires new genetic engineering techniques [364]. After the successful introduction of genetically-modified (GM) cotton, questions were asked about the potential impact of these crops, such as apart from whether this modified crop will

affect only targeted insects, will it have adverse impact on climate and living creatures or not and to what extent these will be beneficial to the environment by reducing the input of synthetic chemicals used in cultivation. There seems to be a difference in opinion as far as genetic modification of cotton is concerned. One group of people in favour including consumers, farmers and researchers is of the view that genetic modification can attribute characteristics (like pests or insects resistance) that results in less use of harmful pesticides and insecticides, further this technology can be used to promote sustainability and help to revolutionize agriculture on modern lines giving increases of yield as well as quality of cotton fibres [365,366]. However Altieri and other critics [367, 368] are of the view that there is no need for plant biotechnology as it is bad for consumers' health, will impoverish small farmers, increase the use of pesticides and will bring about a decrease in biodiversity. This discussion is very important, especially for developing countries which have not yet decided whether to use this technology or not. Genetically-modified cotton is promoted on the basis of the following three advantages.

- Increase in the yield of cotton crop.
- Increase in the income of farmers.
- Less use of pesticides (more environmentally-friendly).

Different potential risks are attached with GM cotton as compared with non-GM cotton like transgenes that offer a particular advantage but could increase invasiveness of the crop. Similarly, a high proportion of insect toxins in biologically-modified crops may cause toxic effects to other organisms or non-target insects. During the transformation stage, antibiotic-resistant genes are introduced into GM crops but the introduction of these genes can promote the development of antibiotic-resistant bacteria. It is also not clear whether current varieties of herbicide-resistant cotton and Bt cotton are more invasive than conventional varieties of cotton or not. However some varieties of cotton having novel transgenes like salt and drought tolerance which provide a selective advantage can turn out to be more invasive and could cause the development of 'super weeds' in the case of the gene passing to other wild relatives [369]. Different techniques have been developed in order to control migration of genes from GM crops to other wild relatives like seed sterility, induction of pollens and manipulation of crops to produce GM seed without fertilization [370,371]. Tabashnik [372] says that the insect-resistance management techniques (IRM) that are used in Bt crops are effective in managing and minimizing insect attack. Different IMR techniques that include both genetic and agronomic

approaches have been effectively used in Bt cotton, however the most widely-used approach is high dosage [373,374]. However, it is clear that biotechnology has revolutionized the agriculture industry through genetic modification with better resistance towards insects. One such example is transformation using insecticide-resistance genes from *Bacillus thuringiensis* [375, 376]. These kind of modifications have shifted cultivation away from the previous heavy dependence on chemical pesticides.

Eliminating or reducing the use of some kinds of pesticide may have some benefit, however it can also have adverse effects on profit and yield. It is possible to find adverse environmental impact by discarding one pesticide and using another one. Hence for analysing environmental stability, the toxic load should be calculated and compared with current practices and through the introduction of other technologies for enhancing plant resistance [377]. Furthermore, the prospect of transferring specially-extracted genes to other wild varieties and to microbes is a serious concern from the environmental point of view. On the one hand GM cotton ensures sustainability because it is pest resistant and decreases the load of pesticides on the fields, whilst on the other hand, some industrial agriculture reform organizations are trying to prove it has bad impacts on the environment and human health. Whatever theory is correct it is clear that biologically-modified cotton is gaining popularity on a global scale in spite of the high prices of GM cotton seeds [378].

5.5 Potential hazards in cotton cultivation and processing

Cotton is not only a source of natural fibre that is used for clothing and textiles but gives a high quality vegetable oil as well [379]. The worldwide share of cotton fibre in textile consumption is around 38% which is second highest after polyester. Cotton production is difficult due to pest pressure and different environmental factors like temperature, drought and varying soil conditions with respect to different nutritional levels. Globally cotton production is consuming 2.4 % of total arable land and 16 % of the world's pesticides are used only in cotton cultivation. Currently around 2.5 million tonnes of pesticides are used for controlling diseases, weeds and pests each year [380].

The exposure of human beings to pesticides can take place by direct or indirect means. The direct exposure of pesticides is during the application of these compounds, however secondary exposure is through the environment or by consuming contaminated water [381]. Because of

these issues, natural biological methods for controlling insects have been initiated. Cotton cultivation without using fertilizers, pesticides, defoliants is called organic cotton with the objective of maintaining soil fertility and to be not harmful to the environment [382].

5.5.1 Cultivation and cropping

The production chain of cotton comprises of the following key processes:

- Sowing of cotton seeds
- Growth stage of plant
- Harvesting
- Ginning
- Baling

Starting from the growth stage, this includes various inputs like excess water, usage of energy, land for cultivation, different kinds of fertilizers and pesticides. In simple words the potential hazards of cotton can be categorized as excessive use of water during production coupled with excessive usage of pesticides and insecticides that are threatening not only surface and ground water but also causing severe impacts on human beings and other living creatures. The need and usage of the above mentioned resources vary in different kinds of cotton like organic cotton and conventional cotton. Most of the environmentalists and researchers are convinced that conventional cotton is socially and environmentally hazardous compared with organic cotton since it consumes more fertilizers, insecticides and water as compared to any other variety of crop [293]. According to the World Health Organization, the pesticides Methamidopho, Aldicarb and Parathion are most dangerous for human beings and unfortunately these are included among the most-used pesticides for cotton production. Laursen [383] showed that the average t-shirt weighing one pound of cotton, if grown in the USA, consumes around 1/3 pound of fertilizers in growing its cotton fibre. Another survey by the National Agriculture Statistics Service, the statistical branch of the US Department of Agriculture, showed that fertilizers having nitrogen are more dangerous for the environment and fertilizers used for cotton contain around 92 % of nitrogen content.

Excess usage of chemicals, land used for cultivation, water consumption and emission of different gases are important parameters that need to be addressed while analysing the impact of cotton cultivation on the climate [359]. The cultivation of cotton requires enormous amounts of

water which includes 'green water' that comes from precipitation and 'blue water' which comes through artificial irrigation (73% of production). Around 2.6% fresh water available throughout the world is being used for the production of cotton, hence causing reduction in the availability of freshwater to cultivatable areas and also posing a serious threat to the environment [384].

Almost 53% of cotton fields globally are irrigated and that set of field results in 73% of cotton produced worldwide; irrigation is mostly used in regions having a warm climate like India, Pakistan, Uzbekistan, Egypt and some parts of China [385], which already have a deficiency of freshwater. In this regard the impact of cotton cultivation on water is not only depletion of water sources but also deterioration in the quality of water as well. Cotton cultivation and processing adversely affects water. In the cultivation stage this impact starts with the concentration of nutrients like potash, phosphorous, nitrogen and pesticides that mix with surface and ground water.

Environmental aspects of cotton cultivation are not only confined to water and air but cultivatable land is also an important parameter especially for those feeding from or living on it. Stalled agricultural productivity and land degradation are also important aspects from an environmental perspective due to excessive usage of agrochemicals [386, 387]. Toxic elements that come in water from the use of pesticides become attached to soil and transfer to other growing plants. Not only this, but harmful elements are also able to be deposited on the earth making the situation worse.

Having analysed all these input variables used in the cultivation and cropping of cotton, a cleaner and innovative concept for cotton production was introduced in 2009 by the name Better Cotton. It means managing all processes of cotton production in such a way that makes it environmentally and socioeconomically better than conventional cotton [358]. For Better Cotton six principles have been advised which are: effective usage of water, better crop protection, protection of natural habitats, improvement in soil management, preservation of fibre quality and promotion of decent working conditions. The Better Cotton Initiative is supported by a wide range of well-known retailers and branding organisations.

5.5.2 Cotton Processing

The fact that around 25% of cotton worldwide is harvested by using machines while 75% is handpicked can be a cause of ergonomic problems. America and Australia are using 100%

machine harvesting but this is not possible in developing countries for various reasons. Ginning is considered as an agricultural operation and as a continuation of harvesting [388]. The major hazardous aspects of ginning are the confined space, noise and production of cotton dust (which, if properly controlled, should be as low as 1 mg/m³). The dust and fine fibre problem is also evident in further processes such as in yarn and fabric manufacturing where it causes lung disease after long exposure. The cotton dust is particulate matter having soil, botanical trash and microbial matter [369]. As far as the impacts of spinning, weaving and textile processing are concerned from a cotton economic point of view, they are not very much different from that for other staple fibre types in that they all cause the consumption of large amounts of electricity which causes an increase in atmospheric acidification potential and elevated amount of CO₂ emissions [389,390]. Noise was a major issue with old spinning machines but this is now improving. In spinning mills the high humidification and temperatures required to assist fibre processing have a bad impact on the health of workers so well-designed air-conditioning plants need to be installed to replace the older methods of controlling humidity and temperature and workers should be properly trained to follow health regulations especially in developing regions.

The working conditions are further aggravated in dyeing and printing where enormous amounts of energy are used coupled with steam, different chemicals like bleaching agents, salts, softeners, wetting agents and dyes such as direct, azoic, indigo, reactive, vat, sulphur dyes, and pigments coupled with different finishes like flame retardant, water repellent and stain resistant agents contributing to the hazards at work [391, 392]. Dyes exist in different forms like granules, liquids, powder, pellets and tablets. Direct exposure to powder dyes by inhaling or through skin contact can cause eczema, occupational asthma and severe allergic problems. Azo dyes, through reductive cleavage, give off aromatic amines which are potential carcinogenic agents, hence the direct exposure to dyes during wet processing should be minimized.

Water resources are depleting globally because of increases in population, bad practices towards unnecessary wastage of water coupled with damaging water quality [393]. Around 2.6% of water is used for cotton consumption globally. On average 44% of used water in cultivation and different processes is not for serving domestic markets but for exports. This means that half of the water problems are generated because of its demand in foreign markets [384]. The water after absorbing different pesticides, herbicides and fertilizers not only diffuses into the land hence

damaging underground water but also goes into surface water through rain and through evaporation and mixes with the environment. In a study conducted in Brazil (the 4th largest producer of cotton) analysing hazardous elements in rain water, it was found that rain water carried 19 hazardous elements out of which 12 are used in cotton cultivation. In this regard the concept of a 'water footprint' was described by Hoekstra in 2002 [394]; it can be described in simple words; the quantity of fresh water needed to produce goods. Water footprint is further categorized into internal and external water foot print. By 'internal water foot print' it means using domestic water for producing cotton-related products for the inhabitants of the same country. However the 'external water foot print' is the annual amount of water used for producing cotton-related products for the inhabitants of other countries. The amount of water consumed in textile wet processing for cotton such as in dyeing, bleaching, printing and finishing is about 160 m³/tonne [384].

The biggest issue in the wet-processing of cotton is the excessive wastage of water with little recycling in developing countries which is responsible for the contamination of surface water after discharging into streams whilst still containing high contents of toxic dyes and other chemicals [395]. In some developed countries water, after purification, is further diluted in order to lessen the concentration of different hazardous elements on discharge, a practice which requires further wastage of water.

5.5.3 Hazards in use

Out of diverse and widespread bad impacts of pesticides, fertilizers, dyes, different finishes and chemicals, the most critical impact is on human health. Such impacts can be categorized in different ways like incidental or accidental, occupational or non-occupational, chronic or acute. The exposure to the above can be through oral (mouth), dermal (skin) and respiratory ingestion. Of these modes of exposure, the skin plays a major role while using cotton products. It is clear that clothing products during their entire life time release small proportions of either absorbed or chemisorbed quantities of different pesticides, fertilizers and other chemicals used in textile processing. Further excessive amount of waters are also wasted during laundering. Since cotton has high moisture regain it absorbs different surfactants that are also released in daily usage and can cause for skin problems. However while analysing the exposure risk all sources should be kept in mind [396]. The oral route plays a major role for exposure to hazardous chemicals, skin

is also a significant factor with the least impact being through inhaling [397]. Not only are dyes, insecticides or fertilizers hazardous but so are finishes using formaldehyde-based resins used for imparting durable press and easy-care characteristics in cotton.

As a first step towards improved production of cotton, farmers, with the strong support of retailers and brands should be motivated towards employing the Better Cotton concept to optimize the usage of pesticides, insecticides, and fertilizers from a cultivation point of view. Further down the line, more focus should be on using recycled cotton, this will not only reduce the burden on landfilling but also help to reduce bad impacts on the environment in the form of pesticides, herbicides and fertilizers.

6 Conclusions and Recommendations

Cotton is a key contributor to the economy of developing countries in particular, with India the top producer, followed by China then the USA. No other country comes close to their level of output but in the next group (each with less than half the production of the USA), Pakistan takes the lead over the rest of the world. Responding in a similar way to pressures experienced by farmers of any crop, cotton growers have had to decide how best to respond to the need to protect their crop as it develops, particularly from attack by pests. The vast majority have selected to achieve this by buying and sowing (expensive) genetically-modified seed, but then being able to cut down on the application of chemical pesticides and thereby reduce the associated costs. The consequence is that a high proportion of the cotton to be found across the world in commercial, household and personal goods is GM cotton.

There seems to be a difference of opinion as far as the genetic modification of cotton is concerned. One group of people in favour including consumers, farmers and researchers is of the view that genetic modification can attribute characteristics such as pest or insect resistance that result in less use of harmful pesticides and insecticides (more environmentally-friendly), can assist with sustainability and be of help in revolutionising agriculture on modern lines giving increased yields as well as improved quality of cotton fibres. Critics are of the view that there is no need for plant biotechnology as it is bad for consumer health, will impoverish small farmers, increase the use of pesticides and will bring about a decrease in biodiversity. This discussion is very important, especially for those developing countries which have not yet decided whether to

use this technology or not. Organic cotton, by contrast with GM cotton, accounts for just 1% of world production and whilst in principle it appears to have the capacity to address most of the important environmental issues associated with growing cotton, the costs to farmers associated with its implementation and accreditation and the unreliability of an ‘organic premium’ appear to be the major reasons for its low level of contribution to the total world crop. To put this in perspective, in 2014 GM cotton production occupied 18.5 million hectares and was growing at 3-4% per annum, whereas the area devoted to organic cotton production in 2017 was only about 300,000 hectares with around a further 260,000 hectares in the process of becoming organic. There is some middle ground, occupied by organisations such as the Better Cotton Initiative and Fairtrade, and although they may have differing emphases, they apply selected principles and criteria to cotton growing relating to the use of seed technology, irrigation systems, cotton variety, reduction of the use and types of pesticides for the production of cotton and decent treatment of small farmers to achieve what may be described as ‘controlled cotton production’. Improved irrigation systems are becoming increasingly important and the concept of the ‘water footprint’ should prove useful. The range of improved viscose rayons and their close relations are some of the more-competitive fibre types in comparison with cotton, often demonstrating similar fibre properties with lower environmental impact in their production than cotton itself.

Beyond cotton growing, there have been significant developments in cotton processing, with the accent on advanced methods of process control in ginning. Improvements in spinning, with the accent on productivity and energy efficiency have been substantial and similar advances in weaving and knitting are of interest to cotton processors (although noise pollution and energy efficiency remain major concerns for weaving; less so for knitting), but many of these advances could also be applied to other fibre types, so should be viewed with the eye on maintaining competitive levels of (high) productivity.

Dyeing and finishing are of key importance to cotton fabrics, particularly for the enhancement of wrinkle resistance, water repellancy and stain repellance and in reducing cotton’s flammability. Significant advances are being made. However, the wet processing of cotton is one of the major sources of pollution from the cotton textile industry so all advances have to be considered in terms of their environmental impact alongside the particular performance feature being sought, which adds to the burden on researchers seeking new and improved performance from dyes and

finishes applied to cotton fabrics. New approaches are emerging and the application of plasma technologies, nano-finishing treatments and the focussed use of energy from ultrasonics are showing promising results. Continued focus on reducing the environmental burden currently associated with wet processing will be necessary over the medium to long term.

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