Textile Science and Clothing Technology

Hua Wang
Hafeezullah Memon *Editors*

Cotton Science and Processing Technology

Gene, Ginning, Garment and Green Recycling

Springer

Textile Science and Clothing Technology

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Foreword

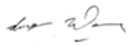
As the Editor-in-Chief of the Journal of the Textile Institute and a Professor in Fibre Science and Textile Technology, I am delighted to provide this Foreword for an important contribution to the textile literature.

Cotton is the most important natural fiber in the world. Cotton textiles played a key role in the first industrial revolution and will continue to play a significant role in the economies of both developed and developing nations. Worldwide, the livelihood of hundreds of millions of people depends on cotton production and trade. Cotton textile products are among the most comfortable textiles for discerning consumers.

The editor of this book, Dr. Hua Wang, started exploring textiles over 40 years ago. He has in-depth knowledge of cotton textile production, consumption, and trade. In this book, he has assembled top-notch scientists across the whole cotton value chain from cotton cultivation and harvesting to spinning and textile finishing. Dr. Wang himself authored the chapters related to cotton properties and testing using advanced instruments. The co-editor of this book is one of the emerging scientists, Dr. Hafeezullah Memon, who has authored more than 60 scientific papers and presented his research at many international and national conferences.

Most of the authors contributing to this book are from the top institutions in developing countries, including Pakistan, India, Bangladesh, Iran, Uzbekistan, Ethiopia, and Uganda. The choice of authorship was made considering the importance of the textile industry in developing nations and the need for a comprehensive reference book for their undergraduate programs in textiles. Moreover, this book has already been supported by the World Textile University Alliance.

I believe this book will serve as an excellent guide for anyone who is interested in understanding cotton production, textile processing, and commerce.



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Preface

The publication of this book is of considerable significance if we look at the significant changes in the pattern of the international cotton trade. Today, the global trade volume of textiles and clothing has reached $425 billion. India and China have become the emerging world manufacturing powers. Asia produced a large number of colorful cotton textiles before the industrial revolution. After 1750, with cotton textiles leading the industrialization process of Europe, it also opened the transformation of the global economy. After the modernization of the textile industry, it is now back to Asia, and China has once again become the world's largest manufacturing economy. Brazil's cotton production is close to the threshold of 2 million tons, and it is possible to continue to increase in the future. The United States, India, and other countries have encountered specific problems in the planting period, making people worry about the production of cotton. For example, Texas in the United States has experienced long-term drought, diseases, and pests in India, and water shortage in Australian cotton.

American cotton accounts for about 40% of the world's cotton trade. U.S. cotton exports play an important role in the world cotton situation. As an important international bulk agricultural product, cotton plays an important role in the global commodity trade. More than 150 countries in the world participate in the cotton import and export trade. Moreover, cotton trade is frequent, and the scale of trade is large. The change in international cotton trade patterns has a profound impact on global cotton production and marketing patterns. Global cotton exports have formed a new pattern, i.e., the United States, Africa, and India as the core, Brazil, Australia, and Uzbekistan as the central three countries. Under the new pattern, global cotton consumption with China, India, and Pakistan as the core, Bangladesh, Indonesia, and other Southeast Asian countries as the leading players. In recent years, India and other South and Southeast Asian countries are very suitable for the development of labor-intensive industries (cotton industry) due to the low domestic labor price and other factors, so the cotton consumption shows a significant growth trend. However, in the new cotton consumption pattern, China's cotton consumption has declined in recent years, but it is still the world's largest cotton consumer. The overall decline of world cotton production has not caused a rebound in cotton prices, so China should guarantee the sustainable and stable cotton production, to prevent farmers from blindly expanding or reducing the planting area to cause dramatic fluctuations in cotton production. At the same time, it should be recognized that the current world cotton production depends on not only the quantity but also the quality of cotton.

As we all know, China is the largest developing country in the world. In the past 70 years, China has become the largest textile and clothing manufacturing country, globally. Therefore, I would like to introduce the achievements of cotton research and technology and the experience of cotton textile technology and industry development to developing countries all over the world through this book, because the world textile history has proved that the industrialization of all developed countries in the world starts from the development of the textile industry. In recent years, China's cotton industry policy is gradually institutionalized and predictable. No matter how to increase the quota of sliding standard tax or carry out the rotation of reserve cotton, it will be announced in advance. The government pays attention to the accuracy and timeliness of market regulation. The price fluctuation of the cotton market is gentle, and there is no significant rise and fall. China plays a vital role in global cotton production, consumption, and trade. As far as the cotton market is concerned, the Chinese and global cotton market is stable. Because China is both a "world factory" and a "world market." At present, the population of China has reached 1.4 billion, the domestic demand market is enormous, and the consumption upgrading trend is obvious. From 2012 to 2018, China's retail sales of clothing, shoes, hats, and knitwear have maintained a steady growth trend, reaching 1523.1 billion CNY in 2018. There is no doubt that China will still be the largest textile and clothing consumer market, globally. In the last 2 years, the Chinese government has vigorously promoted the reform of tax reduction and fee reduction, encouraged innovation and optimized the business environment, introduced a series of policies and measures conducive to the long-term development of the industry, and formed strong support for the domestic demand market.

Furthermore, this book reflects the current situation of cotton breeding and planting technology in the world. Modern cotton planting is emerging technology formed by information, precision, intelligence, and modern equipment, including information technology supported by satellite data service, precision sowing, precision fertilization, and growth monitoring and early warning, as well as controlled-release fertilizer, drip irrigation fertilizer, high-efficiency foliar fertilizer, rapid nutrient diagnosis and nontoxic green pesticides, Bacillus thuringiensis (Bt) cotton. Satellite navigation makes it possible to plow and sow the land day and night, reducing the agricultural manipulator's tension and the scheduling pressure of sowing season time. With agrarian plant protection, unmanned aerial vehicles, i.e., such as flying hand as a tool, are applied with pesticides, plant growth regulators, and defoliants, and many "new farmer" faces appear in the cotton field management. The mechanical cotton picker is the top modern agriculture equipment for mechanized harvesting that can reduce labor intensity and labor quantity per unit area and improve production efficiency, significantly.

The research of cotton cultivation clarifies the high-yield cultivation of cotton by the utilization of cotton nutrients; control of plant diseases and insect pests; salt, alkali, and drought-resistant cultivation; prevention of disasters; and physiological, biochemical, and ecological research. Cotton cultivation has been twice (double cropping) at the same time. However, the biological yield has been thrice economically because the number of bolls per unit area, boll weight, and crop yield have increased along with improved fiber quality, due to high photosynthetic efficiency during boll development artificial light and heat sources (warm water).

Breakthroughs have been made in the field of basic cotton research. In recent years, cotton scientists have made significant breakthroughs in cotton genome sequencing and functional genome research and made substantial contributions, and systematically reported the sequencing of diploid A and D genomes, the sequencing of tetraploid AD genomes as well as the assembly of high-quality heterotetraploid upland cotton and island cotton genomes. At the same time, based on the high-quality assembly sequencing, re-sequenced each ecotype and studied the gene locus of various character control. The completion of these achievements marks that cotton scientists are at the forefront in the world of the genome and functional genome research.

Besides, this book shows the latest achievements of cotton textile processing technology. The labor productivity of spinning has significantly increased with the continuous improvement of the textile manufacturing industry's efficiency through the constant breakthrough of the automated technology of cotton textiles using of a series of advanced equipment. The average 10000-spindle labor force of ring spinning has decreased from 300 in the 1980s to 200 in 2000, and nearly 70 in 2015. Among them, more and more enterprises use the whole process of digital, automation, information, intelligent production lines, and use robots instead of personnel. The advanced production lines employ only ten people per 10000 spindles. The textile enterprises have improved the requirements of yarn quality and raw cotton quality. The new type of cotton textile equipment put new requirements for cotton quality forward. Different spinning equipment has different requirements for fiber quality index. Besides, rotor spinning, air-jet spinning, and friction spinning all require raw cotton to be clean, without or only allow a small number of impurities.

In the future, the first main direction of the world's high-quality raw cotton production would be to improve basic quality, i.e., the cleanliness and consistency of raw cotton. Second, to improve the genetic quality, improve the fiber length and reduce the micronaire value, coordinate the length, strength, and fineness (micronaire value) indexes, and match the high quality with the early maturity. The third is to improve the quality of machine picked cotton to improve the early maturity to improve the defoliation effect and reduce the impurity content of seed cotton. Fourth is to improve the primary processing of seed cotton level, to minimize the damage of length during ginning.

As the Editor-in-Chief of this book, I am much honored to invite so many famous experts to complete this book together. I also thank Dr. Hafeezullah Memon for his assistance throughout the process. I am indebted to many world-famous cotton-breeding experts, cotton-planting experts, and textile experts who jointly contributed to this book for the World Textile University Alliance. This program is to prepare teaching materials, establish cotton-planting and textile training centers, train cotton researchers, cotton planting personnel, and textile engineering faculties for cotton-producing countries in Asia, Africa, and South America, to develop their economy, and improve their ability to working population. Finally, I would like to thank Springer, a prestigious international academic publishing institution that has published this book globally with full of academic and application value. I believe that this book will bring knowledge, technology, and development for the cotton and cotton textile industry of developing countries in the world and help all developing countries embark on industrialization.

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Contents

Chapter 1
Introduction

Hua Wang and Hafeezullah Memon

Abstract Cotton is one of the most prominent fibers of the world that have been used for many years around the world. This chapter highlights the important history of cotton fiber and cotton trade. Also, the potential of this natural and eco-friendly fiber has been highlighted. Moreover, this chapter discusses some leading disputes of this century over the cotton trade. Finally, the potential financial attributes of cotton fibers are highlighted, and it is believed that cotton would keep its place in the world textile and clothing consumption.

Keywords Cotton trade history · Cotton returns · Cotton trade disputes · Cotton economics · Cotton financial attributes

1.1 History of Cotton

Cotton is one of the oldest natural fibers under human cultivation, with traces over 7,000 years old recovered from archaeological sites [1]. Though it is going through difficult times these days yet the cotton has a long history for human use, as early as 5000 BC or even 7000 BC. It has been used in Central America and the South Asian subcontinent for 5000 years [2]. Cotton cultivation first appeared in the Indus Valley civilization of 5000–4000 BC [3]. In the first century AD, Arab merchants brought fine cotton cloth to Italy and Spain. Around the ninth century, the Moors—Muslim inhabitants of the Maghreb, introduced cotton farming methods to Spain [4]. Cotton was introduced to England in the 15th century, and then to British colonies in North America [5].

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At least 2000 years ago, cotton fibers were used as textile materials in Guangxi, Yunnan, Xinjiang, and other regions in China [6]. At first, people did not realize its economic value. Suleiman, a famous Arab traveler in ancient times, wrote in his "Suleiman Travels" that the cotton seen in today's Beijing area was viewed as a "flower" in the garden during his travel in the 9th century [7]. According to the legend of Gaochang in the book of Liang [8],

> 草，实如茧，茧中丝如细纩，名为白叠子
>
> grass is really like a cocoon with the silk in the cocoon is like a thin silk which is called Baidiezi.

It can be seen that cotton, an important raw material of the textile industry, was initially regarded as something like flowers and grass.

There are about three different ways for cotton by which it was introduced into China. According to the analysis of flora and historical data, it is generally believed that cotton spread from south to north to central China. The South Road was the earliest Asian cotton from India, which was spread to Hainan Island and Guangdong and Guangxi regions through Southeast Asia. According to historical records, it was introduced to Fujian, Guangdong, Sichuan, and other regions, at least in the Qin and Han Dynasties. The second way was from India to Yunnan through Myanmar, about the Qin and Han Dynasties. The third way is that African cotton was introduced into Xinjiang and Hexi corridor through western Asia, about the time of the southern and Northern Dynasties. During the Song and Yuan Dynasties, cotton spread to the vast areas of the Yangtze River and the Yellow River Basin is the north road in the ancient book, i.e., The Great Tang Dynasty Record of the Western Regions [9, 10]. By the 13th century, the North Road cotton had reached the Weishui basin of Shaanxi Province.

Historical documents and unearthed cultural relics prove that the cultivation and utilization of cotton by the people of all ethnic groups in China's border areas were far earlier than that of the Central Plains. Cotton textiles in the central plains were still rare and precious until the Han Dynasty. During the Tang and Song Dynasties, cotton began to be transplanted to the Central Plains. At present, the earliest cotton textile relics in the central plains are found in an ancient tomb of the Southern Song Dynasty. That is to say, from this period on, cotton cloth gradually replaced silk and became the main clothing material of Chinese people. In the early years of the Yuan Dynasty, the government set up the Department of picking up the kapok and collecting the cotton goods from the people on a large scale, up to 100,000 pieces per year. Later, it took the cotton as the first one in the summer tax, i.e., Fabric, silk fabric, silk fiber, and cotton (布, 绢, 丝, and 棉). It can be seen that the cotton cloth has become the main textile material. After the Yuan Dynasty, the government strongly collected cotton cloth published technical books on cotton planting and urged the people to plant cotton. It can be seen from the records of "cotton cloth is everywhere (棉布寸土皆有)" and "looms must be everywhere (织机十室必有)" in "Tiangong Kaiwu" written by Song Yingxing of Ming Dynasty, that cotton planting and cotton spinning were all over the country at that time [11].

Due to the poor quality and low yield of African cotton and Asian cotton, China introduced the improved varieties of upland cotton from the United States in succession in the 19th century, and now all the varieties of upland cotton grown in China are from all countries. In the 1960s, many countries carried out the research and experiment of color cotton. In the 1990s, the United States took the lead in making a breakthrough in the transformation and utilization of naturally colored cotton. Colored cotton is naturally grown cotton with color, because of its natural color, without printing and dyeing, bleaching, and other processes [12]. Not only it avoids the pollution of dyes to water quality and the harm of fabrics but also reduces the industrial cost. Therefore, color cotton fabric has become an environmentally friendly product, the favorite of the market in the future, and is favored by consumers.

1.2 The Cotton Would Retain Its Importance Even in the Future

Cotton is a kind of natural fiber which can keep company with nature and human. Scientists have found a small number of cotton bolls and cotton fragments in caves in Mexico, proving that cotton has a history of at least 7000 years [13]. Cotton has maintained a strong vitality regardless of the vicissitudes and species changes. Cotton, as a gift from nature, is used to create a comfortable, healthy, and environmentally friendly, high-quality life. All living things need to absorb nutrients from the environment. Cotton, as a kind of "natural selection", consumes less and gives back more.

The cotton is comfortable as well as environmentally friendly; thus, cotton products should be used to replace chemical fiber products to the greatest extent. Planting cotton fields consumes only 2.6% of total agricultural water and less than 3% of entire cultivated land, but provides 36% of textile fibers for the global textile industry [14, 15]. Cotton is resistant to drought because its roots have a stem-like a water reservoir [16]. Through scientific management, at present, the unit water consumption of cotton planting and the area occupied by cultivated land are still declining. Cotton can also survive in saline and alkaline land, where it is difficult to grow crops and maintain a yield of 90% [17].

The planting of modern cotton can reduce soil erosion and prevent soil particles from flowing into rivers and lakes by increasing the organic matter in the soil. Meanwhile, it can improve the desertification and protect the local water quality. After several years of cotton planting, the soil composition has been improved, and it can also be used to grow corn. So in the desert and Gobi area, cotton planting makes more barren land to an oasis. Nowadays, environmental protection is more important than many years ago, but it has not reached all levels of production and life. The chemical fiber, which is often used to make clothes, needs to be extracted from a large amount of oil, and it will take hundreds of years for waste into the soil to degrade. Brown et al. [18] reported that every time one wash chemical fiber clothes, more than 1900 microplastic fibers are produced. They quickly enter the ocean through drainage, and part of them are returned to the food we eat with the food chain. Compared with man-made fibers, cotton products can be naturally degraded within a few months after being buried in the soil, become organic fertilizer, and returned to nature without burdening the earth. Thus, cotton is the only fiber that offers environmental protection as well as comfort, making it an ideal choice for people as well as the choice for a sustainable future.

People feel comfortable on wearing cotton fabrics because cotton fiber has the following two characteristics. First of all, cotton fiber is naturally hollow, with a natural moisture content of about 8%. When wearing cotton fabric, cotton fiber can automatically adjust dry skin humidity through evaporation and absorption, making people feel fresh and ventilated. At the same time, cotton fiber also has the characteristics of porosity and permeability. A large amount of air can be accumulated between the fibers since air is a bad conductor of heat and electricity. Therefore, cotton fabric is heat insulated and non-conductive, and the human body feels warm and comfortable.

The cotton fabric has no stimulation to the skin and has a good hygienic performance. It is a good choice for skin-sensitive people and infants. Since 1993, Bremen cotton exchange in Germany has carried out a global tracking test on the chemical substances of raw cotton fiber. The results show that all tested cotton meets the EU eco tex standard (product Class 1), and cotton performs well in agriculture, medicine, heavy metal, and other chemical residues. In addition to pure cotton clothing, soft cotton tissues are also gradually becoming more and more people's choices because of their comfort and strength. Soft cotton tissues are not easy to break and crumb that complements its corresponding use over other paper towels, and also supports multiple and multi-purpose applications. For example, after washing the face by soft cotton tissue, no need to discard it, and it can be used to wipe the desktop and shoes for the second time. The use of paper is increasing day by day. To date, only China consumes nearly ten million tons of paper for daily use every year. Pure soft cotton tissue has the potential to replace the paper towel with them. Since soft cotton tissues can be used several times, which would ultimately reduce cutting the trees and, thus, protect the forests.

1.3 Global Trade History of Cotton

Cotton was first planted in the western part of India about 5000 years ago. Cotton and cotton fabrics of India were exported until the 19th century. At the end of the 15th century, European explorers entered the Indian Ocean, and they started to export Indian cotton fabrics and spices to Europe in large quantities. The Indian cotton fabrics were popular in the European market, which caused the cash inflows into India, a big challenge for Europeans, until the industrial revolution. After the industrial revolution, new machines such as flying shuttles and Jenny spinning machines were invented and, thus, promoted Britain's cotton production significantly. However, until the early 19th century, Britain's cotton production was still lower than that of India, and it was mainly exported to West Africa and other places. Britain's cotton textile industry won the final victory over Indian textile products by Britain's successful construction of a new cotton textile industry system. The British established plantation agriculture in their North American colonies, and following Portugal started planting in Brazil, the Netherlands in the Caribbean islands, and France in Haiti. They farmed cotton and sugarcane in large quantities and then transported cotton raw materials and sugar to their suzerain. The combination of mechanization, plantations, and long-distance ocean transportation eventually led to the collapse of India's long-standing cotton textile industry.

The issues and disputes related to international trade are not new throughout global history. According to Sven Beckert, author of "Empire of Cotton" and Professor of History at Harvard University, capitalism, which shaped the current global political and economic pattern, has nothing to do with "fair competition" from the beginning, but is full of naked national plunder, exploitation, and theft. In the book, "Empire of Cotton", Beckett points out that the history of the cotton industry is closely connected with the history of modern capitalism [19]. The geographical discovery at the end of the 15th century and the subsequent establishment of the transatlantic trade network put Europeans in the center of the global cotton trade. In the era of "War Capitalism", European countries established trade networks connecting America, Europe, Asia, and Africa through land plunder and slavery. The innovation of cotton textile industry technology and war capitalism ended in the 19th century [20]. The former controls core technology and the largest share of profits, while the latter provides raw materials and consumer markets. In this hierarchical cotton imperialist order, the top Western countries always master the most core technology and reap the most significant proportion of profits.

Now, the many countries of the world are following this set of logic that once helped the western countries to obtain the advantageous position of the world division of labor. From this point of view, Sino US trade friction is not so much a clash of civilizations as a clash of interests. Figure 1.1 represents the major cotton producing

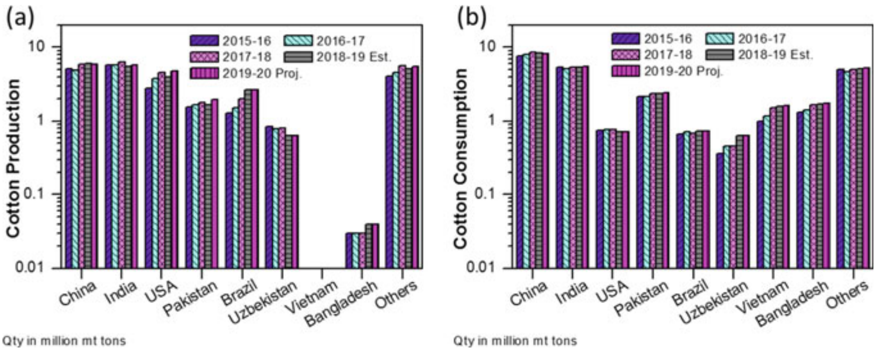

Fig. 1.1 Production and consumption in major countries [21]

and consuming countries for last five years. In the “cotton Empire”, every country is trying to defend interests and occupy the dominant position as much as possible. This is the internal power of the current global economic order.

1.4 International Trade Disputes over Cotton

1.4.1 Global Trade Disputes over Cotton Are Continuing

Cotton has become a strategic material related to the national economy and people’s livelihood and an important raw material of the cotton textile industry, which plays a significant role in the national economy of many countries. According to statistics, there are 75 cotton-producing countries on five continents. As a natural fiber economic crop, cotton industry chain from production, circulation, processing to consumption has an important impact on the development of the national economy, especially the employment and income of cotton and upstream and downstream industries. Cotton is also an important international trade product, with the global trade volume reaching the US$18 billion per year, which attracts the attention of all countries in the world. Both developed and developing countries have taken various measures to protect their cotton farmers and the cotton industry and expand their export markets to gain more benefits in the cotton trade. Therefore, cotton has aroused world trade disputes.

1.4.2 WTO Agricultural Negotiation for Development

It is a hot topic of cotton. At the end of 2001, the WTO began a new round of negotiations, namely the Doha round. The most prominent feature of this round is to emphasize the development of developing countries. In 2003, four least developed countries in Africa, Benin, Burkina Faso, Mali and Chad, which take cotton cultivation as an important basis of their national economy, jointly launched the cotton sector reform initiative of the Doha Agricultural Negotiations of the WTO. They put forward that the cotton production and export of the least developed countries have been plagued by trade distortions, requiring cotton to be in the trade and development sectors. Other issues have been thoroughly resolved before the agricultural negotiations. In the “four cotton countries”, cotton is the main economic crop and also the main export of agricultural products. In 2004, they exported 218.1 thousand tonnes of cotton to China; and 11.5% of China’s total cotton imports [22]. Among them, Benin, Burkina Faso, and Chad account for more than 70% of total export revenue. The international cotton subsidies, mainly from developed countries, have seriously impacted the cotton industry in Africa, and also severely hit the economies of these least developed countries. In response to the strong demands of the four cotton countries, since 2004, the WTO agricultural negotiation has set up the cotton issue for regular discussion, which is the only issue aiming at a single product in the agricultural negotiation.

After more than ten years of arduous negotiations, the cotton issue has made periodic progress. In December 2015, at the Nairobi ministerial conference, the Ministerial Decision on cotton was adopted [23]. Developed members and developing members who announced their ability promised to provide "duty-free and quota-free" market access to cotton in the least developed countries. Developing members who were not able to provide double exemption also had to bear the responsibility of promoting the import of cotton from the least developed countries. The decision also called for the immediate elimination of cotton export subsidies by developed countries and implementation by developing countries no later than January 1, 2017. The Nairobi decision also acknowledged the efforts of some WTO members to reform their domestic cotton policies, but stressed that more efforts are needed. Finally, the members also agreed to improve the transparency of the cotton trade and strengthen the monitoring of trade policies. However, the root cause of the problems faced by the developing cotton industry is the distortion of international cotton trade caused by the domestic support of developed members (including yellow box and blue box). It is still a long way to go to solve this problem fundamentally.

1.4.3 Dispute Settlement Mechanism to Promote Fairness (Brazil vs. US Cotton Subsidy Case)

The large-scale subsidies of developed members of cotton also have a negative impact on the interests of other cotton-producing countries. For this reason, Brazil sued the United States to the WTO in 2002 on the ground that the United States cotton subsidies violated the WTO rules, and the WTO dispute settlement agency ruled that the United States lost the lawsuit in 2004 [24]. Brazil sued the US government for providing up to seven types of subsidies for cotton production, including direct payments that are not linked, countercyclical payments that are related to prices, and "second step subsidies". Between August 1999 and July 2003, American cotton producers received 12.47 billion US dollars in subsidies. During the same period, the output value of American cotton was 13.94 billion US dollars, with a subsidy rate of 89.5%. The Appellate Body of WTO decided that "the second step subsidy" has the nature of export subsidy and domestic content subsidy. In violation of the WTO commitments of the United States, the United States was forced to cancel the "second step subsidy" and adjust the export credit plan. Also, the appellate body found that the "production flexibility contract payment" and direct payment notified by the United States, as the green box may stimulate production, which does not meet the criteria that green box has no or only slight distorting effect. Brazil believes that the US multi cotton support subsidy program has increased US cotton production and exports, thereby lowering world cotton prices, causing damage to Brazil and other members.

Brazil versus the US cotton subsidy case is the only dispute case related to the cotton industry in the WTO at present and has great significance in the history of WTO. The ruling of this case increases the opportunity for developing members to use the WTO dispute settlement mechanism to challenge the developed members' huge agricultural subsidies and safeguard their interests, which causes great pressure on the developed members who provide a large number of agricultural subsidies. At the same time, the clarification of the WTO Dispute Settlement Mechanism on the fuzzy terms of WTO is conducive to the development of trade liberalization and the improvement of relevant rules, especially in the time and field where members are difficult to reach a compromise and collegiate. Since 2004, cotton, as a subject involving trade, economy and other fields, has attracted special attention of the world. WTO has been committed to promoting the reform of cotton trade, trying to solve the problems of cotton subsidies and trade barriers.

Cotton is an active product in international trade as an agricultural product of processing raw materials. Although the planting industry is relatively small, it embodies the reality of deepening potential economic relations and highlighting interest conflicts between countries under the background of global economic integration. To resolve the contradictions and achieve win-win results, one should maintain the position and authority of the multilateral mechanism of international trade to create a benign trade environment and follow the rules first. At the same time promote the reform of agricultural trade of WTO, especially solve the internal defects of multilateral rules, to ensure that trade rules take reasonable care of the interests and concerns of different members.

1.5 Financial Attributes of Cotton

Cotton is one of the international commodities, and its financial attribute is increasingly prominent. With the rapid development of the financial derivatives market, the financial attributes of commodities, especially international bulk commodities, are more and more obvious. When commodity exchange develops to a particular stage, money is used to measure the value of commodities, and then the price comes into being. With the development of the commodity economy, the importance of price is self-evident. All commodities have prices, which are the core elements of the market economy and the basis of all economic activities. The value of goods is expressed by price, and the fluctuation of price reflects the scarcity of goods or the relationship between supply and demand. However, with the development of society, supply and demand information and other factors that can affect the price are difficult to be fair to all people, and the phenomenon of price deviating from value inevitably appears. Especially when some people realize that this kind of deviation may bring huge benefits, speculation will follow. According to the N. Gregory Mankiw, Professor of Economics at Harvard University—the author of the book, "Principles of Economics", commodity prices are determined by the relationship between market supply and demand [25]. But once the price does not reflect the relationship between supply and demand, or even deviates significantly from the value, the commodity becomes the medium or carrier of speculation, and the financial attribute of the commodity determines the price of the commodity market. Under normal circumstances, the necessary attributes of commodities play a leading role in the price of commodities, and the trend of market prices is determined by the relationship between supply and demand. However, under particular circumstances, the financial attributes of commodities can play a leading role.

Cotton is still one of the dominant fiber of the textile industry, and its economic downturn will lead to global demand reduction. It can be said that the textile industry is one of the sectors prone to be affected by the global economic recession. To be saved from the economic downturn, the first thing is to achieve reasonable expansion based on combining the existing cotton business. This primary consumer industry would still guarantee success despite the intense competition. Those enterprises that do not adapt to the development and will not follow careful strategies would be eliminated. At the same time, an e-commerce platform should be established for international textile products based on the cotton trade that may integrate advanced technology and traditional ways of production trade, covering the information of all well-known fibers, i.e., cotton, wool, cashmere, linen, man-made fibers, and others. This platform would provide a professional, safe, and efficient textile production information system and one-spot trading platform for fiber producers, value-added product manufacturers, traders, consumers, warehousing and logistics centers, transporters, and bankers. In the next few years, China is also planning to establish submarkets in the United States, India, Uzbekistan, and other major cotton-producing countries to centralize cotton prices and returns. Furthermore, bringing innovations in business models might offer ways to cope with the current situation. Experts believe that the business which combines financial innovation is a business with excellent development potential in the current environment.

The most basic function of the cotton stock market is price discovery, which leads to avoiding loss, getting projected profit, and other functions. In addition to the impact of macro and commodity supply and demand, the price relationship between stock and goods in stock, related to stock markets, contract periods, and stock varieties, also has an obvious impact on stock prices. At present, "basis trade", which is widely used in the cotton market, is the most important indicator of the relationship between the stock and the prices. In the aspect of cross month arbitrage, the stock market has a wide range of extended trading and inter-month forward and reverse trading, with a high degree of attention to the inter-month accounts. In terms of cross-market arbitrage, cotton import business, and cross-market forward and reverse arbitrage transactions widely exist in the stock market, which pays great attention to the cross-market price difference. The cotton-growing areas in the United States are mainly distributed in a large area from west to east in the south of the United States. The four main cotton growing areas are Southeast, South Central, Southwest, and West. More and more attention has been paid to the cotton stock price, which has become the primary reference basis for the US government to formulate relevant cotton policies, and also the central place for cotton farmers and cotton related enterprises to hedge other major cotton-producing countries except for China.

China's cotton price index (CC index) is becoming more and more influential in the market. China's cotton trading market, after more than one year's research and preparation, was jointly discussed and confirmed to timely and genuinely reflect the price level of China's cotton market [26]. Department of economic construction of the Ministry of Finance, the Department of Economic and Trade Circulation of the National Development and Reform Commission, the Rural Economic Research Center of the Ministry of Agriculture, and the Cotton and Hemp Bureau of the Domestic Supply and Marketing Cooperative discussed it together. The outcome was released in early May 2002 In June 2002, the "China cotton price index" was officially released, which is abbreviated as "CC index" in English.

The release of China's cotton price index has not only been widely welcomed and concerned by domestic and foreign cotton related industries but also become an essential basis for China's national macro-control departments to grasp the local cotton price trend. At the beginning of the publication of the China cotton price index in June 2002, the daily quotation of 105 textile enterprises was calculated and generated by the national cotton trading market. Since June 2003, China's cotton price index has been published more frequently, instead of at 10:00 a.m. on Monday and Thursday. The number of quoted enterprises has increased to about 180. In November 2003, to ensure the fairness and authority of the release of China cotton price index, China cotton price index was managed by China Cotton Association and released simultaneously on the website of China Cotton Association and China cotton information network.

1.6 Conclusion

Cotton is a vital natural fiber for human beings, and it is an environment protecting textile and clothing material given by nature. Cotton is a fiber which pays to nature more than it gets from nature. Cotton is an international agricultural product or a financial instrument. The cotton fiber would retain its place in the world textile and clothing consumption. There is a necessity to follow suitable strategies for cotton production and cotton business.

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Chapter 2
Status and Recent Progress in Determining the Genetic Diversity and Phylogeny of Cotton Crops

Altaf Ahmed Simair and Sippy Pirah Simair

Abstract The significance of plant genetic diversity (PGD) is predictable as an exact part since the public explosion of urbanization, and the decline of cultivable land is the severe issues subsidizing to food security in underdeveloped countries. Agricultural researchers realized that plant genetic diversity could be apprehended and deposited, such as gene bank, DNA library, etc. In the biorepository that preserves genetic material for a long time. However, the preserved plant genetic resources should be used to improve crops to meet upcoming universal challenges related to food and nutrition security. This article reviews the most significant areas related to cotton crops; (i) the importance of plant genetic diversity (PGD) mainly arable crops; (ii) investigation of existing PGD analysis methods in the pre-genomic and genomic age; and (iii) modern tools available for PGD analysis. This review will help the plant science researchers to use the available modern resources and latest tools for a better and quick assessment for the use of germplasm from gene banks to their ongoing breeding programs. By introducing new biotechnological practices, the management of the genomic alteration process is now enhanced and accepted with more accuracy than old classical breeding skills. It should also be noted that gene banks are investigating several problems to improve the levels of distribution of germplasms and its use, especially replication of plant uniqueness and access to the databanks for research accomplishments. Therefore, as plant breeders and crop developers are essential components in successful food production, accessibility and approach to different genetic sources will guarantee that the universal demand for food and livelihood becomes maintainable. Molecular methods have a severe and unavoidable leading role in the challenges of phylogeny and speciation. In recent times, there is a new class of cutting-edge practices that has materialized, mainly an amalgamation of earlier and more basic techniques. Most advanced cutting-edge

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marker-based procedures tend to combine beneficial topographies by several basic methods to detect genetic gap and quirkiness. Mast innovative, cutting-edge marker-based techniques are used with a new class of DNA components, such as chloroplast microsatellites, to depict variation in the genetically altered genome. Furthermore, the latest technologies, such as RAPD and AFLP, also apply to cDNA-based patterns to study gene expression and blur the impression of biological responses. Furthermost imperative and latest improvements made indent for molecular marker techniques are discussed in this review, which improves the understanding of weather kegs and its practical usefulness for scientists.

Keywords Cotton · Genomic tools · Phylogeny · Diversity · Classification

2.1 Introduction

Human resources are closely linked to the outcomes of the economy. However, an exhilarating and crucial element is that the situation of the population is dual, i.e., on the one hand, it is used for the production of goods, and on the other hand, all production is intended for the population. Individuals are not only manufacturers but also consumers. A more significant population may be needed as it offers more employees, but it may be unwanted because it will need a large number of products to satisfy the increasing demands for the population. The demand for commodities is increasing rapidly due to overpopulation while the supply does not match it, and consequently, prices are growing too fast. So we need to increase the number of industries to regulate the amount because the industry is now producing goods that not only meet consumer needs but can also be cost-effective. Industrial expansion is a privilege of emerging countries, but at the same time, all possible preventive techniques must be adopted so that contamination of the atmosphere cannot make any problem for the international community. The biome is greatly affected by human activities and industrial growth. Numerous industrial chemical substances are going to be used in various industries in the name of development without checking a harmful effect on the environment. No doubt, there is no question that the use of chemicals is necessary for better performance of products, but on the other hand, the use of such chemicals has created problems for man force, environment and also increased the cost of items. To improve the circumstances and succeed global magnificence, we must use the best knowledge of natural resources, intensely change our performance, improve our economies, and regulate emissions and high-price goods used in our everyday life. Knowing new technology would be a must for those who want viable goods for a prosperous future [1]. The garment industry is mainly engaged in the pattern, manufacture, and selling of wool, fabrics, and garments. Produced or manufactured products used in the chemical industry may be raw materials. Throughout the twentieth century, with the relentless technical advancement in machines, synthetic fiber, logistics, and business globalization, the textile industry has undergone significant changes. The business model, which has been dominating the industry for decades, is facing radical changes. Cotton and fur manufacturers are not the only sources of fiber, as chemical factories have manufactured DuPont discovered contemporary synthetic fabrics of superior quality for many applications, such as the rayon found in 1910 and Nylon in 1935 low-cost silk alternatives for items ranging from women's stockings to sportswear.

There is a long cycle of chemical and nonchemical handling in the production phase of textiles. Tissue finishing involves pretreatment, tinting, printing, and finishing. Several textile chemicals include exceptionally engineered chemicals such as fungicides, fire retardants, water-repulsive, and distort sizes. These are reasonably necessary chemicals, including emulsions and fats, starches, sulfate oils, waxes, and certain surfactants. More than 60 different textile chemicals are used in wire forming, pretreatment and finishing, lamination, fabric covering, and various other uses.

2.2 Origin and Distribution

The cotton industry has had to suffer variations in the fabrication and usage of this natural product worldwide over the last few years. As we all know, cotton in textile fabrics is linked to all levels. Cotton is now grown in almost 100 countries worldwide. However, only three countries India, China, and the United States of America compete with new lines on the market by producing two-thirds of the world's cotton. Recently, China has become the world's largest importer and producer of cotton. Though, their government has approved to introduce a program to help local farmers grow their farms. As a result, the Asian giant cut the material's imports, dragging prices down to 2009 rates. It rebounded to some degree when the United States chose to limit acreage. Through this sense, India has been a significant producer of cotton and a demanding leader. However, the government is looking at the prospect of withdrawing any of the world's reserves, which might further drive prices down. The fluctuation in world production in natural cotton fiber and the demand for supplies contributes to the textile industry's move to synthetic fiber. Those are cotton, polyester, polypropylene, or acrylic. There is no doubt this conquest is directly associated with expenses. Nevertheless, this is not the only reason; we must note these products are chosen in addition to mass manufacturing for the reason that of their other benefits, such as longevity and ease of use in specific uses.

The best knowledge of natural resources must be used, our behavior drastically modified, our economy improved, and the emissions and high price goods used in our everyday lives regulated to improve the living conditions and achieve universal strength and awareness of natural sources of biomaterials and fibers would be necessary for those who want cost-effective products to achieve their successful future [1].

2.3 Adaptations for Natural Habitat

Cotton is a kind of sustainable and environmentally friendly fabric that has significant advantages in your life. Cotton has been cultivated for more than 6000 years as seed, fiber, and even fuel; that's why everyone calls it living material. Cotton can be used in clothing, bedsheets, and towels, but it can also be used for making currency notes, pulp, cooking oil, animal feed, packaging, and biofuels. The benefits and durability of cotton are enormous.

Cotton (*Gossypium spp.*) yields natural soft single-cell trichomes on the various parts of the plant and provides the textile industry with the primary source of natural raw materials. It is considered economically one of the most important crops globally and is also useful as an exemplary method for thorough evolutionary scientific investigation [2]. Annual or annual shrubs, up to 2 m long with leaves up to 10 cm thick, cordate at the base. The flowers turn yellowish-white and slowly pink-violet. Fruit capsule 4 cm long; wide ovoid to subglobose; beaked apex; 3–5 cells. Each was holding up to 11 hairy seeds. The cotton that we use is made from this plant's seed fiber, which can be up to 2.5 in. thick, and has developed to help plants disperse seed.

Cotton is the world's most extensive non-food product, accounts for half of the world's textiles, explosives, gasoline, livestock feed, and toothpaste. This defied the war for new goods, but at the expense of using vast quantities of fertilizers and chemicals, and scandalous antiquity of workers misuse. This beautiful, sleek, and trendy material costs more than the wool, linen, and nylon competitors do. The trade-in cotton was the driving force of the industrialized insurgency, helping to fund the British Empire. This became the slave-trading backbone that became influential in the American Civil War. Growing up, this "white gold" today needs to use many pesticides to kill life. As Britain was a large manufacturer of cotton in the 18th and 19th centuries, it was driving local cotton weavers into factories or working-class households. The Luddite term has come to mean for those people who dislike technology. The Luddites were cloth craftsmen who opposed the advent of computers by killing them, which left them homeless. One of the most critical developments in cotton ginning history was the invention of the 1793 cotton ginning machine.

2.4 Evolutionary History

Cotton is coated with more organic compounds than other crops. Cotton currently occupies less than 3% of the world's arable land, but it uses a fifth of the world's pesticides! New and healthier chemicals are being produced, but they are costly. As a result, in developed nations, the use of cheaper and more dangerous chemicals causes about 20,000 accidental fatalities per year. Humans started growing cotton in Indus Valley (Pakistan) seven thousand years ago; even today, cotton is cultivated in many parts of Pakistan. The cotton crop in lower Sindh, Pakistan, is shown in

Fig. 2.1 Cotton crop, especially in lower Sindh, Pakistan

Fig. 2.1. Cotton was grown in what is currently Mexico and Peru after 2000. Pieces of cotton cloth were discovered in Mexico and Pakistan, dating back to 5000 BC. Cotton traveled from Pakistan to India, Japan, and South Korea, to Western Europe and Spain throughout the 1990s.

For textiles, blankets, paper, banknotes, fishing nets, bags, bottles, wallpapers, bandages, medical stitches, ropes and boards, long cotton fibers are woven into threads and are used. Short cotton fibers are used in explosives, sausage fur, silk, cellophane, rayon, photography film, nail polish, rubber molded, and solid-fuel rocket. This also makes ice cream smoother, lip chewing and swallowing, and products run effortlessly. The crushed cottonseed contains valuable vegetable oil that can be used in feed for cattle, fish bait, and organic fertilizer. Cotton production is facing a substantial period of transition, such as the loss of market share in competition with synthetic fibers, the high prevalence of BT (*Bacillus thuringiensis*) and Herbicide tolerance genes in cotton varieties and the increase in demand for fiber quality to produce high-quality fabrics due to improvements in textile technology. Fibers on the global market [3, 4] recently, through the next-generation sequencing technology, which can dramatically minimize costs by sampling in vast volumes, provides an incentive for diploid and tetraploid cotton sampling genomes. With an abundance of molecular mapping knowledge, modern genomic technologies, cotton genomic characteristics, the discovery of several modern genes, controlling components (including microRNAs, and the development of new genetic tools (such as gene silencing or gene-editing techniques for genome manipulation) [2].

2.5 *Gossypium* Diversity

The abundance of plant genetic resources (PGR) offers plant breeders the ability to grow new varieties and enhanced varieties with ideal characteristics that include not only desired features of farmers (yield capacity and large seeds) but indeed preferred features of breeders (pest tolerance, photosensitivity, etc.). From the advent of agriculture, people have used the inherent genetic diversity of crop species to fulfill the self-sufficiency needs of food and shelter. Today, with agricultural advancements and associated science and technology, the emphasis is on improving the quality of life [3]; we also question if we can fulfill the world's clothes demand. So, it is more significant to regard agriculture not only as a tool for food production but also as a necessary means of maintenance for the agricultural and non-agricultural sectors. Maintaining the cultivable crop organisms within the reservoir is a theory of future agriculture, even maintaining a museum of cultural and theological knowledge of various cultures in various geographical areas, offering historical proof of their existence. The former plays a significant role in supplying resilient and productive genes, contributing to long-term change in productivity related to environmental damage. With new biotechnological tools and technologies emerging, this gene modification method is accelerating, shortening the breeding time, and could be more effective (ignoring environmental impact) and quicker than traditional breeding techniques [5] (Fig. 2.2).

2.5.1 Assessment of Genetic Diversity in Crop Plants

Evaluation of genomic assortment within and among plant populations is typically performed using a variety of strategies such as (I) morphology, (II) biochemical characteristics/assessment (alleles), and (III) DNA (or molecular) marker analysis, including post-genomic single nucleotide polymorphism (SNP). Markers may display genetic patterns identical to those we found for every other phenotype, i.e., dominant/recessive or co-dominant. When it is possible to differentiate the genetic characteristics of homozygotes and heterozygotes, then a marker is co-dominant. In general terms, co-dominant markers provide more details than competing markers. Morphological indicators are based on features that are easily visible, such as flower color, seed shape, growth patterns, and pigmentation. It does not need advanced equipment, but these field trials typically involve vast areas of ground, making it significantly more costly than molecular tests in Western (developed) countries, taking into account labor costs and availability; this is similarly expensive in Asia and the Middle East (developing countries). These markers are located only close or related to genes that control traits. These markers include descent, which is both dominant and co-dominant.

Similar markers have similar genetic features (these may be dominant or co-dominant, may amplify anonymous or distinctive loci, which may contain reported

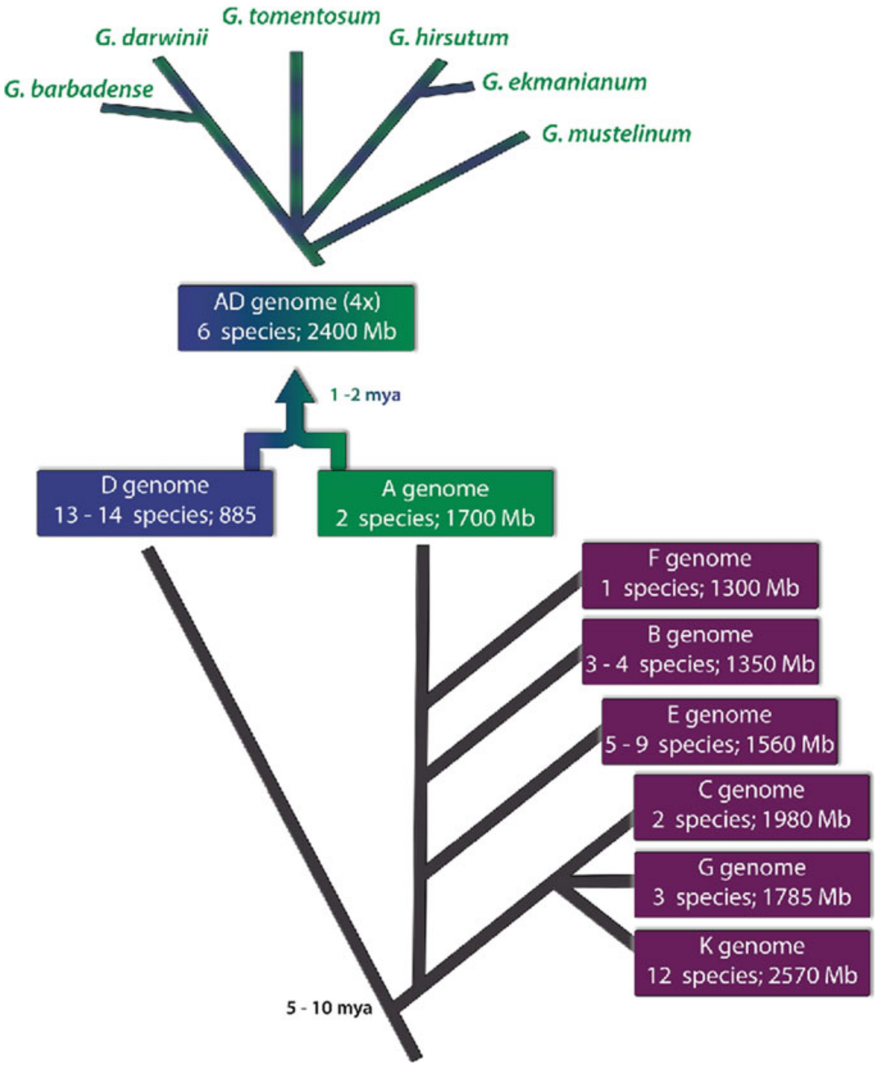

Fig. 2.2 The evolutionary history of *Gossypium*, as inferred from multiple molecular phylogenetic data sets. The closest relative of *Gossypium* is a lineage containing the African-Madagascan genus Gossypioides and the Hawaiian endemic genus Kokia. Following its likely origin 5–10 mya, *Gossypium* split into three major diploid lineages: the New World clade (D-genome); the African-Asian clade (A-, B-, E- and F-genomes); and the Australian clade (C-, G-, and K-genomes). This global radiation involved several trans-oceanic dispersal events and was accompanied by morphological, ecological, and chromosomal differentiation (2C genome sizes shown in white ellipses). Interspecific hybridization is implicated in the evolution of approximately one-fourth of the genus. Allopolyploid kinds of cotton formed following trans-oceanic dispersal of an A-genome diploid to the Americas, where the new immigrant underwent hybridization, as female, with a native D-genome diploid similar to modern *G. raimondii*. Polyploid cotton probably originated during the Pleistocene (1–2 mya), with the five modern species representing the descendants of early and rapid colonization of the New World tropics and subtropics

or non-expressed sequences, etc.). Molecular markers can be identified as a genomic site that samples or different promoters (Primers) can detect. Irrespective of their presence, the chromosome properties they represent and the flanking regions at the ends can be easily distinguished [5, 6]. The molecular markers may or may not be related to phenotypic genomic phenotype expression. These have many benefits over conventional phenotypic equivalents as in all tissues. These are stable and measurable independent of cell proliferation, differentiation, production, or defense status. Besides, climate, pleiotropy, and epistasis do not affect them. We are not explaining anything about the methods of the pre-genomic period, as our paper deals with genomic developments and their assistance in determining the genetic diversity of crops.

Several members of the *Gossypium* genus, shown in Table 2.1, are grown to manufacture thin and oddly shaped single-cell fibers worth about $20 billion a year worldwide, sustaining one of the world's biggest industries (Textiles), with an annual economic effect of about $500 billion worldwide. Cotton production and the textile industry are in many ways closely related to the use of petrochemicals. The practical implementation of cotton genomics provides a method of increasing the quality of crop production, the consumption of biological alternates for petrochemicals, and customer happiness with the end product [7]. Cotton (*Gossypium*) also offers a rare ability to promote knowledge of nature. In general, the progress of cotton produced from wild descendants includes a sequence of interesting events that allow scientists to study the evolution of a new organ, lint fiber, and to understand better the role of polyploids in biodiversity growth and crop efficiency and superiority. Cotton is the world's largest commodity for plant fiber and cultivated commercially in temperate and warm areas in over 50 countries [8], net territory spanning 34 million hectares. Cottonseed coat extends into tubular fiber and turns into the thread.

Relevant production areas include the United States, India, China, the Middle East, and Australia, where climate conditions match natural cotton output, including hot and dry weather, and sufficient water typically obtained through irrigation. Of the five leading cotton-growing states, China has the highest degree of production (1265 kg/HA), followed by the USA (985 kg/ha), Uzbekistan (831 kg/ha), Pakistan (599 kg/ha), and India (560 kg/ha). India's cotton planting region ranks first globally, accounting for over a quarter of the world's cotton planting area, led by China, the US, and Pakistan. Total cotton production is approximately 26,247 million tons, with China, India, the United States, and Pakistan producing the most, led by Uzbekistan, Russia, Australia, Greece, Brazil, and Egypt [9].

There are approximately 50 recognized cotton varieties worldwide, four of which are grown. Four of these are two diploid (*Gossypium arboreum* and *Gossypium herbaceum*), and two (*Gossypium hirsutum* and *Gossypium barbadense*) are tetraploid. About 80% of the world's cotton field is tetraploid. Diploid cotton, though, is cultivated in Asia and the Middle East. India is the only nation with the industrial production of both cultivated varieties and some of their hybrids. The abundance of cotton varieties and agro-climatic cotton zones in India is greater than in other big cotton-growing countries in the world [10, 11].

Table 2.1 Diversity and geographic distribution of the major lineages of *Gossypium*. Genomic placements of species enclosed by parentheses are yet to be determined

Genome group	Number of species	Recognized species	Geographic distribution
A	2	*G. arboreum*	Africa, Asia
		G. herbaceum	
B	3(4)	*G. anomalum*	Africa, Cape Verde Islands
		G. triphyllum	
		G. capitis-viridis	
		(*G. trifurcatum*)	
C		*G. sturtianum*	Australia
		G. robinsonii	
D	13(14)	*G. thurberi*	Primarily Mexico; also Peru, Galapagos Islands, Arizona
		G. armourianum	
		G. harknessii	
		G. davidsonii	
		G. klotschianum	
		G. aridum	
		G. raimondii	
		G. gossypioides	
		G. lobatum	
		G. trilobatum	
		G. laxum	
		G. turneri	
		G. schwendimanii	
		(*G. sp.nov.*)	
E	5(9)	*G. stocksii*	Penisula, Northeast Africa, Southwest Asia
		G. somalense	
		G. areysianum	
		G. incanum	
		G. trifurcatum	
		(*G. benidirense*)	
		(*G. bricchettii*)	
		(*G. vollesenii*)	
		(*G. trifurcatum*)	
F	1	*G. longicalyx*	East Africa
G	3	*G. bickii*	Australia
		G. australe	
		G. nelsonii	

(continued)

Table 2.1 (continued)

Genome group	Number of species	Recognized species	Geographic distribution
K	12	*G. anapoides*	NW Australia, Cobourg Peninsula, NT
		G. costulatum	
		G. cunninghamii	
		G. enthyle	
		G. exiguum	
		G. londonderriense	
		G. marchantii	
		G. nobile	
		G. pilosum	
		G. populifolium	
		G. pulchellum	
		G. rotundifolium	
AD	5	*G. hirsutum*	New World tropics and subtropics, including Hawaii
		G. barbadense	
		G. tomentosum	
		G. mustelinum	
		G. darwinii	

Ecology is closely related to the history of the biological development of the organism. Throughout the cycle of transformed descent, living individuals periodically transfer genetic material from one generation to the next, which is then registered throughout the offspring's DNA. The capacity of Molecular biology to collect this information and helping to understand the nature of organisms and the evolutionary foundation for their life has become the pillar of contemporary evolutionary science [10]. We study the molecular techniques briefly and approaches accessible to contemporary ecologists to gain a deeper understanding of the genetic basis of speciation, variation, and evolutionary adaptation as they engage with the dynamic ecosystem.

2.5.2 Tools for Cotton Genetic Improvement

One of the genome research's key goals is to utilize genomics methods to facilitate or assist in the continuous genetic development of crops. The production of genomic resources and techniques in cotton has allowed the solution of several essential science problems that have previously been difficult to solve. These include, but are not restricted to, the creation of genome-wide genetic maps, the classification, and mapping of genes and loci, which regulate qualitative and quantitative genetic traits, the identifying and analysis of genes involving in cotton fiber initiation, elongation, and secondary cell wall biogenesis. These genomic resources and tools can foster or encourage genetic improvement in cotton in a variety of ways. Marker-assisted selection (MAS) can currently and in the future be one of the most essential and practical applications. MAS technologies will provide breeding systems with several possible benefits. For starters, DNA linked to interest genes may be used to boost selection efficiency in new generations' breeding process. This approach has significant advantages in screening and choosing costly or challenging to execute phenotypes, such as recessive or polygenic, environmental or regional variables, and late expression of phenotypes [12]. However, the use of MAS in the cultivation of cotton is also in its infancy. In the past, cotton genome work has concentrated on improving genomic tools and instruments to achieve the ultimate aim of genetic advancement in cotton.

Many genetic works include removing DNA from a single individual and then amplifying (i.e., making several copies) identical DNA fragments using a polymerase chain reaction (PCR), refer, Fig. 2.3. The advantage of PCR is that it only takes a limited volume of DNA (e.g., nanometers). It is incredibly helpful if researchers cannot access a sufficient number of tissues (such as unusual plant or animal species) or need sufficient quantities, such as population genetic studies. For example, an ecologist may ask: What is the genetic variation across a broad range of environmental gradients of a community of one species? The response is to collect DNA from

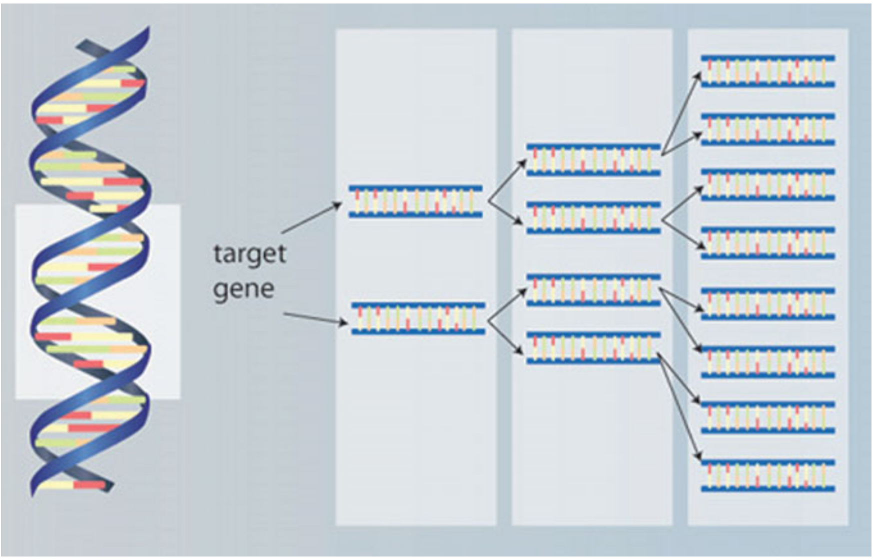

Fig. 2.3 A groundbreaking process created by Kary Mullis in the 1980s, the polymerase chain reaction (PCR). The polymerase chain reaction is a process commonly used that enables scientists to take a tiny DNA sample and amplify it to a sufficient degree in detail to rapidly-produce millions to billions of copies of a single DNA sample

various persons in multiple communities and then perform a genetic diversity test based on PCR. These surveys can conclude the historical processes contributing to variations in population genetic makeup under different geographic and environmental conditions. Alternatively, one may want to know the connection between evolutionary background and species community members. For example, PCR is used to amplify unique coding or non-coding DNA regions from various species, aiming to reconstruct each species' phylogenetic background in the complex. When established, phylogenetic trees resulting from this analysis will include details on the population community's extent and which populations are nearest to each other. It also offers insight into biological (such as spatial niche utilization) and behavioral influences (such as foraging), leading to the abundance of diverse organisms [12].

2.6 Markers and Methods

In molecular biology, there are several common forms of DNA markers including microsatellite (a portion of repetitive DNA consisting of a small repeat sequence of 1–9 base pairs. Generally used to classify individuals), a minisatellite (an extremely repeated piece of DNA consisting of a set of elements, the same as microsatellite), and restriction fragment length polymorphism (RFLP) that breaks DNA at appropriate points to provide the same amount of DNA sequence data (sequencing is operation). Determine the exact nucleotide sequence of a specific DNA molecule and analyze the similarities and variations to classify animals, populations, and individuals). The bands created from these approaches are visualized in various ways. Traditionally, electrophoresis of the agarose gel reveals the MSAT and RFLPs. However, nucleotides that shape the DNA chain, however, need more detailed resolution, typically with polyacrylamide gel and autoradiography. Standard identifiers today are visualized by chemical fluorescence and genetic analyzers, which may track the fluorescence radiation of designated primers or DNA sequence fluorescent nucleotides. These approaches and strategies for labeling and simulation rely mainly on the form of the question to be solved in the study. By recognizing the many details given through specific marker methods, we identify three molecular methods widely used in work on molecular ecology.

Three separate tag forms can easily be differentiated from the type of details received. Identified markers involve markers created using a process named amplified fragment length polymorphism (AFLPs) [13]. This method utilizes restriction endonucleases coupled with PCR to create thousands of identical fragments that can be used inside individuals or within organisms of the same genus for the genetic fingerprint study. AFLP has the benefit that it does not need to learn an organism's genome in advance. In absolute terms, researchers are uncertain about the area of a genome where this approach targets.

Though this technique typically offers a rich source of knowledge about the appropriate levels of genetic diversity. AFLP markers are also sometimes used as the first phase in researching the distinctions within communities of organisms. The downside of using AFLPs, however, is that the kinds of knowledge that they may provide are minimal. For example, since these markers' source and nucleotide composition remain uncertain (i.e., they remain just fragments of various lengths in the genome), their usage in the reconstruction of a collection of biological evolution background is restricted. Besides, AFLP markers are generally referred to as dominant markers and are classified as either "existing" or "nonexisting." This means that the gel bands representing homozygous (AA) or heterozygous (AA) genotypes are not always determinable. Because fragments of AFLP constitute specific restriction sites that occur or do not occur in each organism, only one allele (if any) is amplified, restricting the amount of usable knowledge. Another related form, named random amplified polymorphic DNA (RAPD), often generates dominant markers widely observed by the agarose gel electrophoresis. However, this process was mainly replaced by AFLP, which typically uses chemical fluorescence and gene analyzer to visualize.

2.7 Taxonomic Assessment from Random Molecules to Appropriate Methods

One of the essential things to pose while utilizing genetic science is: the particular problem that suits me the best? The response to that question must be decided by many considerations, all of which must be assessed individually and jointly, to establish a cohesive strategy for beginning an active molecular ecological research. Figure 2.4 shows a flowchart for initially determining which solution is better for your specific question. While there are several various approaches to tackle this issue, a straightforward strategy is to begin at the study's taxonomic level.

2.8 Molecular Markers

DNA markers are "points of reference" in the genome selectable for their similarity to the QTL. Selecting QTL-based DNA markers improves society's efficiency, usually lowers costs, and reduces personal phenotypic collection. Molecular markers represent the detectable genomic DNA differentiation sites that can be divided into approximately 1.

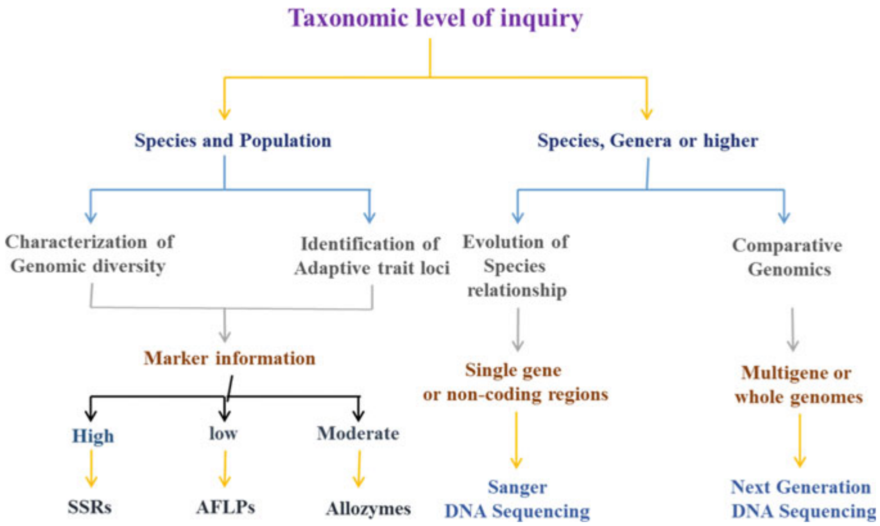

Fig. 2.4 Taxonomic level of assessment

2.8.1 DNA Markers Based on Restriction Enzyme

The RFLP chart of the first interspecific cotton community (*G. hirsutum* × *G. barbadense*) with 705 RFLP loci described 41 association classes spanning 4675 cm on 11 pairs of homologous chromosomes [14, 15]. An RFLP map was published in 2005 that connected 63 fiber QTLs to a subgenome (chromosomes 3, 7, 9, 10 and 12) and 29 fiber QTLs (14Lo, 20, and the long arm of chromosome 26) affiliated with the D-subgenome [16]. RFLP has been commonly used to classify a vast number of QTLs relevant to fiber content, weight, power, uniformity, wall thickness, and micronaire value (the compressed cotton fiber air permeability measure) [6, 16].

2.8.2 Polymerase Chain Reaction (PCR)-Based Markers (Mostly SSRs)

The second category of molecular markers is successful, named AFLP, which is also used to test cotton genomes [17]. In current years, AFLP markers have been used to track cotton fiber transcript differential expression during elongation and secondary cell wall thickening in interspecific (*G. hirsutum*) RI lines (*G. barbadenose*) [18].

SSRs are DNA markers that are most insightful, flexible, and simple to detect [19]. They were used in essential agricultural and economic genes, genetic association mapping, and relevant cotton imbalance studies [20, 21]. Though the conventional approach of establishing microsatellite markers is expensive and time-consuming [22], the analysis of molecular variation, population composition, and elite alleles of upland cotton varieties was carried out on a significant number of SSRs. As a consequence, numerous fiber quality features correlated with marker loci and fiber growth have been established [23–25].

2.8.3 Single Nucleotide Polymorphism (SNP) Markers

Three new markers, indel (insertion-deletion), SNP and microsatellite retrotransposon amplified polymorphism (REMAP) have been used with the production of cotton molecular markers to increase the map density of allotetraploid cotton varieties [26]. SNP markers may be used in cotton to attach genes to suitable properties of fibers. About 2500, SSR, and SNP markers have been used to classify about 100 genomic regions using (RILs) lines [27].

A broad community of gene-related SNPs [28, 29] was defined by contrasting four wild-type transcriptomes (*Gossypium tomentosum*, *Gossypium mustelinum*, *Gossypium armourianum*, and *Gossypium longicalyx*) and two cultivated cotton species (*G. barbadensis* and *G. hirsutum*). In this research, Li2 mutant and its near-isogenic wild type (NIL) *G. hirsutum* cv was identified using RNA sequencing combined with supermassive isolation analysis sequencing (sBSAseq). The Dp5690 was screened to establish the gene sequence of Ligon lintless 2 (Li2), and tetraploid cotton has established a unique subgenomic SNP [30].

An expansin protein plays a significant part in the consistency and duration of fibers. Using the NGS test, they described SNPs correlated with six expansin genes [30]. Form α cyclin-dependent kinase (GhCDKA) has maintained cyclin binding, ATP binding, and catalytic regions. They play a crucial function in the production of fibers. The CDKA gene expression was confirmed by Northern blot analysis and qRT-PCR. CDKA locus linked SNPs were allocated to chromosome 16 [31]. Via comparative study and resequencing, 24 million SNPs were established between the cotton A- and D-genomes. This study reveals that the genome has a considerably higher diversity (duplication and deletion), similar to the D-genome. For *G. hirsutum*, 1472, reported transition events involving 113 genetic overlaps between homologous chromosomes [32]. 220 and 115 BAC contigs (overlapping DNA fragments) of homologous chromosomes 12 and 26 have been found in *G. hirsutum,* and their physical duration corresponded to 73.49 and 34.23 Mb. Within both chromosomes, a large number of monogenic and non-monogenic loci were observed [11]. New marker sites and connection classes were added to various cotton varieties utilizing the information sequence-based markers and the DNA sequence details. Several ESTs and BACs were physically grounded and aggregated on genetic maps of high intensity and were biologically annotated and categorized into various cotton types [26].

The single dominant gene Ligon lintless-2 (Li2) developed significantly shorter fiber than wild species *G. hirsutum.* They have carefully grown Li2 cotton near-isogenic lines (one mutation and one natural type) across five generations of backcrosses (BC5). Hybridization was used to map the chromosome 18 connection at the Li2 site. The SSR marker NAU3991 has been traced successfully and has been entirely connected to Li2 locations [33]. Marker-assisted cotton seed culture and in vitro mutagenesis will explain how Li2 mutation is controlled in cotton [15].

Similarly, mapping and linking the study of *Gossypium raimondii* established the Li1 gene on chromosome 22. Some genes in the Li1 mutation were shown to have been mutated, contributing to the early termination of fiber elongation. Several subsequent kinds of research have found influences influencing the downstream position of Li-related genes [34].

Furthermore, molecular markers, marker-assisted selection (MAS), and marker-assisted backcross (mAb) have recently been strictly checked [35]. Cutting amplified polymorphic sequences (CAPS) and derived-CAPS (dCAPS) markers obtained from genes of interest along with SNP markers have become highly useful markers in seed molecular culture. Based on phytochrome genes, transcription factor (HY5), and unique dCAP were established through a comparative analysis of PHYA1, PHYB, and HY5 genes. Such experiments showed that such experiments were directly linked to cotton's fiber consistency and early flowering characteristics [36, 37]. A significant QTL may monitor fiber quality traits such as fiber duration, micronaire weight, intensity, and uniformity, clarifying the fiber quality molecular basis. One of those QTL fibers was identified in the *G. hirsutum* RIL community and marked between HAU2119 and SWU2302 markers. RNA sequencing and RT-PCR also identified three candidate genes, including QTLs [38].

2.9 Mapping for Fiber-Related Traits in Cotton

From an economic point of view, cotton's genetic advancement hinders cotton's successful breeding. Molecular cotton farming is an ongoing method for QTL development and mobilization. The advent of aided breeding in genomics has been an essential tool for screening agronomic features, stress reaction characteristics, and fiber parents. Over the past decade, cotton genome work has moved from some QTL mapping based on marker genotyping to GWAS based on a large-scale marker-dependent whole-genome interaction (GWAS) and genotyping dependent on next-generation sequencing-based on high-throughput (NGS) [39].

The allotetraploid cotton interspecific association map was developed using upland cotton F2 populations. Two thousand seven hundred and sixty-three (2763) markers were aligned with 26 association classes spanning 4176.7 cM of the genome [40]. Among the 601 distorted SSR loci identified in the At-subgenome, the number of independent aberrations was lower than in the Dt- subgenome [41]. Ninety-five polymorphic SSRs identified 185 cotton genotypes with great fiber traits. Other marker-trait relationships, such as average boll weight, ginning rate, and fiber traits such as micronaire size, short fiber length, fiber bundle intensity, and evenness index, are also shown on the table. The findings revealed that MGHES-51, MGHES-31, and MGHES-55 were strongly associated with all of these traits, which would pave a base for potential molecular marker-assisted breeding and cotton gene cloning [42, 43].

Molecular variation, population density, and polymorphism are calculated using SSR. The genome-wide maps of over 500 inbred cotton varieties obtained from China, the United States, and the Soviet Union helped to classify 494 fiber content based SSRs. In other research, 13 of the 216 fiber-quality markers in this analysis were listed as fiber-related markers [44].

Gene-based markers were developed based on the candidate genes and EST sequences to diagnose cotton organisms' polymorphism and conduct genetic and physical mapping. EST-related microsatellites have been used to expand the number of microsatellites that can be used for genetic mapping and to better with functional genomics to compensate for fibers' formation. EST-dependent high-density genetic maps dependent on SSR have been documented in several cotton fiber genes [45–48]. Early EST-SSR experiments were performed on cotton mapping sites in interspecific RIL (*G. hirsutum* × *G. barbadenose*) populations. At the same time, recent research aimed to locate colored fiber loci (Lc 1 and Lc 2) [48]. In the last years, 352 wild and domesticated cotton loci have been identified and allocated, and 93 domestication scans of 74 Mb and 104 Mb allotetraploid cotton A- and D-subgenomes have been conducted. Also, GWAS has defined 19 candidate loci for fiber quality-related traits. This research provides the likelihood of subgenomic asymmetric domestication for the collection of long fiber orientation. The impact of acclimation on cis-regulatory variations was demonstrated by the genome-wide screening of I-hypersensitive DNase and the association of heterogeneity with gene function [49].

The cotton research group may access a vast range of additional genetic and genomic tools for cotton via a single database. Cotton DB, founded in 1995, is, in this sense, one of the earliest databases on plant genomes [50]. The International Cotton Genome Project (ICGI) aims to organize cotton genomics research production, including creating full saturated genetic and physical maps in cotton [9]. A cotton microsatellite database (CMD) was established with the help of Cotton Integrated, which is a valuable tool for obtaining cotton microsatellite knowledge (CMD) and aims at achieving ICGI targets [51]. Eventually, the CottonGen database was a more extensive and reliable database covering biological, genetic, and breeding knowledge gathered from cotton, enhancing data analysis, processing, distribution, and retrieval (John et al. 2014). There are 103 maps in CottonGen [52].

Methods of genetic engineering focused on recombinant DNA, that is, molecules containing different DNA strands from various origins, are used to produce new genetic variants. It includes the insertion of exogenous DNA or RNA sequences into the genome of recipient species utilizing genetics or vectors to establish different and agronomically beneficial characteristics. Such modern species are referred to as genetically modified organisms or GMOs. GM crops started to be planted on a full scale in the mid-1990s, immediately after publishing the first plant genome databases. Four agricultural products have also been branded as genetically engineered seeds: maize, soybeans, canola, and cotton. By 2008, combined, these crops accounted for over 99.5% of genetically modified crop growth.

Delightfully, these crops had exhibited only two transition activities, namely herbicide-resistant and insect resistance, or a mixture of them. It also implies that the use of genetic manipulation as a traditional crop improvement technique is still constrained 25 years after the first commercial development of transgenic plants, although transgenic technology has apparent potential. Disadvantages involve the absence of successful genotype-independent regeneration mechanisms for certain crops, and the particular limiting aspect may be their limitations on intellectual property. Genetically modified organisms (GMOs) are still the exclusive domain of private breeding undertakings in developed countries. There are several components (with patents) that limit research and development of genetically modified crops. An interesting recent phenomenon—which could potentially speed up PGRFA's analysis of intellectual property rights' defense status —is that genetically modified crops are increasingly cultivated in developed countries, such as genetically modified soybeans in South America and transgenic cotton in India and China. When more and more developed countries obtain the ability to comply with the regulatory guidelines on the production of genetically modified crops, in particular under the prohibitions on biosafety laid down in the Cartagena Protocol, a concentrated determination is required to create the capacity to handle restrictions on intellectual property, which hinders the complete utilization of PGRFA's transgenic capacity necessarily.

On the other side, work is assumed to concentrate on developing plant regeneration processes and, more specifically, extending the variety of agronomic traits that genetic transformation might enhance. The aggregating multiple transition events in a receiver organism is always inefficient and contributes to phenotype expression. Eliminating technological obstacles is crucial to genetic transformation in solving multi-gene traits, especially those linked to shifts in climate change, drought, and salinity. It's also essential to remove this barrier for gene aggregation. Plant genetic resource richness (PGR) offers plant breeders the ability to grow new and enhanced varieties; this not only involves the characteristics these farmers like (yield ability and large plants, etc.) but also the characteristics that breeders like (pest tolerance, photosensitivity, etc.). Since the outset of agriculture, the natural genetic diversity of crop organisms has been used to fulfill the necessity of food self-sufficiency. The emphasis is now on supplying the developing nation with surplus food. Developing countries like India witnessed the green rebellion in the mid-1960s, utilizing high-yielding, fertilizer-sensitive miniature hybrids/varieties (especially wheat and rice) to meet food needs. Such long-term studies also culminated in the detection (boom) of wide-scale human genetic variability. They also intensified through specific ways, such as genetic degradation and loss of advanced and adapted genes (loss of terrestrial races). Today, with the advancement of agriculture and related science and technology, we tend to ask one if we could feed the planet by 2050; this problem was posed recently at the 2014 Planet Food Prize, but none addressed this problem since by 2050, the world's population would reach 9 billion.

Maintaining an inventory of plant organisms produced and developed is a concept of potential agriculture. Maintaining a museum shows the cultural and theological aspects of various cultures from diverse regional areas and offers background documentation for the future. The former plays a significant role in transfering adaptive and efficient genes, contributing to long-term growth in food output and other everyday supply, and is often related to harm to the ecosystem. This analysis emphasizes the significance of genetic diversity and the analytical methods and techniques commonly utilized in the post-genomic period. Animals and plant breeders added the necessary genes and gradually removed the unnecessary ones, altering the fundamental concepts of genetics for decades [53]. This engineering method is growing with the advent of modern biotechnological technologies and techniques, which shortens the breeding period and can be carried out more effectively (ignoring environmental impact) and faster than conventional breeding techniques.

2.10 Conclusions

Growers have become aware that various plant genetic resources are valuable properties for humanity that cannot be misplaced. Such materials are prerequisites to be available to feed a growing world population in the future. Genetic variation in crops is essential for further enhancement by giving breeders opportunities to develop new selections and crossbreeds. This can be succeeded and completed by phenotypic and molecular characterization of PGR. Sometimes the large size of germplasms can limit its use for breeding. This can be overcome by using subgroups, such as the core and minicore collection, representing the diversity of the entire species collection. Molecular markers are very much useful and supportive tools for measuring the diversity of plant species. Cheap assay kits, inexpensive machines, high quantity, and suitability for easy analysis and computerization make it more convenient to select modern technology. With high-capacity molecular marker techniques, which ensure the rapidity and excellence of produced data, it is possible to distinguish the more significant number of germplasm within a concise time and limited resources. Resulting entire genome sequencing can be achieved with low cost and time. With the help of prevailing computer software programs, phenotypic and molecular diversity parameters can be measured. It will increase the effectiveness of seed plasma curators and plant breeders to accelerate crop development. Therefore, based on the study, we consider that this review will deliver beneficial and contemporary information in one place; thus, it helps to understand valuable tools for everyday applicability for the students and scholars.

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Prof. Dr. Altaf Ahmed Simair has been a constant source of inspiration for everyone out there. He was born in a small village of district Sukkur, after getting his early education from hometown; he spent four years in Shah Abdul Latif University, Khairpur, from where he did his masters in Plant Sciences with distinction. After graduation was appointed as a lecturer and had been teaching the undergraduates and graduates, he got a Ph.D. degree from the University of Sindh, Jamshoro, in industrial biotechnology later; he went for post-doctoral studies and worked under the advisement of Professor Dr. Changrui Lu, Donghua University Shanghai, China and published 16 research articles. He has already rendered his valuable services to Pakistan's Government as a professor for more than 20 years. Worked as Editorial Member, Member Scientific Committee, and Member Review Committee of various National and international journals and participated in National & International Workshops and Short Training Courses and international symposiums. He is recently serving as Chairman, Department of Botany at Government Collage University (GC University) Hyderabad. More than 40 (National & International) research articles on his credit, which shows his proficiency and scholarly erudition in the realm of biotechnology and biochemistry. He has been honored to write excellent biology books of Sindh Text Book Board from matriculation to intermediate level. His contribution in the form of these books is marvelous and exceptional. His work has always been as helpful and all-embracing as his current work on (Status and recent progress in determining the genetic diversity and phylogeny of cotton crops) is undoubtedly a masterly distillation of his well-equipped pen and his ceaseless efforts for the compilation of this book.

Sippy Pirah Simair has many feathers in her cap; her outstanding achievements bear out her credentials and complete her early education with excellent grades. She spent four highly productive years at the University of Sindh, Jamshoro, culminating with the degree of BS (Hons) in Biochemistry, where she mastered the skills of scientific research and experiments. She wrote three excellent articles on xylanase production and the antifungal potential of shell extract. Her contribution to scientific research is marvelous and exceptional. She is a glaring example of hard work, diligence, and assiduousness. She is currently doing Masters in Molecular biology and Biochemistry at the College of Chemistry, Chemical Engineering, and Biotechnology, Donghua University, Shanghai, China.

Chapter 3
Advancements in Cotton Cultivation

Hanur Meku Yesuf, Qin Xiaohong, and Abdul Khalique Jhatial

Abstract Cotton cultivation requires using cultivation technologies like pre-sowing or bed formation, post sowing, pre and post-harvesting, weed removal, irrigation, and pest management. Drip irrigation, basin irrigation, and furrow irrigation can be used for crop water management during cotton cultivation. Several watering, application of herbicides, nutrition, and fertilizer with irrigation water affect the growth of the cotton crop. Planning of plant, land preparation, and using different sowing techniques like pre-sowing tillage practices, drill sowing, and furrow sowing are used in cotton cultivation. Plant densities and varieties affect the growth of the plant and the crop yield by influencing the cotton plant farming parameters. During the cultivation of cotton, testing of cotton fields such as soil testing and the number of bolls per plant must be done. The consequence of different agricultural parameters, mainly cotton plants' response to temperature, minerals, and salinity should be under consideration while farming cotton plants. The harvesting of cotton can be done manually or by machines. This chapter briefly describes the cultivation technology, irrigation techniques, weed and pest management, consequence of agricultural parameters, and cotton harvesting.

Keywords Cotton cultivation · Irrigation water · Pesticide · Crop output · Weed · Cotton harvesting

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3.1 Introduction

Conventional farming shields agro-biodiversity, genetic differences, and native biological information. Despite farming modernization, numerous agriculturalists keep on working with little scope of various agro-frameworks. If there is enough room between the lines of cotton trees, it is possible to develop short-lived crops such as green gram, black gram or soybean to raise field productivity and boost financial gains without disrupting cotton plant life since the cotton tree has gradual beginning development [1].

Pre-sowing grain medication in a magnetic discipline [2] by pulsed electric field [3] can increase crop yields, seed germination efficiency up to 12.0% [3], crop potential up to 15.0% [3], reduce the incidence of plants and improve product quality. The rate of chemical and biochemical reactions in plant cells, the transport of ions and molecules through the cell membrane, the sowing qualities of seeds and their yield are improved and increased by the influence of a magnetic field [2, 3]. Seed priming is before-sowing seed preparation intended to improve seed propagation and increase the uniformity of seedling appearance under unfavorable circumstances. There are two forms of priming: Halo priming (sopping in a salt solution) and Osmo priming (sopping in other osmotic options) [4].

The final production of cotton depends on various factors, profoundly the climate conditions, the structure of the soil, physical and chemical soil properties, genetic material, irrigation, fertilization, plant density, weed, and insect infections. Precision Agriculture is a plant management program focused around the application of the new technologies to monitor and chart the soil-crop system's variation. Its objective is the rational application of inputs in all production stages based on the identified variability and the most optimal balance of the system [5].

Preparation of the seed that dries and eliminates the leaves allows the mechanical picking of cotton and eliminates foreign content. Usually, crop preparation is conducted two and three weeks before harvest to enable earlier start and faster drying of dew, which enhances thresher-operating times. Leaf dehydration and degradation may be achieved through the frosting, applications of chemical, or heat resources. As all areas of cotton cultivation have predictable autumn conditions, chemical desiccants, defoliants, and boll openers have come into extensive usage. Usually, they are combined and deployed via air or ground rig. Cutting off crops often provides for a one-pass harvest process, avoiding a second field visit. The risk of insect exposure can be reduced by proper crop termination; as a result, reducing the time to harvest. Free amino acid levels may increase stress in cotton plants because of harvest preparation chemicals so that defoliated cotton becomes desirable to Silverleaf whitefly, Bemisia argentifolii, cotton aphid, aphis gossypii, throughout the treatment and harvest interval. The thermal treatment allows early harvesting of cotton without adversely affecting the cotton lint performance or output [6].

Cotton yield monitors, the digital machine format for a farmer-based harvest control adjustment method for a basket-type cotton stripper, detecting the movement of the material within transmission ducts or when the content moves through the basket or gatherer on the collector. The machine is based on the usage of weight detectors to calculate tray load in the hydraulic lifting chamber circuit by measuring the stationary friction. The machine automatically raised the basket to a goal elevate peak to guarantee precise measuring, gave the basket time to calm down, and after that, measured the basket contents. It can be expanded to provide an optical cotton growth detector in the pneumatic air vents that monitor cotton bolls [7].

Automating Cotton Harvesting Machine (CHM) quality assurance systems and collecting knowledge regarding the cotton field's agricultural history based on picture processing using computer vision approaches is an essential activity [8]. The mean pre-harvest damages may reach 2.33% for all varieties. There are a 0.80% output losses because of the mechanical picking technique considering losses for all types of cotton from knapsack cotton picker [9].

3.2 Farming Technologies

Intensive farming technologies and achievements like double cropping, small tree transplantation, plastic mulching, plant preparation, and short-dense early higher-yielding planting trend performed further significant roles than cotton hybrids and other factors to the substantial growth in fiber production. Double cropping of grain-cotton will ease rivalries by increasing the usage of farmland and solar energy efficiency [10] (Fig. 3.1).

Fig. 3.1 Double cropping systems in China: **a** double-cropping of cotton-wheat; **b** multi-cropping of cotton-wheat-watermelon [10]

Simplified small tree transplantation lowers employment expenses and growing job performance. This is a viable transplant option by reducing the labor-intensiveness of traditional seedling nursery and transplanting. Small tree transplantation has many benefits relative to direct seeding [10]:

- It lowers the number of seeds;
- The developing cycle is increased, and cotton maturity is completely assured;
- Water and nutrient intake have been enhanced with adjacent root development being encouraged. Moreover, the root weightiness and adjacent root number of soil-cubes transferring are 43.4 and 18.8% higher than those in direct seeding cotton;
- Cotton sprouting, development, and early growth of seedlings are prone to salinity tension.

Plastic mulching is typically performed shortly afterward manually or mechanically sown to raise the temperature of the land via the greenhouse effect. It preserves dampness to enhance seedling formation, plant production, and financial output by avoiding the immediate water loss from the land. Using plastic mulching in the salty area is necessary to efficiently minimize the deposition of saline in the field soil by preventing water loss and reducing the salinity tension [10] (Fig. 3.2).

Plant pruning primarily entails cutting the vegetative branch, topping of the trees, and trying to remove the branches with bare fruit and aged leaves. Plant preparation is commonly assumed to minimize the nutritional intake of surplus tissue, reduces the amount of boll abscission and boll rot, and improve cotton production and consistency of fiber. Elimination of vegetative roots, replacement of plant toppings, elimination of early fruits [10].

The use of modern agricultural equipment instead of manual operation, the simplification, and the minimization of field management and operations is called light and simplified cultivation (LSC). It also includes the introduction of cultivation equipment and farming innovations to reduce production costs and labor intensity during cotton farming and cultivation [11]. The main innovations needed for the growth of cotton via light and simplified cultivation are [12]:

- One-time fertilization innovation,
- Light and simplified seedling nursery innovation,
- Simplified pruning innovation,
- Water and fertilizer integration innovation,
- Single-seed precision sowing innovation,
- Plant population control innovation.

Shifting agriculture is a very sophisticated agricultural method, and there is growing proof that it will be converted into intensive agriculture technologies, like monoculture crops or tree plantations, permanent annual crops, lawn pasture, or short fallow mechanisms [13]. The enhanced output of cotton, specifically the higher unit output, can significantly be credited to the implementation of a variety of main farming strategies. Some of the cultivation strategies considered as enhanced

Fig. 3.2 Row covering with plastic mulching [10]: **a** plastic mulching after sowing conducted with the machine; **b** manually freeing seedlings from mulching cover at emergence; **c** plastic film coverage (mulching) before sowing conducted with the machine; **d** avoiding the process of seedling freed [10]

cotton production are water-saving drip irrigation under plastics mulching, earliness-stimulating agriculture for maximum use of stored moisture, and short tree length for effective use of sun's energy [14].

Application of smart cotton sowing innovation, advanced planting equipment fitted with GPS satellite mapping, and automated communications systems achieves autonomous automated activity and can operate day and night. Controlled intelligent drip irrigation programs utilize wireless data analysis tracking technologies and drip irrigation management technologies that suit the position of the farm fields and users' specific water level needs, enabling automated regulation of field drip irrigation and fertilization. Continuous advancement of intelligent systems in sowing and irrigation engineering needs study and advancement into smart-automated control systems, plant safety technology, and advanced technology for mechanical harvesting [14]. Significant levels of energy consumption in all cropping schemes included 44–55% for chemical fertilizers, 13–17% for soil treatment, 12–15% for fuel, and 11–14% for manpower [15].

3.3 Irrigation

Subsurface drip irrigation is often costly to build and operate, so, in addition to cotton, farmers usually put the money in a diversity of seeds. Subsurface water supply decreases land water loss and can be modified to match soil moisture value and other climate conditions like temperature. Successive repair work of irrigation machinery is required after set-up, so it is essential to provide technical support, particularly for smallholder growers [16].

Water and nutrient usage improvement and effective moisture loss reduction can be achieved by drip irrigation under the film. Relative to flood irrigation, water savings and gain increases with film-based drip irrigation are enhanced by 20–50% and 10–30%, respectively, and the effectiveness of water and nitrogen usage might have been massively improved. Furthermore, weeds, diseases, and reduction of insect pests decrease in the number of boll rots and increase the yield of cottonseed and the quality of fibers produced by irrigation from the drip. Drip irrigation under film in saline fields may provoke a low concentration of salt content across the root region, which significantly mitigated salinity strain and improved seedling settlement and crop growth [10]. Organic cotton will have less bed bug infestations during drip irrigation and likely increase quality traits [17] (Fig. 3.3).

Cotton water-saving irrigation engineering has the function of increasing the utility of water during irrigation. The more popular water-saving irrigation technique, which combines plastic film mulching with surface drip irrigation, is the drip irrigation under the plastic mulching commonly used in the northwest inland region. It requires a minimum-pressure water delivery piping network, extracts the compressed water by filtering systems, and then dissolves the water-soluble fertilizer to create an aqueous solution. Such formulation systematically infiltrates the localized root areas of cotton to preserve the optimal amount of humidity for water and fertilizer incorporation. The mean intake of water is 12% that of the conventional irrigation and 50% that of the irrigation sprinkler. It decreases by 15–20%, the volume of fertilizer needed. Partial-root zone irrigation under mulching by interlaced drip irrigation results in non-uniform root zone spread of salts in salty fields, which minimized salt loss by specific different physiological and molecular processes [12].

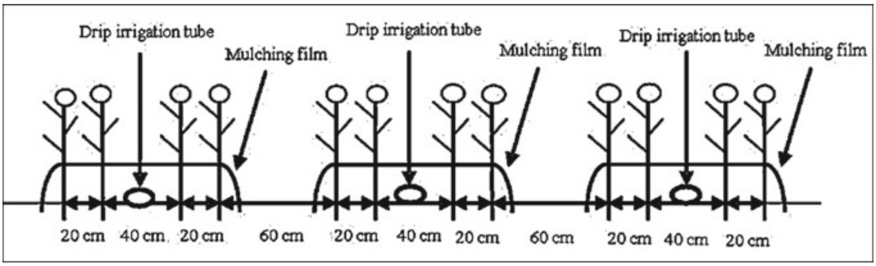

Fig. 3.3 Drip irrigation system with four rows per drip irrigation tube [10]

Furrow irrigation is closely associated with flood irrigation where furrows are prepared in the soil by machinery, and water is flooded into the furrows. The water then gravitates down the furrows and ceases to gravitate at the end of the furrow [18]. Once the cotton plant is small at the beginning of the season, alternative furrow irrigation can minimize some water losses by restricting water loss from the ground. It is based on soil and location; in short, the findings are time- and site-specific [16].

In semi-arid areas, it is necessary to decide the timing of irrigation and to calculate the percentage of complementary irrigation needed due to the unevenness of rainfall occurrences. For such areas, growing crop water-use efficiency (WUE) to improve farmland productivity without raising the amount of water required for irrigation has become very difficult [19]. Sprinkler irrigation is used on a center-pivot sprinkler system. The center-pivot system has irrigation pipes elevated above the ground on wheels. The system pivots from a concrete skid in the center of the field and travels in a circle. As a general rule, center-pivot systems are designed to be used on quarter-sections. With this method, water is spread by injecting water at low to high intensity into the atmosphere. This system is powered by electricity and can make a complete circle in 36–72 h, based on the quantity of water used. Water is pumped with large engines ranging from 300 to 600 horsepower. In recent years, new irrigation technology has been developed and is called the Low Energy Precision Application (LEPA) system. Low Energy Precision Application system is used on center-pivot sprinkler irrigation equipment. However, it differs from sprinkler irrigation in that it spreads water specifically into drop pipes to the furrow and orifices operated emitters at low pressure, instead of spraying water into the atmosphere. Rationales affecting the layout of the irrigation framework for the Low Energy Precision Applications included [18]:

- Precise control of water application,
- Minimization of water evaporation,
- Decreased operation costs by use of less energy and
- Increased irrigation efficiencies.

3.3.1 Crop Water Management

Cotton yields are dependent on inputs such as water, fertilizer, insecticides, pesticides, and heat degree units. Water is the most limiting of these inputs [18]. The amount of cotton's water usage also peaks opinion pieces like a huge problem. Yet the impact of cotton on water has many kinds: depletion of natural water sources for irrigation (inputs), freshwater pollution from fertilizer and pesticide usage (outputs), and water conservation [16]. Improper water conservation and non-professional drainage are two of the causes for runoff that not only carries extra water but also includes pesticide waste products, fertilizers, and salts that were applied to the cotton plant. The quality of soil and the environment are safeguarded by water conservation techniques. Over irrigation raises soil salinity, which results in decreased production. Low-volume drainage, the catchment of rainwater, and the planting of drought-resistant seeds are some steps taken in the agriculture for sustainable water management [1].

3.3.2 Application of Herbicides, Nutrition, and Fertilizers with Irrigation Water

Saltwater irrigation over months of the season dramatically reduced plant length, amount of fruiting limbs for each tree, amount of open boll for each plant, boll weight, seed index, and output of cotton seed for each plant. In irrigation with saltwater, nutrients such as potassium humate, algae extract, and polyethylene glycol (PEG) are introduced to boost the cotton plant's production, output, and anatomical parameters [20]. Fertilizer levels added to irrigation water have effect growth contributing characters (Plant tallness, the number of nodes, accumulation of dried particles) as well as output adding characters (Boll number, Boll weight, Seed cotton yield) [21]. Different sodium chloride concentrations affect the germination of cotton. The optimum propagation rates between varieties are 44.29% for PG2018 and Flash, 35% for Carisma, and 28.57% for Lydia. Also, sodium chloride concentration reduced the propagation rate up to 30%; successive amounts of clogged propagation almost totally for whole varieties [22]. The most important nutrients in cotton are nitrogen, phosphorus, and potassium [23].

3.4 Land Preparation

Land preparation, variety selection, planting, weed and insect control, soil fertility, disease pressure, plant growth regulation, and harvesting are included in cotton crop management. Cotton grows on a wide range of soil types with adequate root range and pH values from 4.5 to 8.5. Land may be prepared in terraces to limit soil erosion. At least a portion of seasonal nitrogen requirements and, in some instances, pre-plant, incorporated herbicides are applied before planting. In tropical growing regions, cotton is planted, so the rainy period falls during blooming, and boll fill and harvesting is accomplished during the dry season. In temperate, short growing season areas, cotton is planted when soil temperatures average 16 °C over ten days [23].

Organic environments of agriculture allow the soil to be richer in organic material, and crop preparation starts with initial tillage activities to work the land. When there are no other tools accessible for seedbed preparation, the increased organic material will also be beneficial in good germination, better plant-standing, and greater outputs. For organic environments, seedling densities are often smaller than traditional, without significantly influencing production [24].

3.5 Sowing Techniques of Cotton

Sowing methods and styles of seeding equipment affect seed placement, the emergence of seedlings, crop development, and production of grains. The choice of appropriate farming techniques such as near planting and short plant length for sufficient usage of sunlight energy [14] depends on the time of farming of rapeseeds, irrigation techniques such as drip irrigation for water-saving and production enhancement under plastic mulching [14], the quantity of residual in the farm and form of farming machinery [25].

The number of the plant in a given area and varieties greatly affected lint yield by influencing the characteristics of the leaves stomata density, size, width, weight, pore circumference, exchange of leaf gas, and chlorophyll fluorescence. The photosynthetic canopy rate and crop output of any cropping method are optimized by proper controlling of important agronomic practices like planting density and choice of the cultivar. Effects of changes in plant geometry and canopy dynamics concerning planting density are the occurrence of infection, water consumption, canopy temperature, and assimilation metabolism enzymatic action. Manipulations of cotton plantation density have significant influences on biomass partitioning, nutrients absorption and allocation of the boll, light spectrum shifts, and crop growth, which can affect producers' yields and income. High density plants will reduce the level of moisture loss and drainage and maximize the use of irrigation water [26].

High-density planting, by comparison, will delay the arrival of the leaf and decrease open boll length, boll weight, and amount of bolls. It also slows the cell death of the leaf and reduces the productivity of nitrogen usage and the effectiveness of nitrogen restoration. A planting density of up to nine trees per meter square, sustain a photosynthetic leaf rate, and the development of reproduction area biomass by growing plant potassium uptake at various developmental stages. Nevertheless, a planting density of more than ten plants per square meter and successive shading can result in infection of diseases, small boll size, fruit shedding, slowed maturity and declined specific tree growth. Plants with low density growing have reduced chlorophyll volume and a greater exchange rate of electrons compared to planting with high densities. Leaves in lower density (sun leaves) are resistant to bright light; shadow leaves, on the other hand, have poor photo safety ability and are more prone to extreme bright sun. Optimum crop density can guarantee stable plant growth by holding a core plant community synchronizing several bolls and lint quality to ensure optimum production [26].

The plant population usually for conventional cotton row spacing varies from 7.4 to 14.8 plants per meter square. Increased seeding rates for ultra-narrow row cotton, i.e., cotton grown in lines less than or equal to 38 cm and collected with a finger-type stripper, are needed to reduce branching and support harvesting by a finger-type stripper and to account for inaccurate grain drills employed to plant narrow rows of cotton. Owing to the revived concern in ultra-narrow row cotton owing to herbicide-resistant finished plant populations varying from 19.8 to 49.3 plants per meter square [27].

High plant density alters the amounts of hormones and photosynthesizing processing, thereby inhibiting the vegetative budding in cotton. An overgrown basal vegetative branch leads in a voluminous plant geometry, which is hard to maintain and grow. Plant population size influences the growing and production of cotton from the basal vegetative part. A large plant population size will greatly prevent the outgrowth of the basal vegetative node. The spaces among two neighboring plants are lowered under high plant population size, providing adjustments in environmental factors [28]. Biologically, the length of the plant is equivalent to all the heights of the internodes above land, indicating the rate of vegetative development. Boll number for each tree, though, is the total of all the boll numbers from the formation of the first boll, representing the rate of growth in reproduction [29].

An extremely high or meager plant population size can have adverse influences on cotton output. Cotton fiber yield shows a curvilinear approach to plant population size, delivering the highest value in sandy land, and temperate climatic conditions at the highest possible plant density range of 4.5–6.0 plants per meter square. Cotton plants experience increasing intra-specific pressures from increased plant density. The production of cotton has been rationally associated with the highest rate of fruit growth and crop output. High levels of fruit production and growth rate are the key factors why optimum plant density has achieved the highest possible cotton yields. In addition to cotton production, there are additional considerations that include fruit maturity, harvest quality, seed costs, and ease of management, causing from amplified plant density that producers may weigh when making cotton seeding rate decisions [30].

Plants at high density can increase the utilization of irrigation water and minimize evaporation and irrigation frequency. Heavy-density planting, by comparison, will delay the arrival of the leaf and decrease open boll length, boll weight, and amount of bolls. It also delays the cell death of the leaf and reduces the productivity of nitrogen usage and the effectiveness of nitrogen restoration. Medium-density encourages the partitioning of dry matter to productive organs rather than vegetative organs and less shedding of fruit relative to denser fields [26].

3.6 Weeding

Traditionally, a weed-free seedbed is prepared through tillage. Though, due to the lack of tillage in Conservation Agriculture, weed volume is estimated to grow, especially early in the season. Because of insufficient manpower, growers sometimes postpone weeding early in the season, focusing on planting. Most of the farmers take advantage of the moisture to continue planting their fields instead of focusing on weed control. Consequently, the lag in weeding also leads to expanded crop-weed rivalry for energy, moisture, and resources [31].

The prevalent weed management method on smallholder farmers under Conservation Tillage is hand hoe weeding. Ox-drawn incorporates strategies of weed management, like plows, and tine farmers are prohibited because they improve tillage. Hand hoe weeding, however, is sluggish and constitutes 50–70% of the overall working hour for smallholder growers, and it is not successful in the Conservation Tillage weed controls [31].

An estimated yield loss due to weed competitiveness is 5.8%, output loss may reach whereas 21–61% based on climate, cultivation methods, and weed species in different parts of the world. Weed species may differ in the different geographical areas, based on the crop region and the sowing time frames. When weeds are controlled at cotton fields, it needs intensive labor and cost-effective. Weed management is vital in cotton farms to minimize high losses. Weed species and densities continuously changed due to irrigation, crop rotation, cultivation, and herbicide use [32].

Combined with herbicides, aqueous extracts of allelopathic plants may help farmers in limiting herbicide dosage, so it is good for environmental safety. Alternatively, the most efficient weed control technique in cotton together with the maximum cotton output is soil solarization using black plastic mulch and application of herbicide in conjunction with manual hoeing. Significant barriers to successful weed control include herbicide-resistant crops, lack of awareness and expertise on herbicides, labor scarcity, climate change peak, higher incomes, weed population changes, lack of sufficient and timely supplies, ever-increasing challenges to invasive weeds and the limited financial capacity of small farmers. In General, the following are used to control weeds [33]:

- Traditional activities (early sowing),
- Hand-picking or hoeing,
- Mulch and soil solarization,
- Tillage,
- Biochemical management,
- Allelopathic methods,
- Chemical weed monitor,
- Weed management practices and cropping systems diversification,
- Understanding the biological aspects of weeds,
- Enhanced mechanical machinery.

3.7 Pest and Disease Management

Cotton is good food for insect pests, with an approximate 148 insect pests spend their lifetime on cotton crops throughout the complete planting season. Depending on the morphological and physiological nature of the crop, which is credited as a self-plant defensive mechanism against herbivores, insect pests determine their correct food depending on their feeding behavior [34].

The development of whitefly-resistant cotton cultivars is one of the experimental solutions which could have the ability to raise the cotton gummy texture challenge. The shape of the okra leaf, glabrous leaf, and a high content of gossypol are characteristics of whitefly resistant cotton cultivars [35].

Stinkbugs comprise insect pest complex affecting cotton and other 12 major crops worldwide. Fluorescent imaging under long-wave ultraviolet light used to identify stinkbug-damaged lint. In a circular area around the puncture wound, the outside of the boll and the inner carpal wall released intense blue-green fluorescence, while undamaged tissue exposures existed at separate wavelengths. Chlorophyll fluorescence is influential over the much lower emission of the undamaged membrane.

The identified signature fluorescence peaks correlated with stinkbug damage result in a fluorescence-based system for easily categorizing between cotton bolls harmed by stink bug and undamaged cotton bolls. It is important to support pest control practitioners with easily assessing the severity of stinkbug harm in a cotton field, depending on the fluorescent fingerprint [36]. Yield loss caused by feeding injury from plant bugs to cotton bolls decreases lint quantity and quality. Lint quantity is caused by the enzymatic action of digestion to boll tissues, and lint quality is caused by boll rotting organisms that are introduced by the process of feeding [37].

Boll rot development depends on environmental situations that persist after eating and injuries. Stylet insertion, screening, and digestive enzyme injection minimize boll development by destroying assimilate aggregation. This causes lint and seed harm to growing during the probing process, and the growing lint fibers get hurt [38].

Integrated Pest Management (IPM) is an environment-based approach that promotes stable crop growth with the least possible disruption to farming habitats and facilitates processes for the natural management of pests. Integrated Pest Management involves the combination of approaches such as biological protection, landscape engineering, alteration of cultural norms, and the use of tolerant varieties that concentrate on the long-term avoidance and harm of pests. Insecticides are used to eliminate only the target organism according to established guidelines. Cotton farming may require as much as 5 kilograms per hectare of insecticides and 7 kilograms per hectare of herbicides annually [39]. The use of pesticides has an impact on wildlife contamination, groundwater, and surface water contamination [1]. So it is important to pick and distribute Pest control products in a way that minimizes hazards to public safety, useful and non-target species, and the ecosystem [16].

Cotton is particularly prone to pests, mainly in moist zones. Growers employ a range of strategies like pesticides and herbicides to deter and destroy insects to safeguard their crops and outputs. Those sprays set some processes in motion that change the field’s natural food chain. Once sprays are employed, they impact not only intended pests but their predators(beneficial insects) as well [16].

The ever-increasing prevalence of herbicide resistance in weeds has become one of the major concerns of modern farming. From an agricultural practice point of view, herbicide resistance can be described as a plant’s inherited ability to live and replicate following exposure to herbicide dosage that is usually hazardous to a coniferous tree of the same species. Since the late 1960s, the use of herbicides has been the primary method used globally for weed management. However, repeated usage of the same herbicide or herbicides with the same mode of action (MOA) eventually contributed to resistant weed species being picked [40].

Herbicide application can improve the ability of smallholder growers during the crucial weed-free time and in wet conditions to successfully dealing with weed influence. In traditional tillage, glyphosate and pre-emergence herbicides like atrazine, cyanazine, and alachlor have been used effectively. Under Conservation Tillage systems, however, the efficacy of herbicides approved for use in traditional tillage processes may vary, with higher weed densities and a particular and varied weed range. Of the herbicide therapies, the most successful broad-spectrum herbicide is a tank mix of cyanazine and alachlor in cotton, which protected both grass and broadleaved weeds, and provided the largest crop output [31].

Table 3.1 Characteristics of alkali and saline soils, reprinted from Ref. [1], copyright 2017, with permission from Elsevier Ltd

S/No	Type of salt-affected soil	pH (1:2)	Electrical conductivity (dS/m)	Sodium (%)	Salts in excess
1	Alkali/sodic soil	>8.5	Variable	>15	Carbonate and bicarbonate of sodium salts
2	Saline soil	<8.5	>4	<15	Chloride and sulfate of calcium, magnesium and sodium salts
3	Saline-sodic soil	<8.5	>4	<15	Chloride, sulfate, carbonate and bicarbonate of calcium, magnesium and sodium salts

3.8 Testing of Cotton Fields

The overuse of fertilizers has endangered 70% of nature's survival, while underutilize fertilizers remove soil nutrients with the crop without regeneration, resulting in farmland deterioration [1]. The mineral components in clayey fields calculated by the employment of characterizations of X-ray diffraction (XRD), infrared spectral absorption pulse diffraction tests, full pattern simulation of diffractograms, or so-called Rietveld methodology and thermogravimetric analysis [41] (Table 3.1).

Cotton production leads to waterlogging and the sloughing of salty fields. Salt-affected fields are usually categorized as sodic soils and saline soils, based on their genetic makeup and traits. Alkali fields exhibit high electrical conductivity and hold abundant sodium salts of carbonate and bicarbonate. Alkali soils have necessary behavior with a pH value of greater than 8.5, and the percentage of sodium is more than 15%. Salin soils show more than 4 deci-siemens per meter (ds/m) electrical conductivity and contain chloride and sulfate of calcium salts in excess. Saline soils have basic behavior with a pH value of less than 8.5, and the percentage of sodium is less than 15% [1].

3.9 Consequences of Agricultural Parameters on Cotton

3.9.1 Cotton Plant Responses to Temperature

Cotton is a warm climate and sun-loving plant, and its development and flowering need relatively high temperatures ranging from 28 to 32 °C, however higher than optimum temperature significantly affects its fiber output and quality characteristics [42]. At the start and end of the cotton-planting period, if the temperature increases, the cotton yield shows a positive effect. In contrast, cotton growth and development are minimized if there is an increase in the occurrence of high-temperature time. Air temperature and soil temperature are crucial factors that determine the degree of cotton growth as well as affect fiber production. Lower temperature than 12 °C in the early stage of cotton growth contributes to delayed growth and development of the cotton plant. In contrast, a higher temperature than 35 °C in the middle stage of growth may have a detrimental impact on the fertilization level, the amount of cotton boll, and the number of cotton buds dropping off, resulting in decreased water use efficiency and yield. During the late growing season, low-temperature influences not only ripening duration, but also influence ethephon's maturing effects, decreases pre-frost blooming, and results in reduced outputs [43, 44].

The highest temperature may cause an escalation shedding of flower buds during the late stages of development. Pollen expansion, pollen tube production, and fertilization are among the most thermally-sensitive phases of the cotton reproduction growth process. Extreme temperature affects physiology, biochemistry, and quality of cotton plant as a result leading to poor agronomic products that cause serious yield reduction in cotton. Also, boll expansion (boll dimension) and maturation time are affected by high temperatures. Freezing temperatures often influence the proportion of germination and placement of seedlings. On the other side, minimum-temperature stress is often disastrous at the time of the cottonseed germination process and also by prolonged extension time and decreased swelling of the cell wall for the lint growth level. The optimal temperature measured at 20–30 °C for aggregation of biomass. Elevated temperature exposure more significant than 32 °C restricts cotton growth and production. All growing phases are usually influenced by extreme temperatures, but the vulnerable and essential is the reproductive phase [45] (Fig. 3.4).

The impacts of elevated temperatures on cotton's agricultural and physiology qualities at different phases of production are as follows [45]:

- At seedling Stage: reduced germination rate and poor seedling establishment
- At leaf area and canopy development: Stunted growth, reduced photosynthesis, less number of flowers, redox imbalance and hormonal imbalance
- At flowering and boll development: poor fiber quality, hormone imbalance, pollen abortion, and low seed setting rate.

Approaches must be implemented, such as increasing the varieties of thicker cuticle and waxy textures, which may mimic sunlight to minimize the excessive heat effect. Changing the line distance within rainfall-fed schemes will improve surface water supply for crops, influence lint output, improve lint quality, and minimize the degree of unpredictability correlated with stress growth. Using canopy temperature detectors, irrigation planning dependent on crop requirements may also play a critical role in improving the damaging effect of temperatures and drought strain. Thus, changing the plantation period will boost the harmful effects of tension by adapting it to different planting regions. Exogenous usage of natural and man-made cotton-growing inhibitors like hydrogen peroxide, ascorbic acid, salicylic acid, moringa

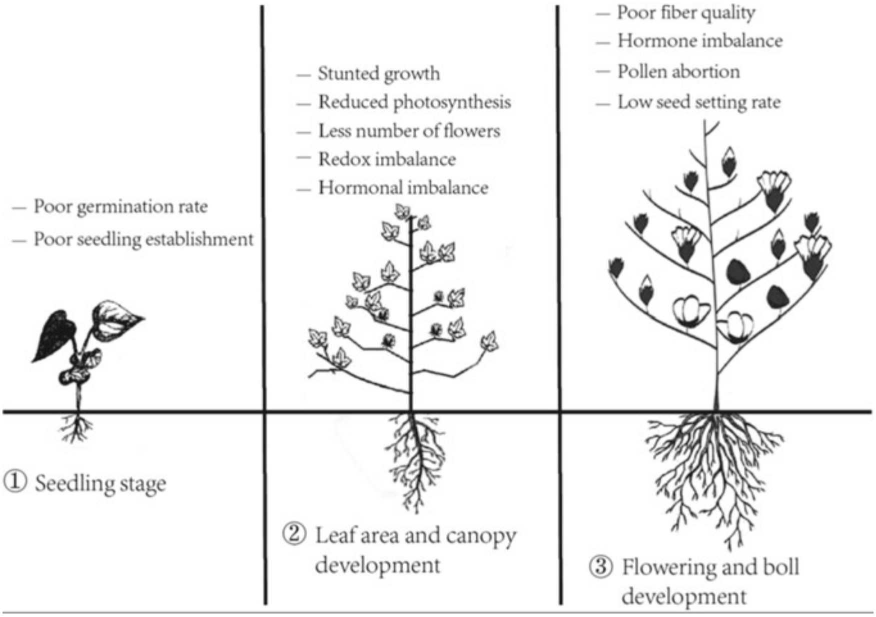

Fig. 3.4 Effect of high temperature on agronomic and physiological attributes of cotton at various developmental stages [45]

leaf extract dramatically improved cotton output under heat exposure by potentiating the cell walls and increasing antioxidant resistance. Similarly, exogenous usage of benzoic acid improves the cotton quality subjected to heat stress by improving the development percentage and nutrient absorption. Identification, as well as the use of cotton genes, affect temperature extremes [45].

3.9.2 Cotton Plant Responses to Salinity

The presences of saline in surface moisture have the impact of salt content on osmotic or moisture-deficit to reduce the plant's capacity to suck up water, resulting in declines in extent of development. The osmotic stress diminishes root growth, leaf growth, stomatal conductance, and photosynthesis. Extreme quantities of the saline entrance to the plants in the photosynthesis watercourse have the salt-specific consequence of salinity, or the ion-excess consequence of salinity will result in injury to cells in the transpiring leaves and cause further reductions in growth. The salt regime of the soil has a significant influence on the production of cotton fiber with high technological quality because the excessive content of readily soluble salts in soils leads to a decrease in the yield of cotton [46].

Saltwater irrigation throughout months of the season dramatically reduced plant height, amount of flowering limbs for each tree, amount of open boll per tree, boll amount, seed index, and production of the cotton crop for each cotton tree. Saltwater irrigation resulted in a decline in the number of open bolls per field, boll weight, seed level, fiber percentage, and cotton crop output per field. Saltwater irrigation throughout months of the season dramatically reduced development, output, and cotton tree ingredients and anatomy conditions. Applying nutrients like potassium humate, algae extracts and polyethylene glycol 6000, to cotton in standard and salty circumstances dramatically boost development, output, and its cotton tree ingredients and anatomy conditions, and have had constructive consequences on enhancing cotton tree output and growing cotton output, particularly under salt content [20].

3.10 Cotton Harvesting

3.10.1 Manual Picking

Cotton harvesting is a boring and extremely laborious activity [9]. Besides, defoliation is required before mechanical harvesting; however, defoliants in the marketplaces are seldom affordable. The cottonseed takes 1,560 operators per hectare to hand-pick, and an adult person will collect 15–20 kg of cotton seed each day. Cotton-picking machines used in advanced countries are technologically developed, however at the same time, they are expensive and convenient only for large-scale landholdings. When the predominant cotton types have staggered the harvesting, mechanical cotton harvesters are still not effective. In the scenario of cotton harvesting by the hand cotton picker, average pulse rate, oxygen intake, workload, and energy usage are higher. In the right wrist hand, right elbow, upper and lower neck, left shoulder, and lower legs, and both feet are the major discomforts encountered by the subjects when harvesting cotton by hand cotton picker [47].

3.10.2 Machine Picking

Machines like Knapsack power-driven cotton picker and Battery Powered Portable Cotton Picker [47] are used to replace manual picking. They have been developed by taking into account agronomic criteria, technical specifications, technological specifications, and ergonomics. In the scenario of cotton picking by knapsack cotton picker and manual process, the mean picking efficiency gains for all the types under research are identified as 95.71 and 96.41%, respectively [9].

3.11 Conclusion

Cotton cultivation technologies like pulse electric field pre-sowing grain medication, precision agriculture, cotton yield monitors such as basket type cotton stripper, and automatic cotton harvesting machine improve germination efficiency by 12%, and crop potential by 15%. Intensive farming technologies and development, as well as light and simplified cultivation, have significant roles in the growth of lint cotton. When using irrigation water during cotton cultivation, water savings and crop yields are enhanced by 20–50% and 10–30%, respectively. Extremely high temperatures and meager plant density have a negative influence on the cotton output. Optimum plant density in the range of 4.5–6 plants per meter square and optimum temperature in the range of 20–30 °C have a positive effect on cotton cultivation and assure stable cotton plant growth. Pesticides, insecticides, and herbicides usage might have prevented 21–61% of output loss. Manual cotton harvesting takes 1560 labor per hectare, whereas machine picking can have enhanced picking efficiency by minimizing laborious activities.

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Chapter 4
The Harvesting and Ginning of Cotton

Mehran Dadgar

Abstract Cotton is going under extensive harvesting conditions all over the countries. Many factors such as variety, geographical climate parameters, traditional points, harvesting and storage experiences, moisture and trash content, and ginning technology are causative on fiber quality. The harvesting and storage time, harvesting methods and instruments, physical storage conditions, and tools are essential factors. One significant factor that affected the final quality of fibers is moisture content at the time of containerization. Fibers include seed cotton is being stocked and wait for the ginning and spinning process. The influencing the quality of the cotton lint and seed concerning varying yellowness, densities, trashes, and storage times should be investigated.

Keywords Cotton · Harvesting · Storage · Fiber · Lint · Free fatty acid · Germination

4.1 Introduction

Matured cotton fibers are the unique fiber has the highest matching with the human body. Different factors affect able on the quality of collected fibers after harvesting the same as geographical condition and effect on weather conditions, cultural experiences and practices, harvesting strategy, storage technics, relative humidity, moisture content, and trash values. Seed types and originality is the initial causative factor taking better fiber quality. Varieties with high or low numbers of plant hairs on the plant parts usually need additional or less cleaning equipment. The main factor that shows harvesting quality is the amount of trash entangled with the cotton. It depends on the picking method (handpicked to mechanize) and the distance of harvesting and spinning. Sometimes maybe at same whether possible to find differences at length,

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uniformity, micronaire, fiber strength, percent of short fiber, neaps, seed skin particles, While the weather is an essential factor in the strength and fiber color. Usually, weak fibers damage at lint-seed separation or lint cleaning or ginning [1].

4.2 Graphical Cotton Elements Dictionary

It is necessary to know the elements of a cotton plant by some clear pictures include different elements of the cotton plant (Table 4.1).

4.3 Harvesting

There are many differences around the world about the experiences of production, harvesting, and ginning cotton. The experiences are from hand harvesting to full mechanize. Static data report that cotton bale product in the world is about hundred million bales, which 35% harvested by hand; frothy countries harvest more by machine than by hand and the United States, Australia, and Israel harvest 100% by machine.

The harvesting method depends on the cultivation method. Usually, the density of the cotton plant is 62,500 per 10,000 m^2, the distance between every row should be 70–80 cm, and the plant distance should be about 20 cm. Harvesting of cotton crops can be executed manually or by harvesting machines. In high-density or high-growth fields, the crop is first harvested when about 20% of the bolls are open, which results in better ventilation of the farm and preventing decay lower boll.

One of the most expensive sections of cotton production is the manual harvesting of cotton. Approximately 30–40% of the price of cotton production is the monetary value of harvesting it. Thus, by reducing this price, it is possible to produce economically and cultivate this product.

The answers of previous years showed that, compared to the two types of manual and mechanical harvesting, a two-row combine harvester of 5 tons/day and harvest 5.3 loads/day were able to collect 5.17 tons of cotton per day. To pick up the same quantity of cotton, assuming 30 kg per day, 583 workers needed per day.

The price difference is significant in hand and machine harvesting, and it further illustrated the necessity of using the harvesting machine. Machine-harvested is more beneficial than hand-harvesting [3].

Research has indicated that although the number of plants per hectare decreases with increasing row spacing, the number of balls per hectare does not vary and does not decrease yield due to better plant separating. Since the leaves had to plant for machine harvesting so that the harvested ones had the more dependable quality, minimum external materials, and fine leaf, "pesticides" were used to get rid of the leaves from the plant before harvesting. Chemical Pesticides used when 60–70% of bolls are open. Some chemical materials help the leaves to fall and to cause sooner mature bolls. It is recommended that we deliver the cotton products to the cotton-ginning factory as quickly as possible after each harvest.

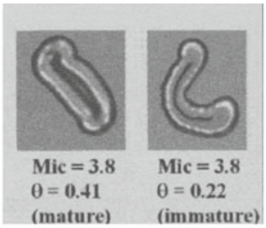
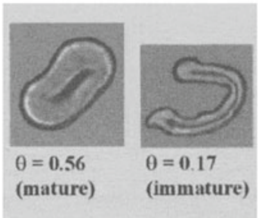
1. To prevent loss of quality,
2. Avoid harvesting premature and decayed bolls
3. Delay harvesting until moisture (dew or rain) is dry.

Table 4.1 Pictures of different elements of a cotton plant

Word/Name	Picture
Cotton plant	
Cotton in the flowering stage	
Boll, pod (closed boll)	
Boll (opened boll)	

(continued)

Table 4.1 (continued)

Word/Name	Picture
Plant include of open boll and close boll	
Cotton fiber (matured and immature)	 
Organic linted seed	

(continued)

Table 4.1 (continued)

Word/Name	Picture
Delinted seed	
Cotton seed de-oiled cake	 [2]
Pick a bale of cotton	
Cotton yarn	

4.4 Time for Harvesting

Harvesting may be executed in one until three stages, depending on the percentage of mature cotton fiber. The most suitable time for harvesting is the time that most of the boll opened. This state should not waste time because of seasonal rain. Although the harvesting time is different from the type of cotton seeds while there is a reasonable

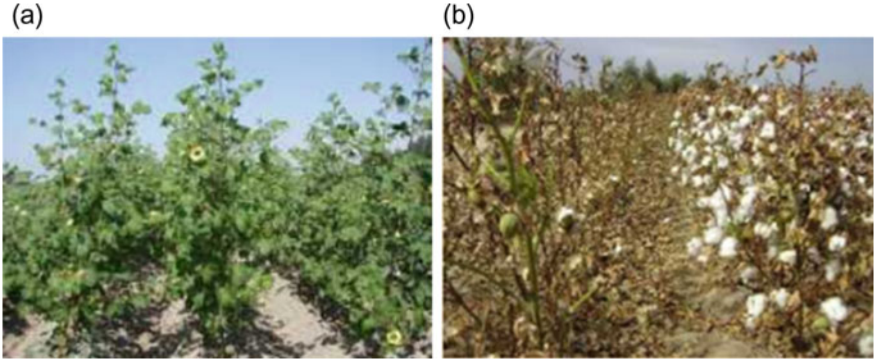


Fig. 4.1 Rows of the **a** cotton plant with flowers **b** plant with cotton bolls in an agricultural site in Iran

time for all kinds of cotton. Exact times for harvesting depend on the conditional region's topology, cotton type, cultivating dates, Farm agriculture management, and product selling condition [3]. Usually, if the cotton is sown in the second half of May, the crop can be harvested from 15th November to 15th December [4].

Manual harvesting of cotton usually takes more than one time. The first crop is generally late September to early November. It is urged that the first crop harvested when 60–70% of the boll are open. Usually, harvesting ends in the beginning decade of December because, with the arrival of autumn cold, the remaining bolls will not have the chance to spread. Figure 4.1 displays rows of the cotton plant with flowers and plants with cotton bolls in an agricultural site in Iran.

In the below table, some type of Iranian cotton and their specifications have been remarked as an example. Time of harvesting related to the time of cultivating, so the time of growing mentioned in column 7 in Table 4.2.

4.5 Harvesting Machines and Attachments

These days, two main classes of machinery are using in the cotton harvesting industry, cotton pickers Fig. 4.2, and cotton strippers Fig. 4.3. While cotton strippers maybe include or exclude field cleaners. Every one of those packages the seed cotton and collects fibers modules. Modules may be produced on board by adding module builders to the machine or maybe creating in the next step in case the machine does not have this structure. So, all types of modules builder are [7]:

1. General and traditional seed cotton modules
2. Half-modules
3. Circular modules

There is some excellent condition for harvesting by machines. In harvesting by picker and stripper model, it is suitable if plant height should be less than 1.21 m and

Table 4.2 Some types of Iranian cotton and specifications [5, 6]

Case	Date of cultivating	Micronaire microgram/inch	Fiber length (mm)	Boll weight (gr)	Plant high (cm)	Time to grow up (day)
Sahel	Mid-April to the end of May	3.9	29.5–30.5	6.9	120–145	1507–165
Sepid	Mid-April to the end of May	4.02	29–31	5.6	120–140	135–150
Golestan	Early April to late June Second cultivation	4.1	29–31	5.14	85–95	135–130
Armaghan	Early April to late June Second cultivation	4.3	28.9	5.16	85–110	135–125

Fig. 4.2 Typical spindle-type cotton harvester [8]

about 0.6–0.91 m, respectively. Otherwise, the foreign matter will be harvested by machine [8]. The characteristic of the spindle picker machine is pickup open bolls and does not damage the closed bolls, and finally, it is possible picking in various times. The cotton picker can harvest rows with a spacing of 96 cm. Hence it is necessary to cultivate with a spacing of 96 cm [3].

In some cases, soil type, low moisture, and high wind are parameters that force to use the stripper type. Regions the same as Texas, Oklahoma, Missouri, and Kansas in the United States include this limitation and prefer to use stripper type. Spindle and stripper types contain about 6% and 30% of plant parts, respectively, although some

Fig. 4.3 Typical striper harvester for cotton [8]

strippers equipped with field cleaner that helps to remove 60–70% of the foreign matter [8].

The harvesting components of a spindle picker are presented in Fig. 4.4. Row spacing for spindle pickers should be about 38.1–106.7 cm. This machine can work at 95% efficiency, but generally operated at 85–90% and can pick one bale per hour by one picker and can increase to 12 bales by six-row spindles. The spindle pickers are included main parts that need to maintain that named "spindles, moistener pads, doffers, bearings, bushings, and cam track." Moisture is necessary for spindles to keep them uninfected and to enhance the attachment of the character to the mandrel. The best time for harvesting by picker is while relative humidity is below 60%, and morning is more suitable to the afternoon because of nearest to advised humidity. For spindles, cleaning pure water is enough, while wetting agents or a soluble oil may also be added to the water. These additives are usually helpful when harvesting rank cotton has green leaves.

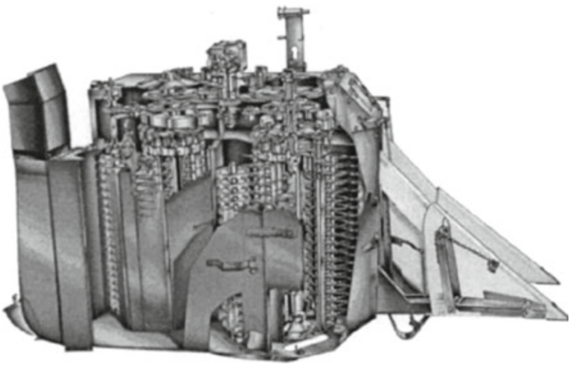


Fig. 4.4 Harvesting components of a spindle picker [8]

(a) (b)

Fig. 4.5 The front-side (**a**) and backside (**b**) view of JD7760 harvester in an agricultural site in Xinjiang, China

Two types of strippers are working in the harvesting industry, finger-type, or roll-type. The finger-type is made of multiple metal fingers that can take the angle about 15°–20° angular with the earth. While roll-type strippers use two stripper rolls with angled 30 to the soil and able to going around in opposite directions with the upward direction next to the works, each cast consists of three brushes and three paddles mounted in alternating succession. The comparative data of stripper and picker harvesters show that two-row strippers can pick one bale per hour with a non-selective method and collect about 99% of bolls. This capacity increase for an eight-row model to 15 bale per hour. On the other side, one-row spindle picker able to pick one bale per hour with a selective method and collect just open bolls. This capacity increase for a six-row model to 12 bale per hour.

In 2008 the John Deere company presented the on board module spindle harvester type 7760. This machine was able to deliver cylindrical modules by on-board section simultaneously. Due to the reduction of necessary labor for harvesting, this machine finds good to sell (Fig. 4.5).

The comparison of numbers of machines used for cotton picking mentioned in 2010 and 2011 was 80 machines of round module machine that included approximately 44% of the 4.2 million harvested bale crop. While this comparison for 2011 and 2012 was 200 machine of round module machines that included approximately 75% of the 4.4 million harvested bale crop. It shows the increase of using harvesting machines at one year and confirmed that the most significant percentage of crop harvested by machines while consuming expensive plastic wrapping is the lack of these machines [9].

JD 7760 is a more industrial machine than "non-module building" with powerful doffers and different airflow dynamics that delivering a higher volume of air across the machine heads. This possibility helps the JD 7760 to harvest cotton with higher moisture content. Consequently, it can start earlier in the morning and harvest longer into the night when moisture levels (dew) is higher. Dynamics airflow may increase concerns about the shortening of the fibers and the generation of entanglements (neaps). The typical recommendation is, “surface moisture should not exceed 12% “during harvesting, and humidity can be measured by a handheld moisture meter. Cotton with a high degree of moist can be prone to fiber degradation, elevating the temperature, more fiber degradation, and finally, module fire. Besides these, quality and reflectance will be affected by different levels of moisture. In particular, soil compaction, more significant color variability, trash content in JD 7760 is the other concerns that justifiable because of the different level of blending in different picking systems [9].

In the 1970s, A&M University of Texas invented the module builder and harvesting technology, and also initial stock changed [7]. Recently all cotton harvested by machine and stored at modules automatically. The figure of the blade can show as the packed brick of cotton fibers and seeds. The United States accepted the below dimensions as standard dimensions for the module is Length (m)/Width (m)/Height (m)/9.75/2.44/2.44.

Typically, 192 kg/m^3 packed at a standard size that could be about 12 or 15 cotton bales of stripper-harvested or picker-harvested, respectively. Usually, modules create and fall on the ground and generally covered with tarps to protect from rain and other condition damage. Then trucks pull up the modules by rolling chain floors [7]. Cotton strippers work by stripping seed cotton and lots of burrs, sticks, and remaining leaves from the stalk of the cotton plant. Cotton strippers may have a separating unit called a field cleaner that takes out many of the burrs and sticks from the seed cotton. Seed cotton stripped out by strippers include much trash (burrs, sticks, and leaves), so maybe this type outfit with the filed cleaner unit to help better and cleaner outputs. Figure 4.6a shows one type of stripper.

Cotton pickers use spindles with barbs to take hold of the seed cotton out of the bowl as they spin. Figure 4.6b shows a cotton picker. Finally, after harvesting, there will be a seed, lint, and some amount of trash that packaged and ready for ginning. Accumulated seed cotton dumped into the module builder box. The best level of trash content collected by the stripper with the field cleaner and without the field cleaner, respectively [7]. Cotton strippers with or without field cleaners have

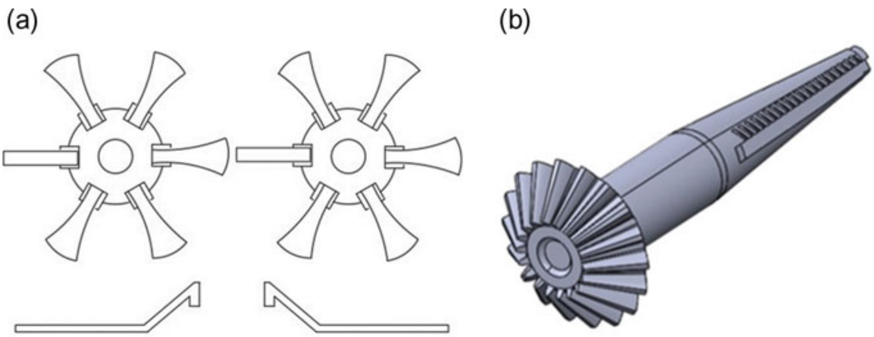


Fig. 4.6 **a** Modified stripper roll configuration with one bat and five brushes per stripper roll timed brush to bat and **b** cotton picker spindle [10]

an enlarged role in the USA harvesting industry. Recently, two significant producers of harvesting equipment, John Deere (producing cotton strippers in the USA) and Case-New Holland (CNH), developed the models with the capability of packaging modules of seed cotton on board exactly after of cotton picking. Comparison of the main parameters of "John Deere", "Case-New Holland (CNH)" and "conventional module builders" machines have been detected as follows.

- John Deere manufactured in the USA, Case-New Holland (CNH) manufactured in Holland and "conventional module builders" manufactured in all countries.
- "John Deere" and "Case-New Holland (CNH)" both have On-board module builder.
- "John Deere" produces cylinders shape of the module while "Case-New Holland (CNH)" and "conventional module builders" produce a rectangle shape of the module.
- Package diameter of "John Deere", "Case-New Holland (CNH)" and "conventional module builders" is "up to 2.44 m (8 foot)", "4.88 × 2.44 m (16 × 8 ft)", 2 * (4.88 × 2.44)" respectively.
- Package length of "John Deere", "Case-New Holland (CNH)", and "conventional module builders" is "2.44 m (8 foot)", "42.44 m (8 ft)", 2 * (2.44 m)" respectively.
- Package density of "John Deere", "Case-New Holland (CNH)" and "conventional module builders" is "240 kg/m^3 (15 lb/ft^3)", "144 kg/m^3 (9 lb/ft^3)", 144 kg/m^3 (9 lb/ft^3)" respectively.

Typically on board packaging modules has a smaller size than a traditional module. Although the on board models are expensive, it economizes because they do not need extra labor and boll buggies for seed cotton handling using conventional module builders.

According to Wilkes, if seed moisture content levels remain below 10% of wet-basis (w.b.), the compressing seed cotton to densities between 112 and 320 kg/m^3 (7 to 20 lb/ft^3) did not affect fiber quality [10]. Of course, the on-board module builder allows for achieving higher per-capita productivity than a traditional harvester. This reason creates market interest in cotton strippers containing on-board module builders [7]. Curley's research [11] showed there was 19% trash (picked by a cotton stripper with a field cleaner) and was 38% trash (picked stripper without a field cleaner) for three samples (32, 136, 354) kg and finally advise using the filed cleaners.

4.6 Fiber Quality

The area of mechanized harvesting increased by 10% per year in 2008 and 65% in 2014 [12]. If the comparison is made between hand and machine harvesting, the mechanized will be two grades lower [13]. Because of this effect, 60% of companies unwillingness to buy or use the machine in Xinjiang [14]. Mechanized harvesting has an economic point and an uneconomic point. The economic point is speed harvesting, and the uneconomic point is adding trash to the fibers. It is inevitable to use mechanized harvesting because of the high price of seasonal labor work [12]. In continuation, cleaning is a necessary stage. The first lint-cleaning step is in the harvesting process when 85% of bolls have picked [15]. While hand-harvesting has 10–30% lower foreign matter than auto-harvested [16–18], some studies confirmed that lint cleaning reduces the trash and improve HVI (high volume instrument) [19, 20], while some other studies confirm that cleaners decreased fiber length and increase fiber strength [20–24] and increased short fiber index [20, 21, 23–25]. Damaging for mature cotton is less than immature cotton during the lint cleaning process [23, 26]. Generally, adding lint cleaners improve HVI. Color and also leaf grade [19]; however, it decreased net returns [27, 28] and has reverse affected on fiber quality [19, 25]. Other researchers [20, 21, 24] published that fiber damage and reducing fiber length and increase short fiber index and nep number is the denouement of the lint cleaning process [21–23, 29]. Besides these, Tian et al. [12] compare the first and second lint cleaning process and understand that happen fiber length demolition, and short fiber index was 4.7 and 5.7 fold greater respectively. Some long fiber is lost during lint cleaning at all steps, and at least two-thirds of the fibers lose to the trash [30]. The findings of previous researches support a recommendation for using one stage of lint cleaning to maximum net return [19, 27, 28], especially when foreign matter content or seeds is shallow [26]. Typically, it is possible to omit a stage of lint cleaning [12, 31].

William et al. [32] mentioned that cotton strippers are "non-selective harvesting mechanisms" that pick both mature and immature bolls from the plants, and frequently, there is unwanted vegetative material. So the comparative results of both picker and stripper system mentioned in some note [26, 32–34]:

- Picker has a higher length than the stripper system.
- Picker is more suitable for ring spinning system.
- Picker is suitable for end-user yarn with high-count yarns and high-value products
- Picker harvest mature and open boll while stripper mature and immature boll and finally include higher lint at harvesting.
- Picker and stripper harvesters' efficiencies are 85–9% and 95–9%, respectively.
- Foreign matter, neps, short fiber content, and yellowness increase by stripper method.
- Foreign matter for picker and stripper is 5–10% and 5–15%, respectively.
- Fiber micronaire, length uniformity, and reflectance reduce by stripper method.
- Nep content for picker and stripper is 190 cnt/g and 220 cnt/g, respectively.

Of course, the relative effects of fiber in the table may be different in different years regard to the rate of the mature boll. Moreover, usually, the improvement of technology causes the increase in the results of fiber quality, year by year, that it could see since 2000. The average of UHML was 25.7 mm in 2000 and was 28.6 mm in 2017, whereas strength changed from 27 g/tex in 2000 to 29.5 g/tex in 2017 [11].

At different stripper harvesting, efficient picking requires that bolls well opened with the seed cotton held loosely in the bur (carpel). Picker spindles cannot well remove seed cotton from immature bolls that are not well open or those in which the seed cotton held firmly.

William et al. [32] and several previous researchers have pointed out that the micronaire of picker type is usually upper than of the stripper model because that pickers harvest less immature fibers. Regard to William et all [32] results, the improvements observed in fiber quality and harvest have brought about by a combination of several genetic and production-related developments, including the following:

1. The adoption of new cultivars with higher yield and fiber quality potential;
2. Improved irrigation practices with higher water use efficiency;
3. Boll weevil eradication;
4. Bacillus thuringiensis (Bt) technology to reduce pressure from lepidopteron pests;
5. Herbicide-tolerant genetics and herbicide methods that reduce weed competition and contamination.

4.7 Harvesting Differences

The at least important reason for researching the effect of the harvesting method on quality is in the storage process. Research results can help the store managers to classify the cotton bales according to their specialty, mill necessary, specific usage, and more consistent to end products [9]. Moreover, it is essential to field managers to know which technology is more suitable for harvesting regard to their local and regional (respect to end-user) to employ that technology, and it may help them economically. In this field, Marinus [8] had research to checked the qualities and results depicted as follows [9].

1. The round module had a cylindrical package, and conventional basket harvesting methods had a rectangle package.
2. Fiber quality of round module had lower micronaire
3. CV % (between bales) of the round module was greater
4. There was no significant difference in HVI—upper half-mean length between both Round module and conventional basket harvesting methods.
5. HVI—Micronaire was significantly lesser for the Round module.
6. HVI—Reflectance was significantly higher for the Round module.
7. Trash was lower for the Round module.

HVI. Micronaire for the round module was slightly yet significantly lesser. It could be attributed to harvesting the more fiber, including immature fiber from the top of plants and less trash, precisely, for this reason, HVI. The reflectance for the round module was higher. The CV percentage of fiber quality between bales was significant for the round module system. This attributed to less blending during the sequential ginning of modules in contrast to conventional basket harvesting methods.

Sui et al. [35] compared the three methods of "machine-harvested cotton" include and exclude "pre-cleaned and hand ginned" and "hand-harvesting". Results show that micronaire fiber quality of machine-harvested cotton that includes pre-cleaned and hand ginned is lower than machine-harvested cotton without pre-cleaned and hand ginned and also hand harvesting and imply that micronaire reduced because picking more immature fiber from flower and differences in trash size comparative to hand harvesting.

Comparison HVI length and strength between "old machine spindle harvesting" and "separate module producing method" and "old machine spindle harvesting and module" and "on board round module" showed there was no significant difference [9].

4.8 The Moisture of Seed Cotton

Hamann [7] evaluated the levels of moisture content and storage time for the samples (including both the fiber and the seed) up to three months from three different cotton-picking methods. Possible storage time of Seed cotton at levels of moisture contents so do not losses quality for four levels of moisture contents include "less than 12% w.b., up to 14% w.b., 15% w.b., above 15% w.b." was "Minimum thirty days, No more than ten days, No more than ten days, Less than three days" respectively [36].

Samples sealed in plastic containers to have fixed conditions. The test designed by varying levels of density, trash content, and moisture as the input test parameters. Hamann monitoring temperature and oxygen levels during storage time and finally ginning done and fiber quality analyzed. Results confirmed that density is independent of a variety of lint and seeds. Also, the adverse effect of the higher level of moisture content obviously on both the quality and the value of the seed cotton and more marked by increasing the storage time. In fresh products, moisture contents are higher for harvested seed cotton burrs, sticks, and leaves than seed cotton [36]. According to Adams and Karon [37] reports, humidity absorbance for cottonseed in 30 days contiguity of the relative humidity of 93% will increase to 20%. This shows the power absorbance of cotton and, consequently, the power of moisture to decay the cotton modules. Besides this vital effect of humidity, the results of Montgomery and Wooten [38] reported moisture contents could flow from 5 to 16% (at afternoon to morning) and trigger microbial action. Sorenson and Wilkes [36] measured the maximum temperature during 30 days while densities fluctuated from 160 to 224 kg/m^3, and moisture content ranges were 8–24.5% w.b., and achieve maximum temperatures of these large samples observed up to 69 °C.

Curley [39] suggests monitoring the moisture and temperature of modules to be aware of microbial activities in a way that if microbial activities are goings-on, then the temperature would increase. Moisture content will increase from 9% at harvesting time to 16% after five days storage, and temperature will increase to 30 °C, and simultaneously growing temperature, yellowness (+b) increasing will be observed [40]. Wilkes [10] reported that sensitively of cottonseed quality was more than cotton fiber quality when subject to high moisture content. Besides, Wilkes mentioned decreasing the germination ability, and free fatty acid content is two main signs of decay seed quality while moisture increases. Germination and free fatty acid decreased and increased respectively, beginning around 12% w.b. of moisture content. Degradation of "cottonseed oil" cause produces a free fatty acid. Increased moisture content creates energy by breaking down triglycerides to free fatty acid [7]. When moisture contents seed cotton elevated 7.5–13.2%, and storage time ranged from 1 to 82 days, free fatty acid will be increased while at 15 days in 13 till 15% w.b. of moisture. The free fatty acid compare to initial levels will be 50 and 130%, and in this range, germination does not have specific change whereas vice versa at moisture level more than 16%, there is not any germination [36, 40, 41].

Besides these results, Hamann tries to bold the effect of moisture on the cotton elements (seed and lint). The test condition could be accounted for briefly (for two constant item PVC containers and three-month storage time), for picker model trash content and density was about 10% w.b., 128 $kg/m^{3,}$ respectively. While the corresponding data for a stripper with field cleaner was 12% w.b. and 192 kg/m^3, and for stripper without field cleaner was 14% w.b. and 256 kg/m^3. In continuation, Hamann adds trash manually to create suitable trash percent for every type of picker, and results show that trash content is causative factors of yellowness, micronaire, and fiber length of cotton lint, while reflectance is the single causative factor of density. Moreover, the free fatty acid of cottonseed affected by moisture [7].

4.9 Why Is Storage Essential?

Regard to Hamann [7] research from 1960 until 2005, the number of gins factories decreased while the range of bales producers is constant or some extent increased. The reason for reducing the gin manufacturer comes from some point of views:

1. The ginning business is one season occupation, and it is difficult to pay to labor to guarantee labor services.
2. The machinery and technology improved, and productivity increased. So if you assume the production line with constant input, it will be finished sooner in comparison to the previous state.
3. This is a seasonal production, and both of these reasons exacerbate the shortening of the life of these factories.

Therefore, the methods of storing fibers should be revised more powerfully and developed simultaneously.

4.10 Conclusion

Harvesting is one of the basic and unavoidable operations in the process of producing cotton fibers. So far, large and limited companies have been active in this field, and picking machines are based on two common methods of picking boll or picking fibers, each of which has its advantages and disadvantages, which were discussed in detail in this chapter. Factors such as seed quality, relative humidity, fiber maturity, and picking method and time are the most effective factors in the quality of cotton harvesting and storage.

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Chapter 5
Physical Structure, Properties and Quality of Cotton

Hua Wang, Muhammad Qasim Siddiqui, and Hafeezullah Memon

Abstract Cotton is the most important and widespread natural textile fiber in the world. Across 75 countries, the production of cotton crops provides income for more than 250 million people. Approximately half of all textile products are made of cotton in the form of apparel, home textiles, and industrial products. As all agriculture crops, cotton is also dependent on the climate conditions, soil quality, and water in which it is cultivated. All of these factors contribute to the diversity of cotton fiber properties. This chapter covers a wide range of essential segments related to cotton production, its structure, and different quality parameters. Best management practices result in better yield and quality of cotton fiber. This chapter also covers the important aspects of BMPs for cotton fiber cultivation. BCI, the better cotton initiative, is also one of the initiatives to make better sustainable cotton production. To enhance biodiversity and to maintain biological cycles, organic cotton can play an important role. This category of the cotton crop is produced with non-genetically modified plants, and by avoiding the use of any fertilizers or pesticides during its production. Keeping in mind its pivotal role, this chapter has also included the latest advancements in organic cotton.

Keywords Fiber testing · Quality parameters · Organic cotton · Best management practices · Better cotton initiative

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5.1 Importance of Cotton Crop

Today, the world is using more cotton fiber than any other natural textile fibers, especially in apparel and home textiles. Despite the fact of being expensive, cotton remains preferred in many minds due to its natural and comfort properties. The word "cotton" brings pleasant memories of soft sheets and comfortable garments into our minds. The word "cotton" has derived from the old Arabic word "Al Qatn" [1]. Cotton products are part of our daily lives from the time; for instance, soft cotton towels are used to dry our faces every morning and until cotton bed sheets are used at night. Hundreds of commodities are made of cotton fiber, ranging from apparels to knitted shoe strings. Clothing and household textile products have been the most significant uses, along with many industrial products such as medial textile.

Cotton has had played an essential role in shaping world human cultures from the earliest historical times. To know how old the cotton is, scientists have searched caves in Mexico and found 5000 years old pieces of cotton cloth [2]. In Pakistan near Indus River Valley, proves of cotton production and cotton cloths were found, dating back to 3,000 years BC [3]. Egyptian pharaohs had also used cotton fiber near Egypt's Nile valley showed proof of making and wearing cotton clothing. Cotton plays a significant role in world trade and to the economies of many developing countries. For many countries, a substantial proportion of GDP and tax income directly or indirectly depends on cotton exports, and it contributes to foreign exchange earnings. Furthermore, cotton crop and their products have a significant role in the economic development of many Asian and African countries, including China, Pakistan, India, and Bangladesh. After the seed cotton fiber leaves the cotton field, its transportation, processing, and handling produce even more jobs and business activities to thousands of families.

Every single part of the cotton plant has its value; cotton fiber lint is an essential segment. It is used to produce cotton yarn and further cotton fabrics. Linter, the short fuzz on cottonseed are used to provide cellulose for many products, like plastics and papers. Finally, the remaining cotton seed has to be crushed and separated into three items that are oil, meal, and hulls. These sub-products are used as livestock feed, which makes cotton crop overall a cash crop.

5.2 World Cotton Production

Asia is the most prominent and fastest-growing region of the world for total fiber production and cotton consumption. Since 2000, global demand for fibers has grown consistently at over 3% per year reaching near 430 million bales. The growth in final consumer demand has been driven by manmade fibers at an average growth of 4.6%, with more than 300 million bales per year [4]. While world cotton production is expected to be decline by 2.4 million bales to 118.9 million bales in the year 2020

Table 5.1 World cotton production in 1000 Bales [6]

Production	2015/16	2016/17	2017/18	2018/19	2019/20
India	25,900	27,000	29,000	25,800	29,500
China	22,000	22,750	27,500	27,750	27,250
United States	12,888	17,170	20,923	18,367	19,800
Brazil	5,920	7,020	9,220	13,000	13,000
Pakistan	7,000	7,700	8,200	7,600	6,600
Uzbekistan	3,800	3,725	3,860	3,275	3,500
Turkey	2,650	3,200	4,000	3,700	3,400
Other	16,005	18,112	21,076	19,117	18,542
Total	96,163	106,677	123,779	118,609	121,592

[5]. The world cotton production for top cotton-producing countries over the last five years are presented in Table 5.1.

As per data provided by USDA for the year 2019/20 world, cotton production is expected 2.3% higher from the previous year to 121.5 million bales [6]. This increase is mainly from the United States and India, while an overall lower output is expected in Australia and Pakistan. The Delta and southeast regions of the United States saw a near 10% increase with even more harvested are in the last thirteen years [6].

With 29.5 million bales, India is the world's largest cotton producer with the highest production during the previous five years. With a 14% increase from last year, India has surpassed China and became the world's largest cotton producer country [7, 8]. China is the 2nd largest cotton producer, with 27.3 million bales, which is slightly down from last year both for area and production. The unfavorable weather of Xinjiang mostly led to a lower yield of the cotton crops [9].

With an estimated 3.5 million hectares of cotton harvested area in the year 2019/20 in china, which is marginally down as compared to the previous year. The crop yields are also fell below the last two years, at 1720 kg/ha [6]. In the year 2019/20, due to severe drought, Australia's cotton crop saw the lowest production in twelve years [6].

5.3 Physical Structure of Cotton

The cotton plant is mostly grown to get fibers that can be spun into yarn or thread, but its seed is also used for extracting oil. It contains 49 species distributed throughout the most tropical and subtropical regions of the world. Among these 49 species, four are domesticated, two old world diploids *Gossypium arboreum* and *Gossypium herbaceum* and two new world tetraploids *Gossypium hirsutum* and *Gossypium barbadense*. The genus contains a vast diversity ranging from herbaceous perennial to small trees [10]. *G. hirsutum* is native to Mexico and Central America. This species is known as American Upland cotton in the United States and varies in length from 7/8 to 1–5/16 in. *G. arboreum* and *G. herbaceum* are native to India, Pakistan, and Eastern Asia with a short length of about 0.5–1 in. These kinds of cotton are not grown in the United States. Cotton fibers, along with seeds, are called raw cotton. 1/3 of the mass of raw cotton is fiber, 2/3 of the seeds. Cotton seeds contain up to 15% of cottonseed oil, which is used in the food industry.

5.3.1 Pima Cotton

Pima cotton is a *G. barbadense* of South American origin. It is known as Pima cotton in the United States varying in length, usually around 33–36 mm, and micronaire value of below 4. It is commonly referred to as Extra Long Staple cotton. This variety is a complex cross of Egyptian and American upland cotton. This variety of cotton fiber is also considered as the finest and strongest among all cotton fibers on earth. The fabric produced from Pima cotton is luxuriously smooth due to fiber's extra-long staple length. These long fibers make the fabric extra soft, strong, and resistant to wrinkling and pilling.

5.3.2 Egyptian Cotton

Egyptian cotton is also an extra-long staple length cotton as Pima cotton. This fiber is equally excellent in a performance like softness and strength. They have the same properties and even have the same generic name, *G. barbadense*. The difference between the Egyptian and Pima cotton is the conditions in which each cotton is grown at different places.

5.3.3 Upland Cotton

Upland cotton is known by its relatively short staple length 22–35 mm, and the micronaire value is around 3.8–5 μg/in. Its generic name is *G. hirsutum*. This variety is suitable for producing qualities for everyday affordable products. 85% of cotton cultivated is constituent of this common type.

5.3.4 Acala Cotton

This is a unique variety of cotton, only produced in California USA, San Joaquin Valley Acala. Acala cotton is among the best quality of Upland cotton produced around the globe, with the same generic name, i.e., *G. hirsutum*. Due to the ideal climate of San Joaquin Valley, Acala cotton get better properties and a longer growing season. However, this finer cotton with increased yield is a little bit expensive due to irrigation requirements.

5.4 Cotton Fiber Composition

The cotton plant is naturally produced in the form of a medium-size tree or shrub containing cotton bolls as fruits. Mature cotton fiber is a single, elongated complete dried multilayer cell that develops in the surface layer of cottonseed. The cuticle is the outermost layer, and it contains mostly the non-cellulosic components of cotton fiber. After the cuticle, as we move from outside to inside direction, the next is the primary wall. After the primary wall, the secondary wall starts, and finally, most inner hollow tube is called the lumen, as shown in Fig. 5.1.

The primary and secondary walls of cotton fiber have different degrees of crystallinity, as well as different molecular chain orientations. The non-cellulosic constituent is principally located in the cuticle, composed of wax, proteins, and pectin. The general composition of cotton is presented in Table 5.2. This part of cotton fiber is mostly amorphous in nature. 2.5% of the fiber weight is held by the primary wall, and this part has a 30% crystallinity index and is mainly composed of cellulosic material. The secondary wall of cotton fiber contains 91.5% of the total fiber weight; it has a high degree of crystallinity index, i.e., 70%, entirely composed of cellulose chains, refer Fig. 5.2 [11].

90% of the whole cotton fiber is consists of cellulose, and 10% of the fiber is non-cellulosic polysaccharides. In a fully mature cotton fiber, the primary wall is

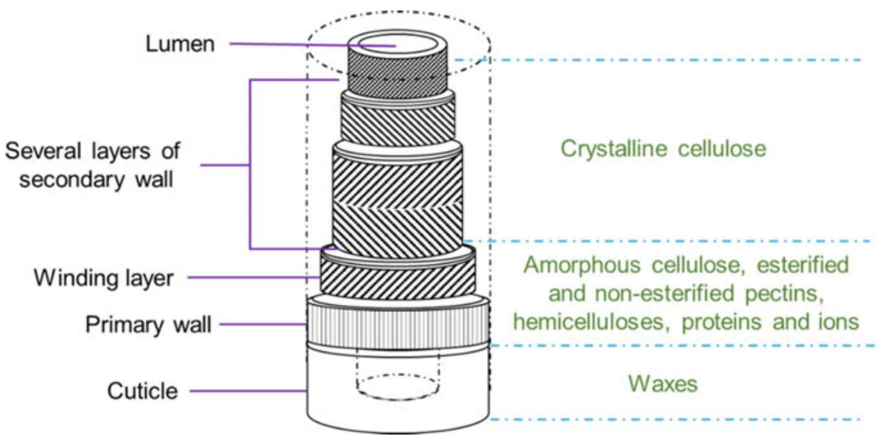


Fig. 5.1 A schematic representation of cotton fiber and its composition (image drawn by Dr. Hafeezullah Memon)

Table 5.2 The general composition of cotton fiber

Constituent	Composition (% Dry weight)	
	Typical %	Range %
Cellulose	95	88–96
Protein	1.3	1.1–1.9
Pectic substances	0.9	0.7–1.2
Ash	1.2	0.7–1.6
Wax	0.6	0.4–1.0
Total Sugar	0.3	0.1–1.0
Organic Acids	0.8	0.5–1.0
Pigments	Traces	
Others	1.5	

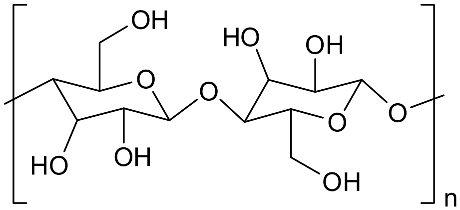


Fig. 5.2 Chemical structure of cellulose (image drawn by Dr. Hafeezullah Memon)

only 0.5–1 μm thick and consists of about 50% of cellulose. In the simple chemical composition of cellulose, linear polymeric chains are consist of Anhydro-glucose units joined by β-1,4-glucosidic bonds. The chain length, or degree of polymerization, of a cotton cellulose molecule, maybe as high as 14,000 units of Anhydro glucose connected to form the chain molecule. In Fig. 5.2, a pure polymer has been presented. The crystalline regions of cotton are nearly having a degree of polymerization of 200–300. Furthermore, the molecular weight of cotton is usually in the range of 50,000–1,500,000, depending on the origin of the cellulose [12]. Hydrogen bonding and Van der Waals forces linked the individual polymers of cotton fiber.

5.5 Cotton Fiber Development

On the surface of a fertilized cottonseed, small cotton fibers are formed from a single epidermal cell, also called lint. The initiation of the lint begins after anthesis; the initiation of cotton seed from a day before to a day after initiation is shown in Fig. 5.3. whereas the initiation of fuzz hair begins 5 or 6 days following anthesis and continues up to 10 or 11 days [13].

As the seed develops, the seed hair elongates to form a circular cylinder, which is tapered at the end, refer, Fig. 5.4. Cell elongation and subsequent cell wall thickening are two phases of cell growth. Both phases are affected by environmental conditions,

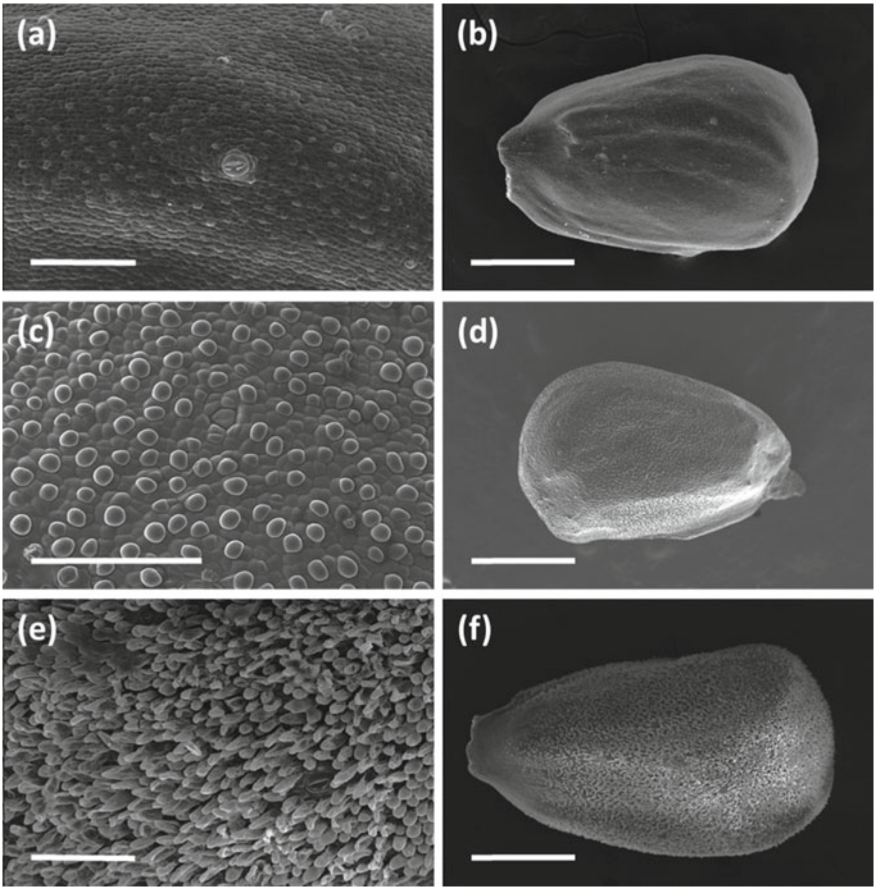


Fig. 5.3 Scanning electron micrographs of cottonseed with the initiation: one day before initiation are presented in **a** and **b**; on the day of initiation are presented in **c** and **d**; one day after initiation is presented in **e** and **f**. Scale bar represents 100 μm for **a**, **c** and **e** and 500 μm for **b**, **d** and **f** (images taken by Dr. Hafeezullah Memon)

such as temperature and solar radiation [14]. The fiber is a hollow tube, due to which cotton fiber has poor thermal conductivity, curled around its axis seven to ten times per one millimeter. As the fiber ripens, cellulose deposits increase, resulting in increased fiber strength. 95% of the chemical composition consists of cellulose; the remaining 5% is fat and mineral impurities. Depending on the growth condition and the variety, the lint hair elongates up to 20 days or more after flowering during germination and emergence and early seedling growth [15]. Early maturing cultivars produce high lint yield at lower main stem nodes [16]. Fiber diameter increases rapidly after anthesis and remains about constant until the boll opening. The thickening of the fiber wall begins right after the fiber length stops to elongate. The deposition of the cellulose begins into the thin outer wall of the cell, known as the primary cell wall,

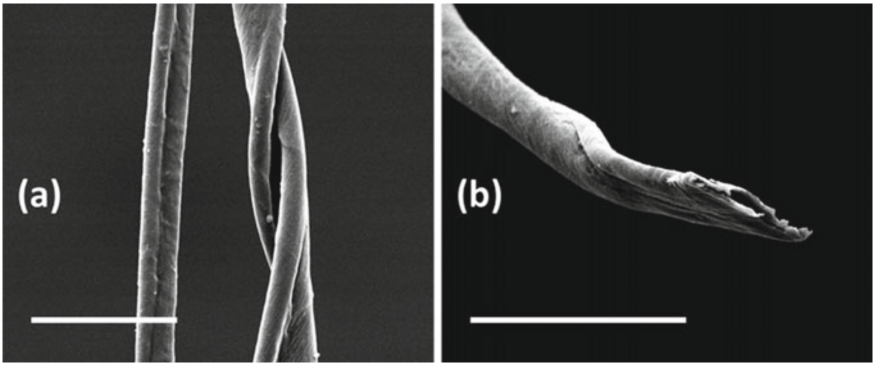


Fig. 5.4 Scanning electron micrographs of mature cotton fibers **a** Characteristic convolution on fibers and **b** broken edge retaining convolution. Scale bar represents 50 μm (images are captured by Dr. Hafeezullah Memon, at Donghua University)

and continues in the secondary cell wall. The formation of the secondary wall takes up to 25–40 days. Cellulose fills the entire cell leaving an open space in the center of the fiber known as lumen.

When the fiber reached its full thickness, then the boll opens, and the fiber starts to dry, causing the fibers to twist and crimp, refer Fig. 5.4a. Due to the contortion between the daily layers of cellulose, fiber gets its characteristic crimps. When these layers get dry, the shrinkage occurs in different directions and results in the convolutions, which make cotton to be spun into yarn and fabric [17]. Between 7 and 9 weeks after planting, the bolls open. There is a loss of water, and the fibers dehydrate, twist, and appear flattered. Before natural dehydration or opening of the cotton boll, the shape of the cross-section is circular [18]. After desiccation, the tube collapses and becomes kidney-shaped with a hollow center.

5.6 Cotton Quality Parameters

Throughout the cotton supply chain, the fiber quality has different meanings from the perspective of a cotton spinner, ginner, and cotton farmer. For a cotton grower, the fiber quality means a better economic return of the fiber properties in the form of better premiums and discounts. Cotton yarn manufactures are concerned with fiber quality that impacts yarn end breakage in yarn-spinning processes and with the defects that can be produced due to the inferior quality of cotton fiber [19].

Cotton farmers and ginners increase the premium by producing better quality cotton by drying the seed cotton to the extreme and increasing lint cleaning. These steps affect adversely as short fibers and neps have been increased, hence reduces the spinnability of the cotton [20]. The cotton producer's production and ginning practices are more influenced by Government loan programs, and cotton merchants usually drive the cotton crop production and ginning operations. As a result, the price of cotton cannot be directly correlated with the quality of yarn produced. The evaluation of cotton quality is based on fiber grade and staple, which in the future may be based on the true spinning value of fibers, which spinner or end-user demands. For marketing and processing, cotton fiber length is one of the essential characteristics. Longer fiber length gets a premium on its sale price. Fiber length is directly related to other cotton fiber characteristics such as strength, fineness, maturity, and uniformity. Longer staple kinds of cotton are mostly stronger, finer, and more uniform than short length kinds of cotton. During the spinning process, production efficiency, waste produced, and the amount of fly generated is affected by fiber length [21].

Length of cotton fiber also directly affect yarn quality parameters, such as strength, elongation, hairiness, and evenness. Newer spinning systems such as air-jet spinning, the role of fiber length, and its distribution get more important because these systems are sensitive to fiber surface area. Fibers with shorter lengths have a higher probability of slippage than fiber with long lengths [32]. Furthermore, if these frictional forces power is less than the breaking strength, the fiber will slip rather than break, and the resultant yarn will be weaker. If all other cotton fiber properties are kept constant, the long length fibers would require less amount of twist to get better yarn strength. Many scientists and organizations have developed cotton classification and quality parameters, which refers to the application of standardized procedures to measure the physical properties of raw cotton that will affect the final product quality, i.e., yarn quality. One of the leading equipment is a high volumetric instrument (HVI), which is used to measures cotton fiber color, trash, micronaire, length, length uniformity, and strength. Some fiber properties are not measured with HVI, such as maturity, fineness, short fiber content, length distribution, which also contribute mainly to yarn quality. These fiber properties can be measured with other equipment called the advanced fiber information system (AFIS).

Textile manufacturers use HVI fiber quality parameters, including micronaire, to check if the cotton purchased is within the specification for the processing of yarns and fabrics of a given quality. HVI length measurement is not able to measure the shortest fibers in the fiber beard; therefore, it could result in inaccuracies while predicting yarn quality. Therefore, depending only on HVI measurements to predict ring-spun yarn quality, especially yarn evenness, which is known to be sensitive to short fiber, is not an ideal solution. AFIS system can provide some of the vital information that can be used along with HVI data and allow us to predict yarn quality better.

The maturity of cotton fiber is among the most important fiber properties. Fiber maturity can affect almost all of the other fiber properties directly or indirectly. Cotton average fiber maturity can change during cotton processing, as during processing, weak and immature fibers can break producing short fibers. The degree of maturity is estimated as the ratio of the outer and inner diameters of fiber. Based on it, cotton fibers are divided into 11 groups from 0 (immature fiber) to 5 (extremely mature fiber) with an interval of 0.5. The most suitable for the manufacture of textile materials are fibers with a degree of maturity of 2.5–3.5. Some of the short fibers are removed during different processing steps before spinning, but not all of them. Cotton is processed through opening, carding, drafting, and combing before producing a yarn. Therefore, the impact of these cotton processing steps on fiber properties should be evaluated. To identify the variation in fiber properties during processing and the impact of fiber maturity on the variations observed, many researchers have worked. Fiber maturity should be improved to get better cotton quality for better performance. There are different instruments and methods to measure cotton fiber maturity, such as image analysis of cotton fiber cross sections, AFIS, Cotton-scope, but none has a speed compatible with HVI cotton classification. Nevertheless, they could be used successfully for research purposes.

Following are some of the advantages of apparel produced with cotton fibers;

1. It is felt relaxed when wears cotton fabrics meanly because cotton fiber has high thermal conductivity and significant moisture absorption. So, this material is indispensable in countries with a hot climate. In cotton apparel, the body breathes wonderful, which creates additional comfort and pleasant sensations.
2. Cotton consists of more than 90% cellulose, which absorbs moisture almost perfectly. For towels, this quality is useful. Cotton has advantages of Soft touch. Cotton gives soft touch, which creates a pleasant feel to the hands and body; this property allows them to produce undergarments, sportswear, bedding, and even products for newborn babies.
3. Mercerized cotton fiber has improved smoothness and silky shine qualities. An inexperienced buyer can easily confuse it with rayon or synthetic material. Cotton can be dyed in bright colors after undergoing the process of mercerization [22]. The color range of mercerized cotton is significantly wider than that of conventional bleached cotton, and the colors are brighter and more resistant to temperature and light effects.
4. Cotton is less durable than other natural fibers but still strong enough to use for the manufacture of fabrics and a wide range of yarn. A single fiber can withstand a weight of 2–8 g. Strength increases when wet and decreases with excessive drying or prolonged exposure to light. The disadvantages of fiber include low elasticity ($\varepsilon e = 6–8\%$). The proportion of plastic deformation in full elongation is 50%, due to the small amount of elastic deformation, cotton fiber fabrics are easily crushed.
5. Cotton can withstand heat up to 150 °C in a dry atmosphere without damage. At 245 °C, the fiber turns brown and lights up. Usually, cotton clothes are ironed with slightly moistened or using steam to remove wrinkles easily. At a temperature of 20 °C and relative humidity of 65%, cotton fiber absorbs about 10% moisture, and at a relative humidity of 90–95%—about 15%. The heat resistance of the fiber in the wet state is higher than in the dry state. Cotton fiber is much heavier than water. Its specific gravity is 1.52 g/cm.
6. Cotton is easy to wash in a washing machine in various modes, boiling with the use of highly concentrated detergents and bleaching using chlorine. Bleaches should be used diluted during rinsing to prevent the product from turning yellow. Moreover, one of the strongest alkalis—caustic soda—is used in the process of mercerizing cotton to give the fiber extra strength, softness, and elasticity.

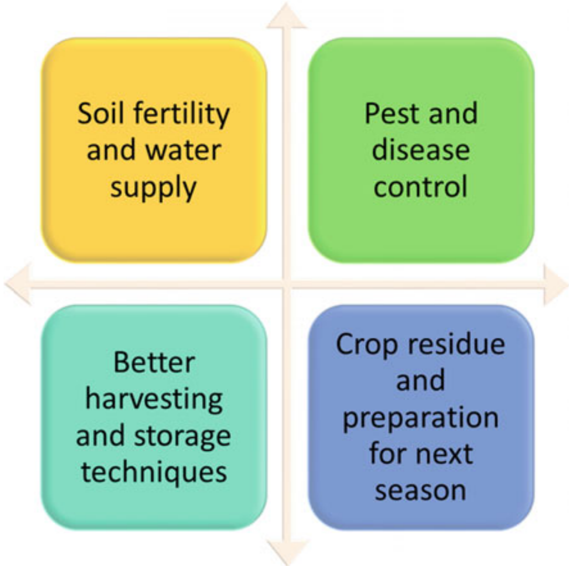
7. Cotton fiber can be blended with various other fibers, both natural and synthetic, which gives cotton the ability to withstand fierce competition with modern materials successfully. New blends have improved characteristics and further expand the range of applications of cotton fiber.
8. High-quality, fine cotton yarn with modern effects is unlikely to be cheap. Fortunately, most mass-market fabrics and yarns are still available to reasonable prices. Fortunately, a considerable amount of chemicals that are used with cotton during different stages of its cultivation and production does not significantly affect the final product. Care must be taken not to use synthetic detergents and deodorizing agents with a pungent odor or bleaches, including chlorine in the process of washing of cotton clothes or linen.
9. Under the action of weather and light, the process of cellulose oxidation by atmospheric oxygen is activated, which leads to a decrease in mechanical properties, i.e., strength or elongation, and an increase in the stiffness and brittleness of the fibers. As a result of exposure to sunlight for 940 h, the strength of cotton is reduced by 50%.

5.7 Best Management Practices for Cotton Crop

Best management practices (BMPs) are a set of best-coordinated activities that give increased productivity and profitability on the cotton farm with improved sustainability. After many years of agricultural practices and research, three pillars of sustainability, namely, social responsibility, environmental integrity, and economic viability, are carefully addressed to formulate these BMPs for cotton cultivation. Keeping in view the financial requirements for agriculture that are high yield with environmental and social concerns, these BMPs are framed. The target is also to minimize water usage and pesticide use for the production of cotton fibers. For the formulation of these BMPs, extensive work has been done on analyzing strengths, weaknesses, opportunities, and threats faced by cotton cultivation [23].

Cotton is a cash crop, and it needs a producer's exhaustive farming requirement. These essential cultivation practices like wide spacing between plant to plant and row to row, long duration, render the crop susceptible to a multitude of pests and diseases at all stages of growth. These practices are results as high input use in terms of nutrients and crop protection chemicals, with fewer returns. The disproportionate use of inputs increases not only the cost of production but also decreases the revenues along with pest resurgence, and ecological hazards. WWF, in consultation with all stakeholders, has developed the concept of introducing BMPs for cotton cultivation. By the adoption of these BMPs, helps to balance inputs with increased cotton fiber yields. Cotton growers can get benefit by executing these BMPs in their respective cotton-growing areas. These BMPs are more environmentally friendly and are focused on the use of locally available resources with the target to expand the input use efficiency. To fully understand the concept of BMPs, these practices can be categorized into the following broad areas, as illustrated in Fig. 5.5.

Fig. 5.5 The matrix for significant areas to focus on for BMPs for cotton



The current cotton crop management generally needs an influential culture of innovation, the dedicated extension of resources, to get high cotton yields and quality. This can be achieved through longstanding commitment to research through industry and government partnerships. With the rapid adoption of knowledge and technology, through a highly skilled workforce, this can be achieved. Other areas of improvement are communication and transport infrastructure within crop areas [24]. Biosecurity incursions, climate change, pest resistance, and water scarcity are some of the significant challenges faced by today's cotton producers.

5.8 Environmental Effects on Fiber Quality

Cotton fiber quality mostly depends on genetics coming from the seed itself, like fiber length and its diameter. As time passed from seed sowing, the fiber growth mostly depends upon soil fertilization and environmental conditions. The worldwide cotton cultivation is limited not only by the required area of land but also by the necessary water supply and the high proportion of herbicides, fungicides, and insecticides. Agriculture accounts for 70–75% of global water use, and cotton's global water foot-print is about 3% of the world's agricultural water use. It is lower than many other commodities and proportional to cotton's land use of 2.3% of the world's arable land.

The international cotton advisory committee estimates that with cur-rent irrigation systems, today, between 3000 and 7000 L of water is need-ed to produce 1 kg of cotton lint fiber [25]. The most sparing and efficient meth-od is drip irrigation, which supplies the ground under to the earth's surface. Drip irrigation, however, is costly, and consequently, only a maximum of 5% of growers worldwide are today equipped with such an irrigation system. Water supply is one of the critical parameters for the development of cotton fiber. During fiber growth and maturation period, it is predictable that both water excess and lack may result in worsened fiber quality. This two-water condition may impair photosynthesis and, therefore, thus decreasing fiber quality. Most of the fiber quality parameters, such as fiber length, micronaire reflects as fiber yield, which can be improved with BMPs. However, fiber quality also depends on the environmental condition, which is not well predictable. That causes fiber quality variability from field to field.

Fiber length and thickening are also depending on the temperature and water supply to the plant. Along with the water supply, fiber maturity depends on photosynthate deposition in the cell wall, and that is more sensitive to environmental stress. The cotton fiber primarily consists of cellulose, and its growth depends on plant photosynthesis. Carbohydrate production will affect fiber growth and development. Many studies found that fiber micronaire correlates directly with the amount of photosynthesis observed 15–45 days after anthesis. The environmental conditions are occurring from 3 to 25 days after anthesis impact length, while cellulose deposition on the secondary wall is affected 15–45 days after anthesis. The night temperature variations affect not only the fiber elongation rate but also the final fiber length.

It has been observed that low temperatures cause an interruption in fiber growth without adverse effect on final fiber length. As the quality of cotton fiber is not the same across the plant, the average quality of the harvested cotton is, therefore, measured as an average of what has happened during the development of each cotton boll. The development of cotton fiber is mainly a cellulose synthesis process. Sucrose is degraded by sucrose synthase, thus providing glucose, the skeleton unity for cellulose synthesis.

Continuous drought conditions experienced before and after flowering harmed fiber length distribution and fiber strength. Late cold spells on some of the farms also influenced the second stage of fiber formation, which takes place when cellulose is deposited in successive layers on the inner surface of the primary wall, after which some low micronaire (fiber fineness) kinds of cotton were identified. Effective defoliation practices could not be maintained on all the farms due to the unfavorable weather conditions experienced, which, therefore, also had a negative effect on the high trash content of the seed cotton. Continued exposure to different weather conditions did have, in some cases, an impact on the white cotton in losing its brightness and becoming darker, varying from white to dull white cotton. Different color values are also the result of one picking process in which seed cotton bolls have been opened for some time and then mixed with newly opened bolls.

5.9 Better Cotton Initiative

Better cotton initiative (BCI) is an initiative taken by WWF in the Year 2005 as the outcome of a ‘round table’ series of deliberations between world cotton experts. This initiative has the goal of finding more sustainable solutions not only for farmers but for the environment and all related stakeholders of the cotton supply chain [26]. The BCI framework is designed to make sure that good practices in cotton production should be implemented and exchange between the farmers. The collective actions should be encouraged to make Better cotton as a mainstream brand name. A holistic approach has been adopted for better cotton production to make this ambitious real. It not only addressed the environmental and social areas but also deals with economic aspects of cotton production activities. The beauty of BCI is the synchronization of all basic elements, starts from the working principles and mechanisms for monitoring, which helps to analyses the impact and progress of the overall program. Furthermore, the exchange of good practices, and scaling up of collective action makes BCI a sustainable for a longer time.

5.10 Organic Cotton

Cotton grown without the use of any synthetic agricultural chemicals such as fertilizers or pesticides is called Organic Cotton [27]. Production of organic cotton promotes and enhances biodiversity and biological cycles. Under internationally recognized organic farming standards of EU regulation 834/2007 and national organic program, USA, which governs the production of all non-genetically modified plants, organic cotton can be produced [28, 29]. Organic cotton is grown in many subtropical countries, including Turkey, China, Pakistan, and India [30]. At least for a period of 3 years, organic fields must go through a cleansing phase, avoiding all kinds of prohibited substances. Soil fertility through better cultivation practices should be ensured while maintaining or improving the physical, chemical, and biological conditions of the crop. The integrated pest management activities should be adopted to balance the farm ecosystems, which ensure the betterment of both plants and the organisms [31].

A balanced farming ecosystem needs to be established to produce organic cotton through a systemic approach. Preferably it includes all types of activities related to farm and crop production. As an essential element, careful selection of cotton seed varieties should be selected, which are compatible with local conditions for climate, type of soil, and resistance to domestic pests and diseases. Compost, mulch, and manures are organic inputs, which are part of soil fertility management based on crop diversification. If pest infestation rises above the economic threshold, the use of natural pesticides can be used to maintain the balanced agroeconomic system. For the pest management system, in the case of organic cotton, the focus should be kept for pest prevention. For any organic cotton producer, the value of the organic certificate is significant. Many certification agencies usually conduct audits for accreditations related to organic cotton productions for the European market (EN 45011, respectively, ISO 65) and the national organic program USA. Some customer demands certain certification agencies, or require additional certifications such as GAP (Good Agricultural Practice) or SA (Social Accountability), Fair Trade, HACCP (Hazard Analysis and Critical Control Points). These accreditations make sure that cotton production follows specific standards.

The term BT/GE cotton should not be confused with organic cotton. Manufacturers of such BT/GE cotton are, for example, SYNGENTA or MONSANTO and BAYER. With the GE cotton, a gene is incorporated, which is intended to make the plant resistant to pests. This reduces not only the need for pesticides but also the diseases caused by the cot-ton grower using pesticides. It results in a reduction of only two spraying cycles per year of cultivation. Unfortunately, these pest-resistant seeds are only supplied to the farmers at an annual charge (loyalty price). The old seeds from the previous year can no longer be used. The largest BT cotton producers worldwide are China and India, followed by the USA, Pakistan, and the commonwealth of independent states.

5.11 Conclusion

Cotton is one of the most common fibers used for humankind over a long time, and even today, despite having many synthetic fibers, cotton possesses its importance over other fibers. There is a wide range of essential segments related to cotton production and its structure that influence the different quality parameters of cotton fiber. Best management practices and better cotton initiatives are discussed for cotton fiber cultivation, yield, quality, sustainable cotton production. The role of, non-genetically modified, organic cotton, avoiding the use of any fertilizers or pesticides, to maintain biological cycles and enhance biodiversity, is also highlighted.

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Chapter 6
Cotton Fiber Testing

Muhammad Qasim Siddiqui, Hua Wang, and Hafeezullah Memon

Abstract Quality cotton fiber is vital to produce quality yarn and, subsequently, better-quality fabrics. As per data provided by USDA for the year 2020/21 world cotton production is expected at 117 million bales (1 bale = 220 kg). The variability in the quality of cotton is dominated due to environmental conditions and depends on the area of cultivation. To produce the best quality yarn and uniform fabrics, we need to measure and control each quality parameter of cotton fiber. Uster Switzerland is one of the leaders in testing cotton fiber characteristics through its state-of-the-art HVI and AFIS fiber testing equipment. Understanding cotton fiber characteristics and their relationships with yarn and fabric quality are essential to produce good quality textiles. In this chapter, the main quality parameters of cotton fiber, along with its basic testing principles, have been discussed. Cotton fiber quality is determined by various parameters such as maturity, fineness, micronaire (mic), length, strength, length uniformity. The market value of cotton is determined according to these parameters. Fibers with better quality will produce better yarn. Nowadays, the High Volume Instrument (HVI) and Advanced Fiber Information System (AFIS) are the two main instruments used to measure cotton fiber quality. HVI measures micronaire, Upper Half Mean Length (UHML), strength, elongation, color, and trash, while, AFIS measures maturity, fineness, length, neps, short fiber content, immature fibers, and trash.

Keywords Cotton fiber quality · Fiber length · Fineness · Maturity · Strength · HVI · AFIS

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6.1 Introduction

Around the globe, more than 80 countries are engaged in cotton production, mostly for its fine fiber. After removing the fibers, the cottonseeds are also used to extract vegetable oil for human consumption. The remaining crushed seeds are used as feed for animals such as cattle and sheep. The small linter of cotton fibers removed from the cottonseed can be the source for cellulose, that makes cotton crop highly useful and cash crop [1].

Global competition in the production and consumption of cotton fiber combined with technological advancement in yarn manufacturing has accelerated efforts to enhance cotton fiber quality. To improve the quality of cotton yarn and to get better mill efficiency, yarn manufacturers must understand the properties of raw cotton. The variation in yarn evenness and strength is dependent on the properties of raw cotton fiber. Spinners carefully interpret the cotton fiber property data, to make their business viable To get the best out of the raw material. The fact that more than half of the yarn price comprises of raw cotton fiber, its proper understanding becomes critical.

For cotton fiber producers, both cotton crop yield and quality are essential considerations. Cotton yield results in better output in terms of quantity, while fiber quality is vital to market the crop with better price and helps to produce more exceptional textile products. Farmers focus on varieties that can give higher yields while yarn manufacturer demands cotton with a better-quality profile that allows them to spin a yarn of more top quality. The importance of cotton fiber quality is different from the perspective of various stakeholders of the cotton supply chain. For cotton farmers, the word fiber quality implies the economic return (premium and discounts) of fiber properties. Yarn manufacturers are concern with fiber quality impact on fiber processing and defects produced in yarn and fabric due to inferior quality raw material.

Recently, the Food and Drug Administration, USA, made decisions about allowing cottonseed as food for people and all types of animals. After separating the fine fibers from seeds in ginning factories, the remaining cottonseed can be consumed in other forms. By crushing the seeds, the oil (usable for cooking) is extracted. The resultant crushed seeds are high in protein content can be used as a protein supplement in many food items.

The cotton fiber quality not only depends on seed genetics, environmental conditions but also on the type of ginning system and drying techniques employed. Measuring the cotton fiber quality parameters is critical both for cotton fiber producers and spinners because it directly impacts the quality of yarn and fabric produced. In the future, the cotton fiber value will be based on the true spinnability of fibers, based on the system of fiber characteristics required by spinner and weaver. The ultimate target is to correlate the cotton price with the quality of yarn produced.

The weight of cotton bale is very country to country. In the USA, the cotton bale weighs around 225 kg while in India and Pakistan, the average bale weight is about 170 kg. The costs for cotton are between 50 and 70% of the entire manufacturing costs for most of the spinning mills. Therefore, it is vital to have fiber quality under

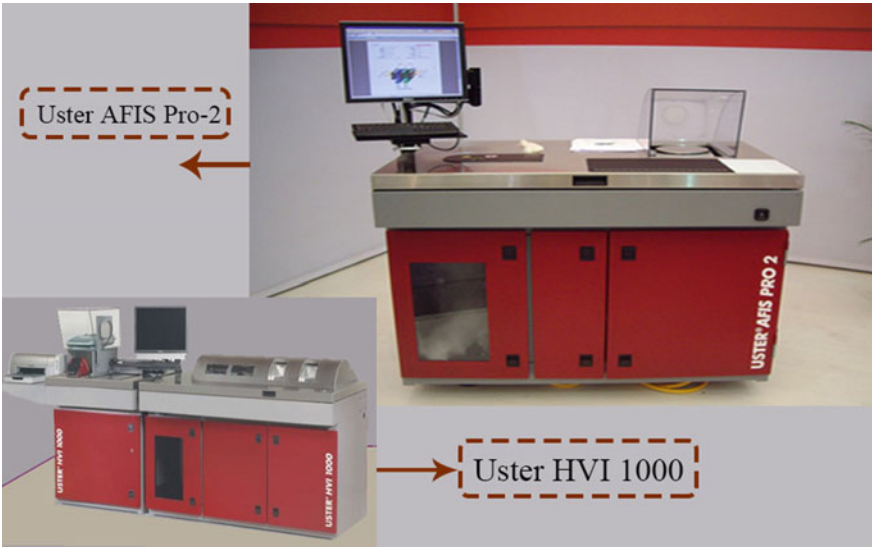

Fig. 6.1 Uster HVI and AFIS lines at Donghua University, China

Table 6.1 Comparison between HVI and AFIS testing lines

Fiber testing though HVI lines (fiber bundle testing)	Fiber testing through AFIS lines (single fiber testing)
Fiber length, UHML	Upper Quartile Length UQL, mean length
Fiber fineness, micronaire	Fiber fineness
Trash (area)	Number of dust and trash particles
Maturity index	Maturity
Short fiber index	Short fiber content
Fiber strength and elongation	Not available
Fiber color	Not available

control during the whole spinning process. With the monitoring of the fiber quality, the fiber damage can be kept under control, the fiber waste can be minimized, and the nep removal efficiency can be optimized.

Currently, the High Volume Instrument (HVI) and Advanced Fiber Information System (AFIS) are the two instruments used to measure cotton fiber quality in most of the spinning mills, and the instruments are shown in Fig. 6.1. HVI system is based on a fiber bundle testing system, which is used for fiber classification and helps spinning specialists to manage bale lay down in the warehouses. For the single fiber testing system, AFIS serves for the measurement of the fiber quality of the spinning process. Table 6.1 shows a comparison of both systems and with all measured fiber properties.

6.2 Fiber Length, Length Uniformity, and Short Fibers

Cotton fiber length or staple length is one of the essential characteristics, which directly influence the quality of yarn and cause costly interruption/breakage in the yarn manufacturing process. Fiber length directly affects the irregularity of the yarn, and with longer fibers, higher tenacity of yarn can be achieved. With the accurate measurement of fiber length and its distribution, all relevant machine settings are adjusted in the spinning process. Fiber length affects yarn strength, yarn evenness, and the efficiency of the yarn manufacturing process. The fineness of the yarn that can be successfully produced from given fibers is also influenced by fiber length. Since cotton trading started, the cotton length was measured through manual procedures using bear hand and eye. In the year 1909, USDA established a first standard cotton classing system based on cotton color and length. A human cotton classer pulls fibers away from a bundle and arranges them parallel from which cotton fiber length characteristics could be determined. Cotton fiber length is much more critical for ring-spun yarn as compared to open-end yarn.

Cotton varieties (*Gossypium hirsutum*), also called upland cotton, represent around 90% of the cotton produce globally. This famous verity has staple lengths starting from 25.4 to 32 mm. On the other hand, the long-staple cotton verity, Pima-type cotton (*Gossypium barbadense*), typically ranges from 32 to 50 mm longer and finer the upland cotton. These verities include long-staple cotton, also called 'Sea Island', and extralong staple, famous as 'Egyptian cotton', are comprised of only 8% of the global cotton share. Nowadays, cotton fiber length characteristics are measured by preparing a "beard" of parallel fibers and then passing through an optical sensing point. The parallel arrangement of fiber beard is prepared carefully from a sample of cotton and grasped by a clamp. Then this cotton sample is combed and brushed into parallel orientation to produce a fibrogram.

6.2.1 Length Measurement Through HVI

In HVI lines, fiber length and UHML are evaluated by measuring light attenuation through a combed beard of fibers. In the HVI baskets, samples are placed, and a comb grasps cotton fibers (lint). These clamped fibers are then combed to make each fiber parallel to one another, forming fiber beards. The instrument then passes light through these beards; the sensors measure the variation in light attenuation across fiber beard to estimate the length of cotton fibers. Upper Half Mean Length (UHML Fig. 6.2), which is the mean length by the number of the longer one-half of the fibers by weight [2], is reported as well as length uniformity. This length uniformity can be calculated as the ratio between the ML of all cotton fibers and the UHML, and that is expressed as a percentage.

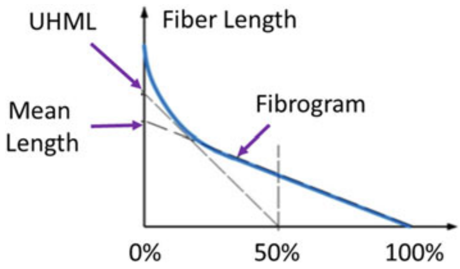

Fig. 6.2 Fibrogram of cotton fiber length showing mean length and UHML. [3] (on page 43)

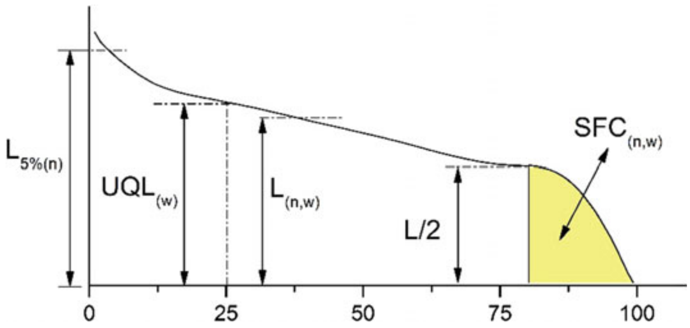

Fig. 6.3 Fiber staple length diagram from a data tested by Dr. Hafeezullah Memon, Donghua University, China

6.2.2 Length Measurement Through AFIS

Separating and testing individual single fibers are the bases for the AFIS system. There are two modules; one module is for testing neps and trash, while the other one is used for testing length and maturity. A fiber sample of approximately 0.5 g weight has to be converted into a sliver form of length 30 cm long and placed in the sampling tube of the AFIS. Furthermore, the individual fibers from that sliver have been separated by a mini card like equipment. These separated fibers are transported to a sensor with the help of high-velocity air-flow. Trashes are directed to another sensor. Fibers enter the electro-optical sensor through an accelerating nozzle which straightens, separates, and aligns the fibers in proper orientation to a near infra-red ribbon beam. The fibers scatter and block light with their optical diameter and in direct relation to their time of flight through the sampling volume. This light is detected and generates voltages that translate into characteristic waveforms. Fibers produce a rectangular waveform characteristic of their length and diameter. Neps generate a triangular waveform in which peak amplitude is several times the magnitude of fiber waveforms. AFIS is capable of measuring the distribution of length, fineness, and maturity.

AFIS can measure mean length by number, mean length by weight, length uniformity, UQL is the average length of the longest 25% of fibers, see Fig. 6.3, and amount of short fibers. AFIS determines the fiber length distributions by measuring the length of each fiber. For a given fiber sample, the length is estimated through an optical sensor when fibers passed through at a constant speed in front of the optical sensor. Fiber length is an essential factor for the cotton industry. The spinning limit that is how fine the yarn can be spun is dependent on fiber length [4].

6.2.3 Length Uniformity

Length uniformity is an indicator of fiber length distribution for a given sample of cotton. It's the ratio between the average fiber length (mean length) and the upper-half mean length of the fibers, expressed in term of percentage (refer, Fig. 6.2). For an ideal cotton fiber, where all of the fibers in the bale have the same length, say the uniformity would be 100%. However, of all-natural fibers, they have variations in their staple lengths, the actual uniformity for fiber lengths will always be less than 100%. Table 6.2 has shown a guide for descriptive designation against the HVI uniformity index for length uniformity measurements. The HVI uniformity index (Unf) can be calculated as under;

Uniformity Index (Unf) = Mean Length/UHML * 100

Length uniformity affects yarn evenness and strength and the efficiency of the spinning process. It is also related to short-fiber content (the content of fibers shorter than $^1/_2$ in.).

Cotton samples with high uniformity index show fewer length variations along the mean fiber length. With a low uniformity index cotton samples, it is likely to have a high percentage of short fibers. These cotton samples show difficulties during fiber processing, and we can't produce high-quality yarns with these fibers.

6.2.4 Short Fibers

Short fibers content is an essential indication of cotton fiber and yarn quality, fiber less than 0.5 in. (12.7 mm) is defined as short fibers. Short fibers can create lots of problems during processing. They have detrimental impacts on yarn production,

Table 6.2 USDA HVI length uniformity index along with the descriptive designation [5]

HVI uniformity index	Descriptive designation
Below 77	Very low
77–79	Low
80–82	Average
83–85	High
Above 85	Very high

performance, and yarn quality as it increases waste during processing [6]. Short fiber content (SFC) is related to immature fiber content (IFC). Higher the IFC higher will be the SFC [7]. Faulkner found less SFC in mature cotton than in immature cotton. Short fiber can create neps, which is nothing but entanglements of the fiber. The yarns with lots of short fibers have a hairy appearance and are weak.

Hequet et al. [8] found that within-sample fibers with high maturity have a longer length. But they also mentioned that this type of relationship is not valid for all kinds of cotton, for some cotton maturity varies only little with the length. They added that growing conditions influence length and maturity distributions. Differences in fiber maturity can lead to variation in fiber length distribution, and alteration in fiber length distribution can lead to disparity in processing efficiency and yarn quality. Krifa [9] observed length distributions for weak, immature, and strong, mature kinds of cotton. The author found a higher amount of short fibers in weak and immature types of cotton. Immature and weak cotton showed a unimodal length distribution, while mature and robust types of cotton showed a bimodal length distribution [10].

Besides, the naturally present short length fibers in raw cotton, excessive beating, and cleaning at ginning and spinning mills generate more short lengths and broken fibers fragments [11]. The presence of these small broken fibers creates inefficiencies in production and reduces the quality of output yarn and fabrics. Behery [12] discussed the behavior of short fibers during cotton spinning and described that the fiber strands are attenuated by passing the fibers in between a pair of drafting rollers. The drafting rollers are spaced at proper distances, which allow most fibers to pass through without bridging this predetermined gap and reduce the fiber breakage. At drafting zones, the roller ratchets are adjusted according to the fiber length characteristics. The naturally occurring variation in staple fibers length in any cotton, the fibers with shorter lengths usually not fully grabbed between front and back drafting rollers. The unpredicted nature of these “floating fibers” causes irregularity in output products [13].

Research studies also presented that the number of short fibers and length uniformity of cotton fibers length may affect fiber movements during roller during drafting [14]. When the slow-moving fibers are pulled by the fast-moving fibers, between two sets of rollers, those point of acceleration plays a vital role in drafting. For short length fiber, accelerated points are scattered in relatively large areas within the drafting zone, whereas for long length fibers, these accelerated points might reside near the front drafting rollers. Moreover, this scattering of the accelerated points caused more sliver irregularity [15]. Usually, the short length fibers freely float in between the drafting rollers. Here these short length fibers can group up together or thin out randomly, causing thick and thin imperfections in the resultant sliver or yarn. These short length fibers also caused a reduction in yarn strength.

Short fibers and length uniformity affect most of the yarn properties, like total imperfections, CLSP, yarn unevenness. Furthermore, whenever a bundle of fibers reaches the front drafting roller, a comparatively high draft is required fiber attenuation [13, 14]. The short fiber content by weight (SFCw), and short fiber Index (SFI), are the indication for the amount of short fiber present in any cotton sample, measured

Table 6.3 Description of short fiber index [3] (on page 45)

Short fiber index (%)	Description
Below 6	Very low
6–9	Low
10–13	Medium
14–17	High
18 and higher	Very high

by HVI and AFIS, respectively. This property is mostly shown as a percentage (%). The description of SFI may be as presented in Table 6.3.

6.3 Fiber Fineness and Maturity

The fineness of cotton fiber is frequently expressed in terms of linear density. It is the relation between weight and length of any given fiber, usually shown in tex or dtex. For any given cotton fiber sample, the average linear density depends on both fiber length and the degree of wall thickening (maturity) or diameter. Fiber fineness and maturity both are important cotton fiber properties which determine the number of fibers required to be spun a specific linear density of a yarn. Fiber luster and degree of dye uptake for a piece of given cotton fabric, depending on fiber fineness and maturity.

Mostly, cotton fiber fineness is expressed in terms of Micronaire values. In this test method, the fiber fineness is measured as the resistance offered by a weighed plug of fibers to a metered air-flow. The change in air-flow or pressure provided by the cotton fibers is correlated with the linear density of individual fibers, as the change in air-flow is dependent upon fiber specific surface area. Approximately 10 g of fibers are needed for micronaire measurement in HVI. The weighed fibers are then placed in a chamber and compressed to a fixed volume. Based on the permeability through fibers, controlled air-flow is passed through the prepared sample, and micronaire values are determined. Lord [16] showed that resistance to air-flow was related to fineness and maturity of cotton fiber.

$$\mathrm{M} \times \mathrm{H} = 3.86 \times \mathrm{Mic}^2 + 18.16 \times \mathrm{Mic} + 13 \tag{6.1}$$

where M is maturity ratio, H is linear density, and mic is micronaire. The classification standard of cotton fiber micronaire values is summarized in Table 6.4.

In earlier days, micronaire was considered as a measurement of fineness only. But later on, it was demonstrated that micronaire is a function of both fineness and maturity. Fineness is generally expressed as gravimetric fineness or linear density, and maturity is expressed as maturity ratio [18]. Textile manufacturers use micronaire as a substitute for fiber maturity. Montalvo [19] mentioned that growers might be discounted for high micronaire even though the fibers have adequate fineness and

Table 6.4 Classification standard of cotton fiber micronaire value [17]

Micronaire values	Ratings
Below 3	Very fine
3.1–3.9	Fine
4.0–4.9	Average
5.0–5.9	Coarse
Over 6	Very coarse

maturity, as high micronaire fiber is in general coarse, which is undesirable for spinning and yarn evenness. Walter [20] mentioned that it is possible for a fine fiber with a small fiber perimeter to have a well-developed cell wall and consequently be fine and mature, and coarse fiber with a large perimeter might have a poorly developed cell wall and be both coarse and immature. Therefore, with the micronaire reading only, one cannot tell how mature or immature a cotton fiber is. Simpson and Fiori [21] stated that the main problem in processing low micronaire cotton was excessive nepping during carding resulting in detrimental effects on yarn and fabric appearance. Also, high micronaire cotton could result in increased end breakage and reduced yarn and fabric strength due to fewer fibers per cross-sectional area of yarn. Hequet et al. [8] reported that the micronaire measurement is somewhat confusing. They explained that cotton having identical micronaire might have very different two-dimensional distributions of perimeter and theta. These distribution differences will translate into different processing efficiency and yarn quality.

According to the National Cotton Council, micronaire between 3.7 and 4.2 is in the premium range, and 3.5 to 3.6, and 4.3 through 4.9 are in the base range, 3.4 and below, and 5 and above are in discount range. Maturity can be measured directly from microscope images of fiber wall thickness or wall area. As the process of sectioning cotton fibers and measuring their cross-sectional area is complicated, it is an unsuitable measure for comparing the maturity of different cotton samples.

Fiber maturity and fineness are estimated by analyzing the shape of individual fibers with two optical sensors. The variation in light attenuation is determined by sensors from two different angles, which indicate the shape of the fibers. AFIS reports the maturity ratio, fineness, and IFC. Brown and Graham [22] reported that the accepted method for determining the fineness of cotton is to divide the weight of a counted number of fibers by the product of the number of fibers and their mean length to obtain the average weight per unit length of the individual cotton hairs. They also mentioned that this method is tedious and time-consuming.

Hequet et al. [8] reported that maturity and fineness of cotton fibers are essential qualitative characteristics to understand the rupture of fibers better when they are subjected to stress. They also hypothesized that immature fibers with a thin, poorly developed secondary wall would be fragile. Hence, they are likely to break during processing. These generate short fibers and neps (the entanglement of fibers) that will result in yarn defects and decreased productivity. Fineness affects processing performance and the quality of the end product, in processing such as opening, cleaning, carding. The slower speed is needed for finer fibers to prevent damage to the fibers. El-Hattab et al. [4] found that yarn strength increased with lower maturity of the fiber. They explained that finer or less mature fibers allow for more fibers in a given yarn diameter, which contributes to increased friction. The immature fibers are weaker than the mature fibers, which cause lots of problem during ginning, carding and may produce uneven yarn, as the immature fiber breaks during these processes. Immature fibers have low dye affinity due to the smaller amount of cellulose with which the dye molecule can bond. The fabric made of immature fiber will appear lighter than the fabrics made of mature fibers.

6.4 Fiber Tenacity

Cotton fiber strength is mostly represented by "Tenacity" and this term describes the inherent tendency of fiber to bear applied tensile force. This property is fundamentally important for cotton yarn manufacturing. The force-elongation curve of cotton fiber is illustrated in Fig. 6.4. Nowadays, HVI can perform fast and accurate measurements for fiber elongation and strength using the same beard that is used for measuring fiber length. The method is based on the principle of fiber bundle test method inspired by Pressley and stelometer testers. In other words, the fiber strength is reported in gram per tex. A tex unit is a weight in a gram of 1000 m of fiber. Therefore, the cotton fiber strength reported is the force in grams required to break a bundle of the fiber of one tex in size [5]. The beard is held by clamp 3.81 mm apart from the comb. Due to this, shorter fibers are not involved in the measurement. The clamp pulls the fibers with a special force that breaks the fibers. Before the breakage, fibers elongated a certain distance, which is measured as the elongation of the fiber bundle. The cotton fiber strength is associated with the molecular weight of the cellulose, its crystallinity,

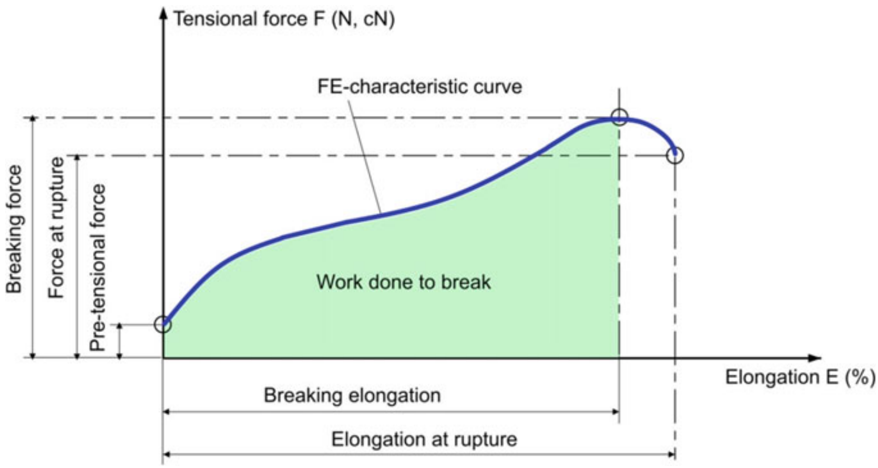

Fig. 6.4 Force Elongation curve with explanation by USTER® [23]

and the extensive inter-molecular and intra-molecular hydrogen bonding. Fiber with strong hydrogen bonding in the crystalline region has good fiber strength.

Fiber strength of the cotton fiber is mostly attributed to its genetics, but deficiencies in plant nutrient and harsh weather may adversely affect its strength. The final strength of the yarn is directly related to fiber strength. Cotton fiber with higher fiber strength is more likely to avoid breakage during the spinning process.

6.5 Fiber Color and Trash

The natural color of cotton is nearly white when it open under natural growing conditions in the field. Many environmental factors influence the change in its color as it opened. The color of cotton lint has always played an essential role in the evaluation of fiber value. Nickerson-Hunter color diagram is used for objective measurements of the cotton fiber color [24]. It describes color in three planes; reflectance (Rd), red/green (a), and yellow/blue (+b). For the simplification of cotton color measurements, the red/green plane is not used. The reflectance indicates how bright or dull the cotton sample is, while the yellowness shows the degree of pigmentation. The Nickerson-Hunter diagram scale have values starting from 40 to 85 for reflectance (Rd), and 5–15 for yellowness values. A three-digit color code is determined by locating the point at which Rd and +b values are intersected each other on the color chart.

For newly opened cotton, if the color is changed from the natural white, it showed deteriorating quality. The reflectance and yellowness of cotton affect the ability to absorb dye. The weather can impact the color of cotton and lead to degradation of the lint. Weathered cotton will not process well [7]. Cotton trash and color are important factors to determine market value in the current cotton grading system. The non-lint particles such as the leaf, seed coat, bark, dust, and other foreign matter are considered as trash, which can result in yarn unevenness, low yarn strength, and finally, low-quality fabrics.

There are two methods for estimating trash; gravimetric and geometric methods. Gravimetric methods evaluate trash content by trash weight, whereas the geometric methods estimate the area covered by trash particles. Among these two methods, HVI is classified as a geometric method. HVI uses image processing techniques to measure trash areas. The trash particles include grass, bark, but these particles cannot be distinguished from one another by this measurement, and HVI does not give the information about the particle size. The trash content of cotton can affect processing efficiency [7]. Most of the trash is removed by cleaning processes during ginning, but 100% removal of trash is impossible, and it could lower the quality of ginned fiber. The presence of trash particles may also affect the color grade; delayed harvest results in lower-grade fiber [25].

6.6 Fiber Neps

Cotton fiber neps are created when fibers are tangled together and form a hard-central knot. Mechanical processes such as cotton harvesting, ginning, yarn manufacturing process in the mill that affect the amount of nep found in cotton, refer to Table 6.5. The natural tendency for cotton fiber to create nep is mainly dependent upon fineness and maturity. Many scientists reported the conditions for the development of neps and their harmful effects on the quality of the final yarn.

AFIS reports sizes and counts of fiber and seed coat neps using different electrical waveforms. Generally, rectangular waveforms are produced by the light blocked by individual fibers. Nep signals are much more significant in magnitude and duration and generate a triangular waveform. Neps are the entanglement of short and immature fibers. There are two kinds of neps; neps, which are present in the raw cotton and the neps which are formed during harvesting, ginning, and processing operations, also known as mechanical neps. The seed coats, which remain attached to the fiber during the opening, can also create neps; such kind of neps are termed as seed coat neps, see Fig. 6.5b. Faulkner [7] mentioned that seed coat neps account for a large portion of imperfection in coarse yarns but contribute less to imperfections in finer yarn. The nep number in yarn depends on both the nep number in the raw material and changes in the number and size of neps during the spinning process. Hebert et al. [26] found that finer cotton fibers have more neps than coarser cotton fibers, independent of fiber maturity.

Hebert et al. [26] reported that immature fibers constitute a significant cause of nep formation in cotton processing. They also found that nep number increased with higher Short Fiber Content, thinner, and less mature cotton fibers. They also observed the relationship between mechanical neps and maturity ratio and neps and fineness.

Table 6.5 Mechanical neps created by each processing step, as determined by a Chinese cotton industry

Process	AFIS neps per gram
Cotton boll in the field	29 ± 2
Cotton boll harvested	80 ± 10
Pre-cleaned cotton at a ginning mill	120 ± 8
Pre-ginned cotton	140 ± 10
1st pre-lint cleaner	200 ± 12
2nd pre-lint cleaner	280 ± 15
Cotton bales	310 ± 20
Blow room lap	400 ± 20
Carded sliver	85 ± 5
Drawn sliver	75 ± 5
Comber lap	70 ± 5
Combed sliver	18 ± 3

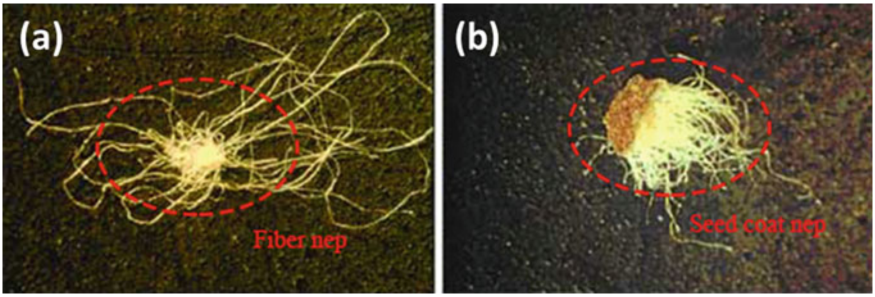

Fig. 6.5 Cotton nep **a** Fiber nep and **b** seed coat nep [3] (on page 57)

They found negative relationships between mechanical neps and fineness and maturity ratio. With an increase in maturity ratio and fineness, nep count decreased. Neps in cotton have been a significant problem in processing. The presence of neps results in decreased yarn evenness and increased yarn breakages. It also reduces production efficiency and increases defects in fabrics. Nep uptake less amount of dye causing dye defect known as a white speck, creating imperfection in fabric.

6.7 Effect of Fiber Parameters on the Quality of Yarn

Yarn is a continuous strand of textile fibers, filaments, or material in a form suitable for knitting, weaving, or interlinking to form a textile fabric. Yarn quality is mostly determined by cotton fiber quality. The fibers must be fine and have sufficient strength to endure processing to produce high-quality yarn. Faulkner et al. reported that fiber length and fineness affect the friction forces between fibers that dictate the count or fineness of the final yarn. They further added that fiber maturity and strength affect a fiber's ability to withstand the forces placed upon it during processing. Cotton fibers pass through different processing stages such as; opening, cleaning, blending, carding, drafting, combing, roving, and finally spun into yarn. Yarn quality parameters include Count Strength Product (CSP), elongation, tenacity, work to break, CVm%, thin and thick places, neps, and hairiness.

6.7.1 Count Strength Product

In yarn manufacturing mills, CSP is calculated by multiplying the yarn count (Ne) by its strength required to break an 840-yard length of yarn (skein). The count is the yarn numbering system based on length and weight. The count of the yarn is equal to 840-yard skeins required to weight 1 lb. Higher the count number, finer is the yarn. Skein break factor increases with increasing fiber length, length uniformity, and fiber strength [27]. Faulkner compared the CSP of picked cotton with striped cotton for carded and combed yarn. He found no significant difference between picked and stripped cotton for CSP, for both carded and combed yarn. El-Hattab et al. [4] mentioned that yarn strength is dependent on fiber length as fiber length improves the probability of more cohesion between fibers, which translates into increased yarn strength. Hequet et al. [28] mentioned that yarn strength could be estimated from AFIS mean length by weight, standard fineness, and maturity ratio.

6.7.2 Yarn Elongation and Yarn Tenacity

Yarn elongation is the distance the yarn stretches before breaking. Tenacity is the tensile stress expressed as force per unit linear density and is directly related to yarn strength. Spinners usually give the least attention to yarn elongation, among all the measurable properties of spun yarns. However, its elongation can never be ignored, as it affects the yarn efficiency during the fabric manufacturing process. Hequet et al. [28] mentioned that cotton breeders often conclude that there is no need to work on elongation as it could result in lower tenacity because of the negative correlation between fiber bundle elongation and fiber bundle tenacity. They also demonstrated that the negative correlation indeed exists, but it is a weak correlation that does not preclude the simultaneous improvement of tenacity and elongation.

Yarn elongation is influenced by fiber properties, yarn twist, and yarn count. Fibers with higher elongation would be expected to spin more efficiently as it might tend to deform more easily during spinning. Smith and Waters reported that yarns of lower twist tend to have lower strength due to fiber slippage. Also, yarns of higher twist tend to have lower strength because of increased fiber obliquity to the yarn axis. They explained that adding twist will generally decrease fiber slippage by tightening the yarn structure; however, above the optimum yarn twist, the potential gains in strength due to increase cohesion are not realized due to the obliquity effect. Therefore, for optimum strength, an optimum twist should be applied.

6.7.3 Fiber Maturity and Trash Content

Frydrych [29] measured the fiber maturity and trash content for small populations of fibers (extracted from yarns). They found a negative correlation coefficient between maturity and yarn tenacity. They explained that with an increase in maturity, the wall thickness and bending rigidity of fibers also increase, causing yarn strength to decrease, even though the fiber themselves were stronger. They did not see any negative influence of trash content on yarn strength in the case of ring-spun yarns, but they mentioned that trash content significantly affects the strength of yarn spun by the open-end method.

6.7.4 Yarn Evenness

Yarn evenness is the measurement of variation in the yarn mass. The testing process of determining sliver evenness is shown in Fig. 6.6. The same arrangement with slight modification (settings) can test yarn evenness also. Several parameters are used to indicate yarn evenness, such as yarn coefficient of variation by mass (CVm), thick places, thin places, and neps. A segment called thick place is usually categorized by a diameter increased from adjusting segments 6 mm or more [30]. The thin place is a yarn defect characterized by a segment that is substantially (at least 25%) smaller in diameter than the average diameter of the yarn [31]. Nep is a tightly tangled, knot-like the mass of unorganized fiber [32]. Montalvo [19] reported that high micronaire fibers were undesirable for spinning and yarn evenness.

6.7.5 Yarn Hairiness

Yarn hairiness is defined as fiber ends and loops protruding from the body of yarn due to broken fibers or filaments. Uster testers series are well known for determining

Fig. 6.6 Evenness testing system, image taken by Dr. Muhammad Qasim Siddiqui at Donghua University, China

yarn hairiness and yarn evenness with high accuracy, Uster Tester 6 is presented in Fig. 6.7. It is usually an unwanted property and is determined by fiber properties and spinning conditions [33]. Üreyen mentioned that yarn twist and fiber strength are the most critical factors affecting the hairiness value, followed by elongation and length. Whereas, Hequet and Ethridge [34] reported that yarn hairiness is highly correlated with the shortest and the longest fibers present in all types of yarn. Fibers with long length decrease the yarn hairiness, while the short length fibers increased hairiness. Altas and Kadoğlu [35] examine the effect of cotton fiber properties and linear density on yarn hairiness for two different yarn counts. They determined that hairiness increases when the yarn linear density increases, and hairiness decreases when the fiber length increases.

Zhu and Ethridge [33] also found similar results. They showed that increasing fiber strength, length, and elongation would reduce hairiness for both ring and rotor spun yarns, whereas, increasing fiber maturity increases hairiness for both ring and rotor spun yarns. Faulkner [7] results contradict this finding. He found that mature kind of cotton were less hairy compared to immature cotton. A certain level of hairiness in the yarn is unavoidable because of the practical limitations of mechanical processing.

Fig. 6.7 Uster tester 6, image taken by Dr. Hua Wang during a factory visit

Therefore, spinners are interested to know the effect of fiber properties on yarn hairiness while selecting suitable raw materials.

6.8 Conclusion

The multibillion cotton supply chain starting from the cotton field to high-end fashion retailers need a careful understanding of the quality of cotton fiber. The quality of cotton fiber depends both on fiber genetics as well as environmental and soil conditions. The better quality of cotton products can't be achieved without measuring and controlling each quality parameter of cotton fiber. Multiple fiber testing equipments are available for accurately testing the cotton quality parameters. Cotton fiber characteristics and their relationships with yarn and fabric quality are critical to producing high-quality textile articles. Parameters such as maturity, fineness, micronaire (mic), length, strength, and length uniformity are determinantal for the market valuation of cotton fiber. Nowadays, the High Volume Instrument (HVI) and Advanced Fibre Information System (AFIS) are the two main instruments used to measure cotton fiber quality. HVI measures micronaire, Upper Half Mean Length (UHML), strength, elongation, color, and trash, while, AFIS measures maturity, fineness, length, neps, short fiber content, immature fibers and trash. The continuous research in the field of cotton fiber is enhancing our knowledge and opening new dimensions for innovation. Producing good quality with minimum resources and wastage can help to improve processing efficiency and increased margins for all stakeholders in the complete cotton supply chain.

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Chapter 7
Cotton Contamination

Biruk Fentahun Adamu and Bewuket Teshome Wagaye

Abstract Cotton is one of the most widely used and comfortable fiber for textile and apparel. Among the different parameters that determine the quality of cotton, cotton contamination is one key factor that also determines its price. This chapter includes what cotton contamination is and constitutes, the origins and kinds of cotton contaminants, effects of contaminants on cotton processing, and the different methods used to detect cotton contaminants. Cotton contamination is that the presence of an impurity, or another undesirable component that spoils, corrupts, infects, makes unfit, or makes inferior a product. Therefore, detecting and eliminating cotton contaminations as timely as possible before processing or within the process is essential. The different techniques of detecting contaminants are discussed in detail. The methods used for detecting cotton contaminations are generally classified as manual, gravimetric, electro-optical, and machine vision methods.

Keywords Cotton · Contamination · Foreign materials · Contamination detection

7.1 Background

7.1.1 Introduction

Cotton fiber shares over 50% economic significance in the world market, extensively used cellulosic fiber amongst all fibers used for textile and apparel. The emerging and manufacturing of new fibers as micro-denier like polyesters and nylons, elastomeric (spandex), and lyocell fibers are computing with cotton fiber. There must be

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consideration of the structural formation of fiber to compute the inter-fiber attractiveness of cotton fiber with others, the chemistry, the significant improvements, process innovation, and product diversity with others [1].

From all fibers used for textile and apparel, cotton is the most acceptable by textile consumers; this is because of its unique properties over other fibers. The advantages of cotton fiber over others are good absorption, biodegradability, breathing, heat resistance, and non-allergenic properties. In addition to textile and apparel, it has lots of applications as used in protection (UV, ray protection, climate control), care(antimicrobial or antifungal finishing, transfer systems with medical or cosmetic substances) and well-being (deodorizing effects, easy-care, climate control) or medical applications [2]. Worldwide, the production of total cotton is approximately 25 million tons annually. The top ten countries that are producing cotton are India, China, United States, Pakistan, Brazil, Australia, Uzbekistan, Turkey, Turkmenistan, and Burkina Faso [3].

Nowadays, modern spinning mills are growing in terms of machine speed, automation, and staple value. These will need the quality of cotton to be high. The quality of cotton fibers is affected by fiber plant growing conditions, genetic nature of the fiber, fiber picking practices, transportation practices, pre-cleaning, gin kind, setting, adjustment and conditions, lint cleanup and control of lint from the gin stand to the baling performs. Ginning plays a vital role in cotton quality preservation [2]. The essential cotton fiber quality parameters are fiber span length and length uniformity, fiber strength, fineness, color rating, the existence of foreign matters(presence of contaminants inside the fiber), i.e., contamination of fiber [1].

Cotton fiber quality and its price are profoundly affected and determined by contaminants present in cotton. One foreign fiber contamination may cause a decrease in the final produced yarn quality, material/clothes, or even there may be a complete rejection of the whole batch. The value/price of cotton is significantly determined by the cotton fiber quality (its color, length, strength, fitness) and degree of contamination.

Therefore, nowadays, contamination is a burning issue in the world of textile, particularly in the cotton process sector. The presence of contamination in the final product results in the degradation of quality. Therefore, contamination issues are a threat to the business throughout the last decade, and it is prevailing at the current additionally among all the areas of the textile sector [4].

7.1.2 What is Cotton Contamination?

Generally speaking, contamination is that the presence of an impurity, or another undesirable component that spoils, corrupts, infects, makes unfit, or makes inferior a product, body, natural atmosphere, and workplace. In the field of textile, cotton contamination is often defined or expressed in numerous ways in which the most acceptable typical conception of cotton contamination is that the presence of trash/foreign matter (organic or inorganic) within the cotton fiber (see Fig. 7.1).

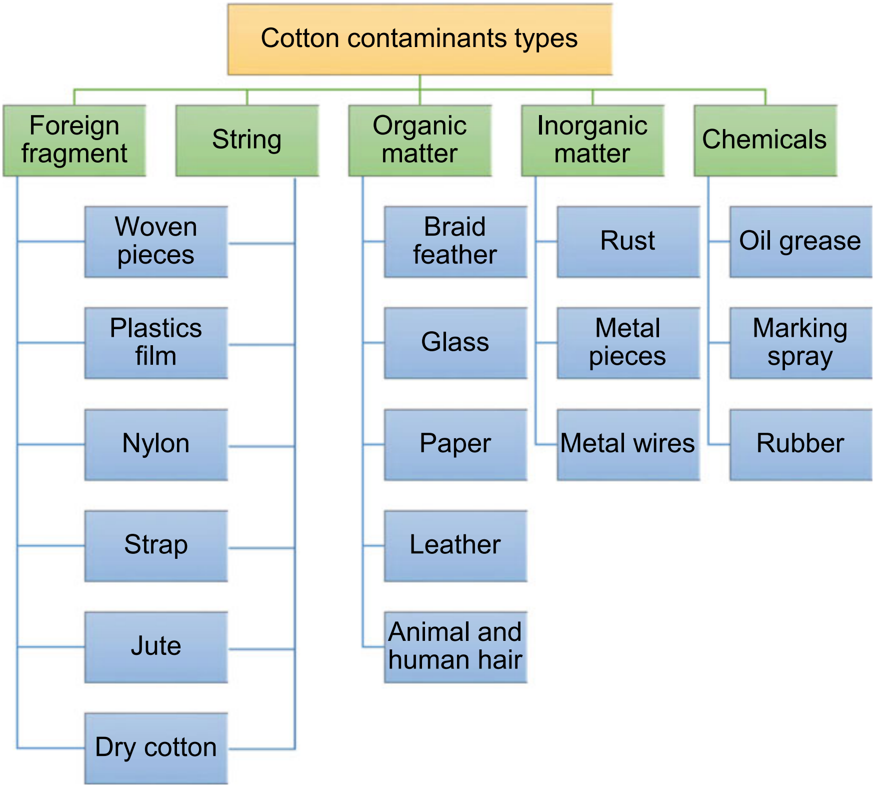

Fig. 7.1 Types of cotton contaminants

Foreign material is associated with impurity, which gets unintentionally mixed with cotton within the harvest and post-harvest processes [5]. The mixing of foreign materials through the product at the production, handling, in the storage is termed as contamination. Some cotton fiber contaminants are like animal fiber, polypropylene twines, field sheets, plant leaves, human hair, plastics, and leather. Cotton contamination in two different textile products are shown in Fig. 7.2.

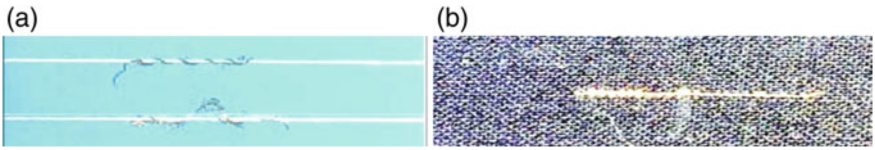

Fig. 7.2 Cotton contamination in two different textile products. **a** Cotton contaminated yarn, **b** cotton contaminated fabric

Various individuals reveal various ideas concerning what contamination constitutes in cotton. The most accepted organization defining what cotton contamination constitutes is the International Textile Makers' Federation (ITMF). ITMF offers survey form on contamination of cotton in an exceedingly helpful qualitative manner once in two years/each alternative year starting from 1989, has been surveying spinners on cotton contamination worldwide.

Cotton manufacturers, merchants, and spinners are benefited from the ITMF survey to remain on their track of contamination levels of the cottons they handle and additionally helps them to formulate contamination management measures. In the year 2016, the level of cotton contamination is extremely unclean, as observed by the spinning mills worldwide, as it was surveyed in 2016, the contamination is decreased from 26 to 23% as compared to the previous 2013, according to ITMF study [6]. Sluijs and Hunter have presented the percentage of contaminants in cotton worldwide from 1989 to 2016 [7]. Different cotton contaminations are shown in Fig. 7.3. The worldwide percentages per contamination class recorded throughout the numerous surveys were put into one place. In the survey year of 2016, organic materials like feathers, leaves, paper, and leather are the most kind of cotton contaminations, which increase progressively as a proportion of entire contamination from 30% in the year 1989 to 55% in the year 2013, then decreased to 47% in the year 2016. The second most predominant contaminants are contaminants of woven fabric and strings; next is jute originated from bale covers and selecting luggage: however, additionally from

Fig. 7.3 Different cotton contaminations

clothing, cleanup pieces, and module cords. The future uppermost contributor probably is inorganic like sand/mud, rust, and metal wires, which is followed by oily chemical substances like grease and oil, rubber, and tar [7].

7.2 Origin and Kinds of Cotton Contamination

Cotton contaminations cannot originate or grown inside cotton balls within the cotton plant; instead, contaminations to raw cotton come almost at each stage, which means from cotton harvesting area to the ginning and spinning processes. Personal operations all through picking, ginning and baling, and even in spinning processes, may add many types of cotton contaminants into the cotton bale [1]. Some of the common categories of cotton contaminants are shown in Table 7.1.

ITMF, in its survey of cotton contaminants from spinning mills, categorize cotton contamination sources in to five basic source categories consisting of varieties of contaminations (as shown in Fig. 7.4). The contaminants may come from a couple of sources, for instance, fragments of seed coat can be due by and large to an inherent tendency for portions of the seed coat to come back unfastened through fiber or else might be due to an insufficient ginning method typically which routinely breakdowns the seeds. The primary source of immature fibers is vegetative in the case of genetic or climatic reasons are dominant; it can be because of insect harm to the growing cotton bolls [1, 6].

In the ITMF survey, the furthermost cotton contaminants are fabrics, strings, organic matter, inorganic matter, and chemicals as main categories (see Fig. 7.4). Under fabrics, contaminants, woven and plastic films, jute, and cotton are included. Strings types of contaminants are made up of plain-woven plastics, film, and jute. Organic contaminants include paper, leaves, feathers, leather, whereas inorganic contaminants include sand, dust, rust, metal wire, and chemicals contaminants contains rubber, grease, oil, tar, stamp color.

Table 7.1 Categories of cotton contaminant [7]

White contaminants	Alien fibers	Colored objects	Oily substances	Dense objects
White plastic fabric White plastic strings White/transparent Plastic film	Hair Feather Colored cotton fibers Coir fibers Colored plastic fibers	Colored cotton fabric Colored cotton yarn Jute fabric Jute yarn Coir yarn Colored plastic fabric Colored plastic string, film	Sticks/twigs Leaves Oily/rusty/black cotton clumps Stamp colored/yellow cotton Tar/crease-affected cotton clumps	Metal pieces Paper Stand, stones Leather bits Wooden pieces

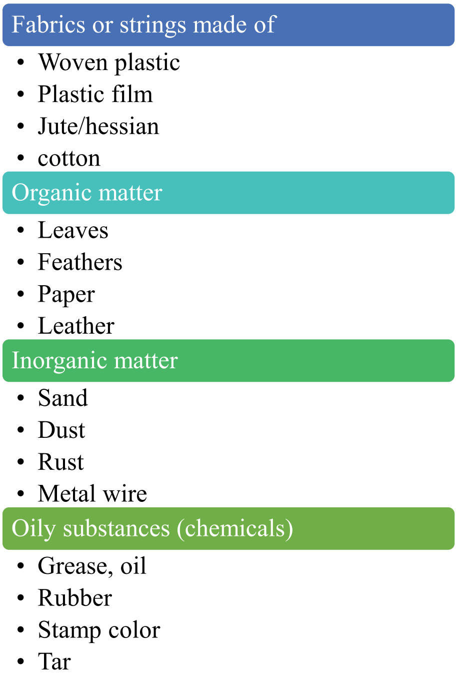

Fig. 7.4 Category and types of contamination according to ITMF [7]

In general, cotton contamination sources or causes could be mechanical/handling and natural (Fig. 7.5). Machine insufficiencies and blunders may contaminate the

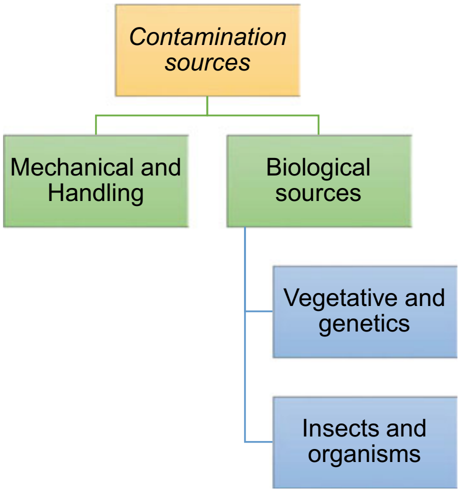

Fig. 7.5 Manufacturing and biological contamination sources

mechanical/handling sources. The biological sources typically partition into vegetative/hereditary and insect/organisms. Among the contaminations, either by mechanical or biological sources, are foreign materials like filaments, yarns, textures, paper, oil, metal, rust, plastic, trashes like a leaf, bark, bracts, non-cotton vegetation, motes, seeds and seed-coat fragments, earth and dust, insect sugars, physiological sugars, neps, short fibers, dead/immature fibers, discoloration.

In general, the types of cotton contaminations may be extensively classified into two classes: fibrous contaminant and non-fibrous contaminant. The weight of these types of contaminants (gram/ton of cotton) will vary from cotton to cotton of different origins. The fibrous contaminants account for about 60–85% of the total contaminants [2].

7.2.1 Fibrous Contaminants

Fibrous contaminants are contaminants that might be fibers other than cotton. These contaminants have a comparable appearance as cotton, which constitutes cotton and plant-related (honeydew, leaves, stems, grass, bark), human hair, polypropylene and polyethylene woven fabrics, feathers, dyed pieces of cotton yarn and jute. These kinds of contaminations are hard for spinners due to tough to split from cotton easily because they have nearly the same buoyancy as cotton fiber. As a result, as these are fibrous, they can be spun in to the yarn structure. Therefore, kind fibrous contaminants are the most dreadful factor of unnecessary contaminants and are horrible [1, 6].

Cleaning rags, cloth hats, and other substances may be left inside or around gin, close to the harvesting and module, which may be dragged into the ginning machine and cut together by the gin; this may position small portions of contaminant inside the ginned lint. If it is assumed that one bale is contaminated and mixed with 25–50 different clean bales on the manufacturing unit, there will be a high loss in acceptability in the quality of the product. Although researches show, the current bale packing resources remain not a severe cause of contamination, in some fabric factories, those substances may also be the possible infection supply. Other potential sources are formed while manufacturers, ginners, and storemen are marking seed cotton modules and packaged bales by ordinary paint, which cannot be removed at the ginning or yarn processing. These stained cotton now shows as a complaint in the final product of yarn or textiles. However, these problems could be escaped via the use of textile friendly marking stock currently on the market. Parts of bale ties, machine elements, and other tools can grow to be trapped within the lint at the gin and placed at the inner cotton bales that could contaminate cotton fiber, besides posing a fire risk, such materials can significantly damage mill device. Fabric and string contaminants primarily begin from module covers, plastic shopping sacks, agricultural protection film, plastic twine, and water plumbing material.

7.2.2 Non-fibrous Contaminants

Non-fibrous cotton contaminants consist of paper, chocolate wrappings, ropes, stones, metal wires, nuts and fastens, pins, apparatuses parts, rubber, leathers, bugs, microbes, which can be one way or the other easier to put off inside the spinning procedure. However, these can purpose damage to system components. Microbes are contaminants going on throughout crop growth and the next garage evidently in cotton, which could have a damaging effect on the structural excellent of cotton lint [2, 8].

Tying up module covers by plastic cord corduroy or rope leads the module covers to deteriorate and tear, leaving portions of a plastic parcel of charge plate on seed cotton as contamination. These plastic cords or rope parts may contaminant some cotton bales if they enter the gin machine. Plastic ditch liners left within the field might also be picked up by using picking apparatus and grow to be jumbled through seed cotton, and if they are not removed will go through gin together with cottonseed, turn out to be torn and continue to be with the ginned lint.

Black rubber doffers in picker's spindle and moistener pads and non-rubber doffer materials can contaminate cotton. The plate of black rubber doffer might produce some small black particles that are not noticeable in seed cotton. Though there are also non-contaminated doffers manufactured, some pickers have not informed about it, and they must pay great attention for a particular spindle to doffer clearance, misalignment of doffers, and spindles cause small doffer particles to be ground off and left in seed cotton. The rubber particles nearly continuously go undetected until the costly processes of spinning, weaving or knitting, scouring, and bleaching is completed resulting in rubber-blemished fabrics or garments.

There is some evidence from the mills that sticky cotton drawn to lubricates on cotton. If the lubricant on cotton is excessive can causes problems in the processing of textile industries since cotton may stick and wrap on mill equipment instead. One believes for oil to be in cotton is excessive picker oils in picker moistening systems, which may also increase fire hazards, become sticky that makes obstacles in rollers, wastage of dying material, and requires extra efforts at the cleaning process that unnecessarily inflates cost.

7.3 Effect of Cotton Contamination on Cotton Processing

There is a negative impact of contamination in the cotton process, yarn, and fabric. The contaminants can increase processing downtime, damage machine parts, increase workload, increases manpower, decreases product quality resulting in lower in the price of the product, decrease efficiency, and performance of the spinners and weavers. If the cotton is contaminated, there is a tendency of cotton to develop sticky that makes the interruption of different rollers, the dying material to be wastage which needs additional energies on cleaning that increase cost, also next to cleaning the remaining embedded contaminated yarn segments might affect the quality and values of cotton fiber. If there is excess oil on cotton lint, the cotton could stick and wrap on machines instead of going proficiently, which causes processing problems in textile mills. Contamination, even a particular foreign fiber, might lead to a quality reduction of yarn, fabric, or garments or the total rejection of an entire batch. It may cause roughness of the relationship between the cultivators, ginners, suppliers, and textile and clothing factories [1, 7]. Measures to reduce cotton contamination are:

- Introducing uniform cotton-picking storage and marketing.
- Using cloth bags instead of jute and fabric.
- Picking cotton fibers in the appropriate time.
- Use metal body open trolleys for quick transportation of cotton from field to factories.
- Luggage must be unfastened by unsewing as a replacement for cutting twine in to small pieces, and luggage should not be beaten on the heap; instead, it should be done separately, and obtained cotton should be adequately cleaned to be added in a heap.
- Cotton fiber moisture must be preserved at 8% and must be perceived carefully by a moisture meter.

7.4 Detection and Controlling Systems of Cotton Contamination

Cotton must pass through various processes or stages during a spinning mill to manufacture yarn from fiber. During these processes, several spinning machines will mechanically reduce the foreign matters in to small pieces, which may not be detected in regular mill processing situations and only come to be visible. In contrast, the assembly process is disturbed by yarn breakdown in spinning or else when the yarn is prepared to manufacture the fabric. Therefore, the fabric is subjected to regular internal control inspection. Cotton contamination denotes a high cost to the yarn manufacturing process. Thus, it is vital to detect and remove timely within the progression as possible [9].

Before cotton fiber are often converted to yarn, the unprocessed cotton fiber necessity to be arranged to eliminate contaminations, cotton contaminants or foreign particles are usually noticeably differentiated from the cotton fibers via color, contrast and construction, lightness, and transparency. For example, foreign fibers like polyethylene (PE) or polypropylene (PP) films are often light and transparent, which makes them difficult to detect using conventional foreign fiber separators. Even the presence of little foreign fibers in cotton makes cotton fibers to look as a discoloration within the fabric dropping its price. These foreign fibers may lead to excessive economic loss for the textile sector when they reach in finished cotton products.

Cotton contamination measurement and detection may be done in the laboratory or non-laboratory, i.e., within the field and before the spinning processes. For casing and commercial trade purposes, laboratory cotton contamination measurements are used. Considerable attention has been given for non-laboratory measurements and detection methods, especially before fiber processing into yarns stages. Several many quality measurement methods are developed either at-line or on-line from breeding/field measurements to post-harvest operations. The most quality measurements that will be done in cotton ginning processes are fiber color, trash, and moisture, and plastic contamination.

Challenges in the detection of cotton contaminants are many in kind, their unpredictable size, shape, position, invisibility, and the same color as cotton fiber. There are some ways of detecting various cotton contaminants, at which, from time to time, there's a rise in detection technical development. Manual vision technic is the oldest one, which is used within the past many years, but nowadays, a high advanced contamination measurement and detection sensors also are developed. Generally, the methods are often divided in to manual vision method, gravimetric mechanical method, ultrasonic and sensor-based, and machine vision methods.

7.4.1 Manual Vision Method

This method is the oldest method of detection of cotton contaminants that are employed to detect cotton contaminants based on especially their color and contrast in contrast to cotton at little scales. The abundant workforce is required within the whole method. It takes much time, thus very costly, and the precision is also terribly low [10]. Some range of spinning mills area unit is currently using to see and take away contamination from each bale of cotton before it is re-packed then allowed for the process within the spinning mill.

The manual vision method is implemented from the beginning of bale by employing an opener with a spikey mesh for the opening of the cotton fiber before the manual arrangement. In countries where labor or workforce value is low, use a substantial amount of persons; manual vision technique is employed. Manual cotton contamination removal lines are going to be designed in a particular method of arrangement to notice even very slight contaminants in cotton packages simply. The operators/cleaners are going to be engaged within the manual cleanup area unit given a comfortable seat, good table with wire mesh to de-dust and apart with a white surface, and proper lighting to detect colored cotton contamination [2].

This method has its advantages, one of which is the removal of contaminants to the tune of 98–99% before feeding the cotton to blow room, and it also prevents pulverization of contaminants. The other advantages are less fiber injury, effective elimination of sand and mud, a decrease in viscosity, load reduction on electronic clearers and improved winding effectiveness, correct information, and degree of contaminants in cotton. The only disadvantage is that the extra value concerned with cotton contamination control function is more labor is needed, more power consumption, more material handling, and inventory is required [2]. In this method, it's tough to view and categorize the contaminants because of irregular size, irregular shape, and location. As a result, automatic instruments for contamination detection and removal in cotton areas are currently developed to supply high performance and accuracy [11].

7.4.2 Gravimetric Method

The principle of detection and removing contaminants by the gravimetric method is the use of gravity principle solely, which is mechanical. During this method, the contamination from cotton will be removed as a result of gravity solely. The visualization and sorting systems will be synchronal through the movement of catch on the conveyor, and associate degree encoder is put in at the shift of the conveyor. Here solely weighty contaminants as compared to cotton may be removed easily. The effectiveness of this method is a smaller amount due to a load of mechanical components [12, 13].

7.4.3 Electro-optical Method

The electro-optical technique is appropriate for internal depth detection of all the cotton takings in an exceedingly cotton processing mill. In the method, the digital image method is employed; this can be one of the best techniques for the elimination of contaminations [5]. In the blow room machines, there are detection devices for contamination built-in that detect huge contaminants early, thus preventing contaminants from being pulverized in the next processes. Though, contaminants lower than one square centimeter cannot be detected. Approximately 60–65% of the contaminants will be removed in the blow-room. However, contaminants of single fiber-like hair, scrappy feathers, and little plastic fibers cannot be detected. In the winding process, finer contaminants will be removed to the tune from 80 to 85% at the value of serious call in the effectiveness of winding and raised weak points within the yarn. The bulk of fine hair and fine plastic fibers still withstand within the yarn [2].

An electronic device to remove contaminations are required at blow room to reduce the contamination in spinning and winding that needs high investments and incredibly masterful specialists to handle and monitor them. The limitations to electronic detection are dependent on the speed of the method and buoyancy, size, and color shade of contaminants [2, 13]. There are different types of sensors used to detect foreign materials from cotton fibers, one of which is a photo and ultrasonic sensors. Photosensors can detect the brightness of materials in the passing flow of fibrous tufts and are relatively cheap sensors. While the ultrasonic sensors can detect contaminants through sound-reflecting surfaces, however, could not detect like threads and strings. Another sensor is a color sensor or one charged couple device (1-CCD) cameras with one CCD chip, at which their detection sensitivity depends on the camera's resolution and camera scanning width. Since this camera work with three adjacent scan lines green, red and blue, the color recognition this color sensor is restricted and results in color noise effect. The highest-end approach camera sensors (3-CCD sensor cameras) are used to for foreign fiber detection, which is much more effective, even if they are expensive. In these sensors, 3 CCD camera sensors, the three primary colors, red, green, and blue, will be separated by a prism and, at the same time, directed into three CCD chips. Since this is a simultaneous process, the variable speed of materials in the cotton fiber flow has no longer a negative effect.

7.4.4 Acoustic Sensor Combined with an Optical Reflective Sensor

The optical sensors will measure and detect contaminations based on typical brightness of staple and recognize opaque colors as contaminations. The optical sensors cannot detect or see the hidden contaminations found within the cotton tufts but can only detect or see visible ones. While the sonic or acoustic sensor measures and detects based on the difference in density of the contaminants with cotton, especially useful to detect colorless contaminants like light-colored polypropylene and polyethylene contaminants which have a different density with cotton. Besides, in acoustic sensors since its acoustic, some waves can penetrate through the cotton tufts, at which time the unseen contaminations can be detected or seen easily. The commercialized sensors working based on this system are Loptex Italian S.R.L and Vetal systems [14].

This technique of measuring and detecting contaminations has some advantages. It can measure and detect contamination through optic and sonic sensors. Consequently, contaminants having different density with cotton and colored contaminants can be detected. This technique is healthy and appropriate used in the blow room line setting. The design of the waste container and, therefore, the measuring field for the elimination of air turbulence generated by values air blasts just in case of a high intervention rate. There is a need to measure the speed of cotton flocks flow by speed meter to assure high accuracy and precision on the contamination elimination process. In this technique, there is a low amount of excellent fiber loss, not more than 0.2% of the entire amount of cotton production.

7.5 Cotton Contamination Measurement Systems

7.5.1 The Visible Light with UV, Polarized Light, and Multiple Detectors Method

This technique is grounded on an optical method, which uses three light sources, visible (white) light together with UV and polarized light sources. This system combines light sources having different wavelengths (both visible and UV light) and different polarization states, meaning that polarized/unpolarized states to notice and detect contaminants in cotton fiber. Here the detection is using combined different lighting states without the use of cameras, inspection chambers, glass channels, or evaluating components having to be present in duplicate or without the UV light and polarized light interfering with one another. This system is built and suitable in the early stage blow room lines opening, cleaning for cotton spinning mills, and short-staple carding machines. This method is commercially manufactured by Trützschler GmbH & Co. KG [14].

7.5.2 Using Different Illumination Methods

The kind of illumination used is another essential factor to determine and detect contaminants. Techniques by using cameras and the human eye would only detect contaminants that differ from cotton in terms of color, contrast, or luster structure. Because of this reason, a different illumination can be applied in the detection of foreign fibers in cotton. Nowadays, using a standard illumination with fluorescent tubes operating in reflected light mode is standard and best practice.

Polarized transmitted light can detect differences in surface luster with polarized reflected light, and corresponding camera filters differences in the surface luster of foreign materials. This is an ideal technique used for detecting transparent and semi-transparent contaminants like pieces of polyester fibers/fabrics or polypropylene fabric from cotton bale packaging. In the system, the raw cotton passing through will be illuminated under polarized light, ultraviolet (UV) light, which makes the foreign plastic fibers to appear as colored, in this time, these foreign fibers will be often distinguished from the raw cotton and can be separated easily. The system has some limitations that there are dull contaminants that cannot be detected by this system.

Another illumination method is using a diffused illumination method which uses ultra-fast CCD cameras to detect cotton fiber contaminants. Four high-resolution CCD line cameras will observe the individual cotton tufts and obtain cotton images from both edges simultaneously, hence improves the detection efficiency of foreign fibers within the cotton tuft. The technique features a transparent channel where cotton tufts are diffusely illuminated within the inspection zone. The deviation in color and size expressed by contaminant width (number of pixels) and length (number of scan lines) describes the contaminants in cotton fiber. There is a tolerance in color, which is defined by threshold levels (limits). Therefore, objects with a color value lower than this limit are considered as being a contaminant. The Cotton Sorter develops this technique by Barco Vision; existing blow-room lines have often installed this technique without adding any fan capacity to elevate the cotton and drop it through the inspection place [14].

7.5.3 Optical Reflective Techniques

This system is fundamental to detect plastic contaminants having a different reflective surface than cotton fibers. Plastic contaminant's surfaces are more likely to be secularly reflective or shiny surfaces while the cotton-based surface, like the surface of a fabric or natural contaminants, is more likely to be diffuse in its physical reflection characteristics. Here there are two detection systems developed by Jossi Systems AG, located in Switzerland. Vision Shield is one system that detects colored contaminants, and another system is called MagicEye M1, which can detect white and transparent cotton contaminations [14].

The cotton flow is irradiated alternately at many various orientations using various ways of illuminating and capturing contaminants to increase the chance of catching contaminant reflectance. One method is using two sorts of cameras, one is color, and the other is black and white cameras, synchronized with the lighting system, which comprises an alignment of LED light sources. All LEDs must be activated to make a balanced level (two dimensional) illumination can be achieved to detect colored contamination by the color camera [14].

7.5.4 Infrared and Near-Infrared Spectroscopy Technique

Some researchers develop a technique using an optimal wavelength imaging system to detect foreign fibers within the near-infrared spectroscopy area, i.e., from 750 to 2500 nm wavelength, the attempted is using infrared or near-infrared radiation for detecting cotton contamination. The technique is based on the truth that the spectral absorption and reflectance properties of different fibers are different [14].

There is a device developed which can measure the reflection or absorbance of wavelengths within the range of 400–2500 nm, i.e., by using a combination of the light wave of 400–700 nm and a near-infrared wave of 700–2500 nm patented by Jossi Systems AG in 1997. So far, it has never been commercialized or verified in profitable manufacturing.

There was also research that was done that uses fast Fourier transforms on the spectra, the optimum wavelength to detect foreign fibers, and, consequently, an optimum wavelength to illuminate and image contaminants. In this experiment, the best suitable wavelength taken was 940 nm, chosen for detecting and imaging of the proper range of foreign fibers of cotton. This technique comprises near-infrared CCD camera, double light sources (couples of LED array light sources within 940 nm band), and a computer equipped with a frame grabber. As soon as the cotton sample illuminated through light radiation of 940 nm, clear images of contaminants can be seen. But most of these kinds of techniques are within the research stage, and they may be used for laboratory studies [14]. Near-infrared and infrared chemical spectra application is also investigated to detect contaminants, though the signal response is unfulfilled by noise and resolution difficulties. Besides, spectrometer instruments are costly and generally impractical to use in tough ginning process applications [14].

Another research verified the use of an attenuated total reflectance—Fourier transform infrared spectral database and to amend the signal loss and insensitivity of direct radiation transmission/reflection techniques to recognize foreign matter in cotton. In the research, Fourier transform infrared spectra (reflectance mode) of retrieved foreign matter were collected and subsequently rapidly matched to an authentic spectrum during a spectral database. For the research, in the database, contaminants comprised are called "trash", cotton parts and grass plant parts; "foreign objects and materials", synthetic materials, organic materials, sugars, and inorganic materials. In the research, the pattern region from 1800 to 650 cm^{-1} or 5500–15,500 nm was selected to give the impression since it, in general, gives the upper matches. Nevertheless, the spectra of samples where the fingerprint region is weak or showed little features, the addition X–H stretch region of the spectrum from 3700 to 2700 cm^{-1} or from 2700 to 3700 nm to the search improved match quality to the database library [14].

7.5.5 Machine Vision Method

White and other contaminants that are similar to cotton fibers are tough to detect, and separate in cotton processing, thus require effective detection methods. A good solution for the detection and removal of these kinds of contaminants is the use of machine vision with a suitable algorithm, with recent advancements in the image capturing systems, segmentation, and feature extraction process.

The simple machine-vision based foreign fiber detection technique primarily contains a line scan camera, frame-grabber, personal computer, and high-pressure gas nozzle. The camera will capture the cotton fiber image, and then the image will be manipulated to diminish noise and to improve contrast. The manipulated images are segmented to differentiate foreign fibers based on the differences in image features of the cotton sample. The foreign fibers positions in the processed images are transferred to the separator to control the solenoid valves that switch the high pressure compressed air to be on or off to blow the foreign fibers off the cotton tufts. The system has main limitations on the PC, as the central processing unit takes a long time; this leads to foreign fibers to be undetected in the actual time of examination.

In this technique of detection, in image processing, image segmentation is a necessary stage that will extract features of objects by the partition of the image into meaningfully connected components. In current research developments, there are many image processing techniques algorisms proposed, such as using co-occurrence matrix features, x-ray microtomographic image analysis, wavelets, color space model, and optimal wavelength imaging.

One algorithm is through x-ray microtomographic image analysis using computer vision algorithms to detect and to classify the cotton contaminants with high resolution and accuracy. This method generates numerous views of cotton then reconstructed by a computer to obtain cross-sectional portions. These portions are then stacked up to produce a 3D view of internal and external structural details. This technique can be used with the fuzzy-logic-based classification scheme to create a highly accurate contaminant analysis tool [11, 15].

The wavelet image analysis method has outstanding features in terms of signal and image processing. Multiscale wavelets with different scales can examine cotton fiber images for the detection of contaminants. It can detect many signal characteristics such as signal trends, signal's high order discontinuous points, and self-similar properties, which is ignored by other analysis systems [11, 16]. There are different wavelengths for imaging of cotton and foreign fiber. The optimal wavelength imaging uses different wavelength values of cotton and foreign fibers to detect foreign fibers from the cotton sample. The near-infrared imaging technique can detect a wide range of foreign fibers in cotton, and an optimal wavelength imaging system will be developed with an image-processing algorithm [11, 16].

Contamination detection based on color space is another method like the RGB space model, YCbCr model, and HIS model. The color space model uses the extracted features of the standard cotton and channel background. The RGB space model uses three basic component values R, G, and B representing color which will be collected by image acquisition devices, then finally, these are used by color display devices. As the main limitation of the RGB color space model, the visual difference between two colors cannot be expressed as the distance between two color points, and a correlation between RGB is much high, and RGB space is sensitive to noise in the low-intensity area. Therefore, the YCbCr model is developed. In the YCbCr model, the pixel values of RGB space transferred into luminance Y, chrominance of blue Cb, and chrominance of red Cr. Therefore, the YCbCr model can process luminance and chrominance information separately by excavating the useful information of the original image as more as possible. There is an analysis done to compare HIS and YCbCr models and found that the HSI model is better than the YCbCr model in the way that the YCbCr model is unable to distinguish the white-colored contaminant fiber from standard cotton while HSI model could detect white-colored contaminant from cotton fiber [13, 16].

Since the white contaminants have the same color or close to the cotton color, they cannot efficiently be detected under the illumination of visible lights using existing machine vision systems. The solution to this problem is using an imaging method based on line lasers, under the illumination of a line laser the white contaminants and cotton will show a difference in optical characteristic on their surfaces. The algorithms are used according to features of the intensity of their reflected lights or distribution of the fluff around surfaces in images [17].

A new high-speed foreign fiber detection system is developed with machine vision for removing foreign fibers from raw cotton using optimal hardware components and appropriate algorithm designing. The system applied digital signal processor and field programmable gate array on image acquisition and processing illuminated by ultraviolet light using the specialized lens of the 3-charged coupled device camera. It is done to identify transparent objects like polyethylene and polypropylene fabric from cotton tuft flow under the fluorescent effect, until all foreign fibers that have been blown away safely by compressed air. To identify blocks like foreign fibers from cotton, an image segmentation algorithm based on a fast wavelet transform is developed. And canny detector is also developed to segment wire-like foreign fibers from raw cotton. The procedure naturally provides a color image segmentation method with a region growing algorithm for better adaptability [18].

7.5.6 Cotton Contamination Measurement Systems in the Laboratory

There are different instruments used in the laboratory for measuring cotton contaminants and foreign matters. Table 7.2 summarizes the type of instruments and type of contaminants measured by the typical instruments. These instruments are mostly used for commercial trade purposes, grading, and research purposes as well. The instruments will measure trash, neps, dirt, immature fibers, plant and insect sugars, short fibers with different detection techniques, for example, using image analysis, light analysis, visual inspection, manual weighing, and liquid chromatography methods.

The trash in cotton can be measured using a High Volume Instrument (HVI) and Premier AFT, AFIS, and premier rapid testers. The fastest and most widely used for measuring trash are HVI and Premier AFT instruments, which use an image analysis system, but they are the least precise and repeatable. Nevertheless, these methods are suitable numerical measuring apparatuses as compared to subjective human judgments. Uster AFIS also can measure trash, which works using a light scattering system. Premier Rapid tester can test trash particle size distribution. However, it cannot measure tiny particle sizes that the AFIS can measure. It remains with only six working units during its state of development. One advantage of premier rapid instrument is that it can measure large samples of fibers, approximately 10 g for premier rapid and approximately 0.5 g for the AFIS. Sampling error can indeed reduce only when larger samples or more replications are taken. Lintronics FCT is another instrument measuring total trash particles and size distributions which employs an image analysis system. Generally, currently, the class size of trash in Lintronics FCT is limited to be trash that is visible to the human eye. FCT use to a certain degree larger fiber samples, which are about 5 g. Uster MDTA instruments are the first instruments that separate the trash and dirt from the cotton lint mechanically.

Neps and seed coat fragments of cotton can be measured using Uster AFIS and Premier Rapid Tester instruments. The difference between these on measuring neps and seed coat fragments is on the size criteria and results in interpretive algorithms sensitivity they use with the electro-optical sensors. Lintronics FCT also can measure neps and seed coat fragments in terms of size, shape, and shade using interpretative algorithms with video images. Cotton short and immature fibers can be measured

Table 7.2 Cotton contamination measurement techniques in the laboratory

Type of instrument	Type of cotton contaminants							
	Trash	Dirt	Neps	Seed coat fragments	Short fibers	Immature fibers	Insect sugars	Plant sugars
USTER HVI	Uses image analysis				Uses light scattering			
Premier AFIT	Uses image analysis				Uses light scattering			
Uster AFIS	Uses light scattering	Uses light scattering	Uses light scattering	Uses light scattering	Uses light scattering	Uses light scattering		
Premier rapid tester	Uses light scattering	Uses light scattering	Uses light scattering	Uses light scattering	Uses light scattering	Uses light scattering		
Uster MDTA	Uses manual weighing							
Shirley Analyzer	Uses manual weighing							
Lintronics FCT	Uses image analysis		Uses image analysis	Uses image analysis			Uses light scattering	
CIRAD SCT							Uses visual inspection	
SDL H2SD							Uses image analysis	
HPLC							Uses liquid chromatography	Uses liquid chromatography

by the use of Uster AFIS, HVI, and premier rapid instruments. Both Uster HVI and Premier AFT can measure and estimate the content of short fibers; though, their reliability and repeatability are generally inadequate to consider them for either marketing or quality control decisions. The premier rapid tester is also can measure cotton short and immature fibers, but further development is essential.

The stickiness of cotton can be measured by using different methods like cotton thermal detector (SCT), Lintronics, and high-speed stickiness detector instruments. Measuring cotton fiber stickiness by sticky cotton Thermodetector is very slow and subjective (human operators count sticky spots) to use in the requirements of the worldwide marketplace. The high-speed stickiness detector (H2SD) can measure cotton fiber stickiness, which is developed next to the SCT instrument. H2SD can count and size the sticky spots in the cotton fiber sample, and it is automated to a remarkable degree incorporating a picture analysis system to count and size the sticky spots throughout a cotton fiber sample. Lintronics FCT is the first commercialized instrument to measure sticky spots contained in a cotton fiber sample.

The sugar level present in the cotton sample is determined by using the high performance liquid chromatography (HPLC) instrument at the laboratory level. Perhaps this is an integral measuring method of calibrating and interpreting results measured from the commercial stickiness apparatuses.

7.6 Conclusion

Cotton is one of the most widely used and comfortable fiber for textile and apparel. Among the different parameters that determine the quality of cotton, cotton contamination is one key factor that also determines its price. Cotton contamination is that the presence of an impurity, or another undesirable component that spoils, corrupts, infects, makes unfit, or makes inferior a product. It can be generalized that the most significant cotton contaminants are categorized in to fibrous and no-fibrous contaminants. The fibrous contaminants include cotton and plant-related (honeydew, leaves, stems, grass, bark) materials, human hair, woven polypropylene, and polyethylene materials, feathers, dyed cotton yarn pieces, and jute.

In contrast, non-fibrous contaminants include paper, chocolate wrappers, cables, stones, metallic wires, nuts, bolts, nails, ginning machines parts, rubber, leather-based, tin, bugs, and microbes. Contaminants have great significance in the final cotton product, as well as its price. Thus, it’s vital to detect and remove contamination as early as time within the process as possible. The different techniques or methods used to detect and remove contaminations are classified as manual, gravimetric, electro-optical, and machine vision.

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Chapter 8
Recent Advancements in Cotton Spinning

Nabi Bakhsh, Muhammad Qamar Khan, Arsalan Ahmad, and Tufail Hassan

Abstract In the modern era among industries, textile industries have played a key role in textile industries. The innovations in textile industries specialization in spinning provide the model of other sectors in modern machinery by increasing production rapidly with a small interval of time, leading the export sector and dominant the conventional spinning technology. The high modernization machines and robotics system invention in spinning technology in the modern era have almost replaced the traditional system of cotton spinning by saving time, increasing productivity, and decrease the overall principle cost. The highly efficient cotton spinning technology changed the conventional spinning technology through innovative spinning machinery. The highly efficient Crosol carding machine has been considered as the most efficient and highly innovative technology in the spinning era. In this book chapter, the highly innovative machines and use of robotics in spinning technology have been discussed, which reduces the time, reduces the yarn faults improve the quality of cotton yarn spinning.

Keywords Advanced spinning · Cotton-based · Low production time · Integrated system

8.1 Introduction

The term spinning may be defined as the process of conversion of natural or manmade fibers into yarn by twisting or other means of binding [1]. Spinning technology is considered as the world's oldest technology in which animals, plants, and synthetic fibers are drawn out and twisted to form yarn. Thousand years ago, by using simple tools, the fibers were spun. According to some historians, it was 20,000 years ago,

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totally spinning was done by hand [2]. Then the hand-wheel was developed for yarn production.

With the passage of time and ease for mankind, the spinning wheel was further improved, and the human becomes successful for omitting personal efforts. During the eighteenth and nineteenth centuries, the ring-spinning, flyer spinning, and Cap spinning machines were developed. However, outstanding to intensive efforts in the 1960s to 1970, some commercial spinning machines were designed, such as open-end spinning and Repco self-twisting machines. The ring-spinning is one of the most used techniques which is still used due to many more applications such as high strength yarn productions, fine count yarn, universally applicable for any material spun.

However, some of the ring-spinning has some drawbacks due to which there is need of some recent advancement in ring-spinning technology such as travelers high-speed damages the fibers, high energy consumptions, low production rate, and the new winding process is required to make bigger packages and more significant expenditure on machine maintenance. In 1967 the rotor spinning came into existence for practical use in the spinning mill. From an economic point of view, the production of rotor spinning is 4–10 times more than that of ring-spinning. The speed of the rotor is around 175,000 rpm.

However, the drawbacks of rotor spinning are considered as high air consumption and low yarn strength. Every step was taken towards modernization with minimum man-power. The modernization in spinning technology aims to achieve quality products at effective rates with nearly zero error.

All the products of the textile industry must be made of high quality and at a reasonable rate-to tolerate commercial success for a very long term. This process requires continuous modernization and development of innovative modern technology from raw material to end product. In this chapter, highly developed machines are discussed, which has a remarkable impact on time-saving, better yarn quality, and cost-effective (Table 8.1).

8.2 Blowroom

In the present day, the blowroom process in spinning technology has undergone a large significant degree of changes in terms of recovery of good fibers, degree of opening, the intensity of cleaning, reduced the number of machines, and removal of a large amount of contaminants. The quality of yarn depends upon the detection and removal of contaminants from cotton lint. The contaminants with similar to that of cotton such as white contaminants present into the cotton fibers are difficult to identify and separate during cleaning and opening, and it requires the efficient detection methods. During the processing stages, the machine vision with a suitable algorithm offers an excellent solution for detecting and removal contaminants. The primary purpose of the blowroom is opening and cleaning of textile material without any considerable loss of fibers. The use of the opening is to increase the volume

Table 8.1 Comparison of major cotton spinning systems [3]

Spinning system	Drafting	Strength impartation	Count (Ne)	Speed (m/min)
Ring	Roller	Mechanical process, true twist, high fiber migration	4–160	25
Rotor	Opening roller and aerodynamic	Mechanical process, true twist, surface with wrappers, low fiber migration	5–40	200
Air-jet (twin nozzles)	Roller	Aerodynamic process, false-twist, core twistless, surface with wrappers, fewer wrapper fibers, low fiber migration	15–60	300
Air-jet (single nozzle)	Roller	Aerodynamic process, false-twist, core twistless, surface with wrappers, more wrapper fibers, low fiber migration	8–40	400

of the material and to remove the impurities. The tuft size in blowroom in between 2–3 mg is considered as optimum, but 0.1 mg is achievable. The increase of opening and cleaning intensity also increases the neps level and fiber loss. So it is necessary for finding the optimum opening and cleaning. The modernization in blowroom will be discussed as under:

8.2.1 Difference Between Types of Plucking Roller of Automatic Bale Opener

In the textile industry, the trend of manual bale opener is almost replaced by automatic bale opener machines. Smaller tuft size is achieved through a bale opener, and better quality of opening and cleaning is performed. The manual bale opening process results in the variation of tuft size fed to bale opener. The automatic reciprocating bale opener is shown in Fig. 8.1.

Fig. 8.1 Automatic bale opener installed in the cotton spinning industry in Uzbekistan

8.2.2 Rieter Automatic Bale Opener

Rieter UNIflocA 11 consists of a single plucking roller known as take-off roller. The take-off roller and narrow grid cause a small tuft size. These rollers can be used for the processing of manmade and cotton fibers. The laydown material is regularly measured the profile by automatic bale opener.

8.2.3 Trützschler Automatic Bale Opener (BLENDOMAT BO-A)

Trutzschlers BLENDOMAT BO-A is fixed of with two plucking rollers with opposite rotating directions, but according to the travel direction of the machine at a time, the one plucking roller is raised while other is working. The plucking roller strips off the tufts by penetrating the bale surface while the three supporting rollers give a firm grip over the bales.

8.2.4 Marzoli Automatic Bale Opener (Super Blender)

The Marzoli automatic bale opening super blender consists of two plucking rollers with 254 blades contains each roller [4]. The four different mixings are performed on the automatic bale opener. The production of the machine with a working width of 2250 mm is considered as 1600 kg/h [5].

8.2.5 Lakshmi Bale Plucking Machine

The Lakshmi Automatic Bale Plucker LA 17/LA 28 fitted with double plucking rollers, and according to requirement, the depth of cut can be programmed; by varying the traverse speed, the variation in the product can be achieved and according to tuft size the grills of tuft size can be performed. The plucking rollers consists of replaceable strips with teeth, and its advantage is that it can be replaced in case of damage without any removing grills and reduces the downtime.

8.2.6 Compact Blowroom Line

Tuft size in the blowroom process is become smaller by using automatic bale opener, the Trutzschler compact blowroom has automatic bale opener, and multifunctional separator with waste refeeding, the less space and low energy consumption is required for transporting the materials to next machine.

8.2.7 Compact Blowroom Line of Trützschler

Trutzschler compact blowroom line consists of a multifunction separator, automatic bale opener, integrated mixer, and foreign part separator. It requires less energy consumption for transporting fiber tufts to the next machine and also less space.

8.2.8 Mote Knife with Suction in Place of Grid bar

In pre-carding and post carding zone, the trend of using mote-knife with an open slot was initially incorporated on a carding machine; nowadays, the same principle is also adopted by Trutzschler in cleaning machine on blowroom. It consists of a suction hood, mote knife, and deflector blade. Due to centrifugal force, the trash particles are released and are separated at knives, and due to suction pipe, the particles are taken away continuously and keeps the hood clean permanently. The setting of deflector blades depends upon the types of cotton processing. The deflector blades can be kept almost closed when the low degree of cleaning or when clean cotton is processed, but for high trashy cotton or a high degree of cleaning, it is fully opened and through the motor or manually the blade adjustment performed.

8.2.9 Mixing/Blending of Raw Material

The cotton fibers from ginning to the spinning mill are different from bale to bale, and these bales are mixed appropriately with spinning a yarn of better quality. And the blending of different fibers is also done correctly at the blowroom stage. The homogeneity mixing of materials depends upon the machine to machine, and when tuft form material is mixed, then better would be mixing in small tuft form. The better homogeneity would be when more number of reverse chutes in mixing equipment used. The two blenders also give better uniformity when working in series than one with a similar total capacity.

8.2.10 Color and Other Impurities Removal

The cotton, when it reaches the mill, it consists of natural as well as added contaminants. These contaminants can be removed either manually or mechanically. The machine sorting has great advantageous over manual sorting; it reduces the time does not depend upon the workers' sincerity. Thus modern blowroom line incorporates the machines which eliminate the impurities.

8.2.11 Barco Cotton Sorter for Detection and Removal of Contaminants in Raw Cotton

The Barco Vision cotton sorter consists of ultra-fast CCD cameras for contaminant detection from cotton raw material in blowroom line, and through high-speed air guns, it removes the contaminants, in an existing blowroom line. The system can be installed without adding any fan capacity for cotton elevating and drop it through the inspections zone. This system consists of a transparent tunnel where cotton is diffusely illuminated in the inspection zone and individual tufts observed by high-resolution CCD line cameras, which requires images from both sides and increase the detection capacity. The contaminants are considered as the deviation in size and color from raw cotton in terms of contaminant's length and width, color tolerances are determined through the threshold limit. The objects having below threshold limits are identified as a contaminant. The camera pixels are indicated horizontally on the x-axis, whereas the color level is indicated on the y-axis. A value of 255 shows the white, whereas zero indicates the black whereas normal cotton is close white level.

8.2.12 Rieter Vision Shield, Metal Shield, Fire Shield, and the Combo Shield

The Rieter blowroom line is fitted with a metal shield, fire shield, vision shield, and Combo Shield of JOSSI System AG for detecting the foreign particles. The function of the vision shield is for identifying and eliminating the foreign fibers, and metal shield detects any metal particles through signal processing and sensors. A metal shield also detects the metallic and non-metallic particles hidden in the tuft. The function of the fire shield is for detecting and diverting any incandescent particles and shut down the machine, and it also activates the various alarming functions.

8.2.13 Loptex Optosonic Sorter

The machine is equipped with Optical Sensors for detecting the colored contaminants and colorless materials through Acoustic Sensors. The raw material is firstly passed in front of acoustic sensors and after optical sensors. Acoustic sensors emit the Ultrasonic waves, and compact surface like plastic detects the contamination and reflecting the waves into the receiver.

8.2.14 Online Parameter Settings

In the blowroom line, one of the essential modernization brought is the online cleaning and opening parameters such as beater speed, the distance between beater and feed roller, the distance between grid bars and beater, and beater speed. The amount of waste extracted and cleaning intensity can be programmed while the machine is in the production state.

8.2.15 Trutzschler WASTECONTROL and CLEANCOMMANDER

The Trützschler's waste sensor WASTECONTROL BR-WCT is involved in a cleaner CLEANOMAT for measuring good fibers in waste. This system detects the waste quality and extent of the cleaning quality of cotton that can be optimized. It is showed that with CLEANOMAT cleaners, the actual achievable line lies very close to theoretical, i.e., the good cleaning with minimum good loss fibers.

8.3 Carding

The experts defined the card in a proverb as the heart of spinning and considered as well carded as a half spun, it indicates the importance of carding machine in textile spinning operation [6]. Besides the comber, the card machine not only performs the working of conversion but removes the seed coat, trash, short fibers, trash, and fragments [7]. The yarn quality is directly related to card sliver quality [2]. Carding is also responsible for fibers orientation in the sliver, and orientations of slivers are directly co-related with properties of yarn [8]. The working concept of the carding machine remained the same since 1770, but the production rate is continuous except drawframe the production rate is not matched with any machine, changing the reason behind the production improvement is nothing but due to the technological improvements [9]. The purpose of carding can be understood from Fig. 8.2.

Due to the improvements in the carding machine, not only it improves the yarn quality, but fabric quality is improved [10]. Due to the engineering precision and the latest generations in the carding machine, the better quality of sliver and yarn can be achieved [11]. Carding is considered as one of the most complex processes in spinning, the operations. Carding is the strong opening of materials into individual fibers, parallelization, and straightening of fibers, and removing of significant proportions of short fibers. The latest innovations in the carding process are increasing day by day and replacing the existing process. The following are innovations in carding process by:

The high productivity card Trutzschler TC07 is considered as a new generation card consists of parameters that ensure the high level of products as well as quality as compared to all existing cards**.** The Crosol carding machine has been proved to be the most suitable carding machine for high spinning technology [12]. The technological

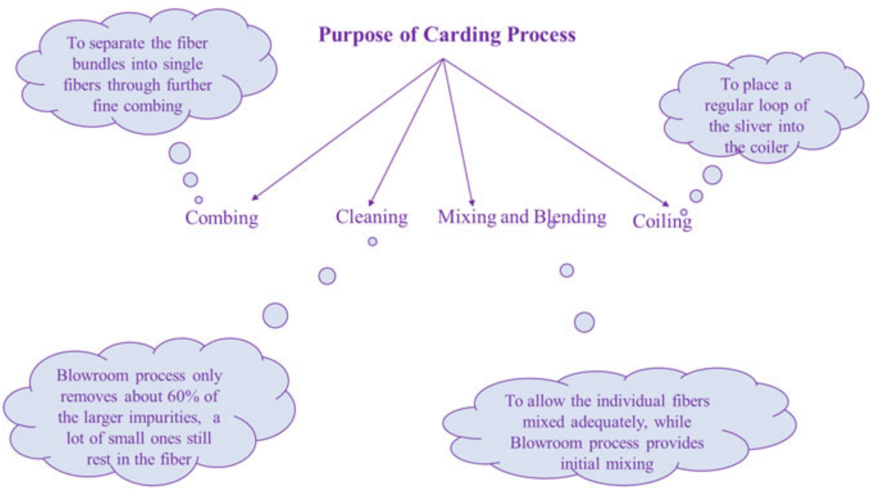

Fig. 8.2 The purpose of carding

development of the card on the yarn properties is analyzed, and the role of the new generation of the card for improving the quality of the yarn is also elucidated.

8.3.1 Neps Removal Efficiency (%) and Neps %

The removal of neps efficiency in C51 is much more as compared to other cards machine. The C51 Card machine removes 57% more neps as compare to other machines [13]. This could be due to better fiber parallelization and orientation in the sliver of the card. Also, because of this reason, the neps percentage in the yarn produced from the sliver of the C51 card becomes lower as compare to other card machines. As improvement in card technologies, neps removal efficiency improves.

8.3.2 Web-Cleaning Device

This device ensures reduced seed content. The drum surface airstream has a direct impact on card quality. The regularity of the web card is adversely affected by the disruption. This device consists of three cleaning units and six carding segments; the aluminum drum with a perfect profile provides a smooth surface and dimensional stability under high speed. The high productivity card TrutzschlerTC07 is considered as a new generation card consists of parameters that ensure the high level of products as well as quality as compared to all existing cards.

8.3.3 Nep Control Device

This system is online controlled and is used for detecting impurities of plant seed particles and neps. With the help of a video, camera images are transferred to a computer. This processing provides information on impurities. The main computer control system guides the vehicles to reach their destination, is viewed by all monitor operations, ensuring the connection card with drawframe.

8.4 Drawframe

Drawframe is the vital step in the spinning process by which the slivers are straightened doubled and leveled. In the process of drawframe by the passage of slivers through pair of rollers, the slivers are straightened, and each pair of the roller are moving faster than others. A modern drawframe (JWF1312B) by Shenyang Hongda Textile Machinery Co. Ltd is shown in Fig. 8.3. In modern drawing sets, there are three

Fig. 8.3 Drawframe Machine (JWF1312B) by Shenyang Hongda Textile Machinery Co. Ltd

passages of pin drafting and roving process. In the auto-leveler drawframe tongue, the online monitoring of sliver weight is performed through pneumatic transducers and other devices.

The regularities of slivers are produced by detecting variations at the feeding point with the help of auto-leveler at high- speed drawframe. This principle measures the auto-leveler at drawframe proceeds on an open control loop principle and the thickness of sliver through the groove and tongue roller. The sliver weight is online monitored in an auto leveler drawframe by pneumatic transducers and other online devices. The degree of unevenness is present in carded sliver when it is feed to drawframe. The drawframe improves the evenness over the short, medium, and long term. In yarn formation, drafting is a crucial stage for yarn quality. Each drafting process introduces the irregularities, and these irregularities degrade the final product of textiles. Some joint development in textile drawframe such as auto leveler, suction devices, and can changing system, with the electronic and mechanical improvements, are developing day by day to be more precise.

8.4.1 Auto Break Draft Setting

The break draft has an essential role in yarn quality, and it must be set correct ABECAUSE Incorrect break draft increases the U %. New Trutzschler drawframe technology optimizes the sliver in one minute by estimating the corresponding values of break draft and takes important parameters like fiber to metal friction and fiber to fiber friction, and break draft is calculated.

8.4.2 Clean Coil

In drawframe, the deposition of spin finish is on the bottom of the collar plate when processing causes the displacement of the sliver layer in the can. To avoid this production loss by frequently cleaning the can. Rieter has a honeycomb-like structure that causes a reduction in cleaning frequency depending on the type and quantity of finishing agents.

8.4.3 Pneumatic Pressure Head

The pressure for sliver can be controlled automatically through this technology, and better fiber quality could be achieved.

8.4.4 Tension Measuring System

There is a long path to travel when the card sliver is feed to drawframe, and due to frictional forces and weight of sliver, there will be tension variations, there are tension measuring sensors used to detect tension variations and adjust roller speed.

8.4.5 Short Term Auto-Levelers

In drawframe leveling takes place in entire speed range even during run-up after can change, short term leveling (SERVO DRAFT) remains in operational condition, Due to this, each meter of drawframe sliver has its optimum quality.

8.4.6 Use a Camera to Monitor the Sliver Quality

This camera is used for monitoring the sliver quality aspects such as fiber imperfection, irregularities, and arrangement; the output sliver is captured by the camera and compared utilizing image processing techniques. When imperfections occur, the machine is automatically adjusted for eliminating the variation of machine speed.

8.5 Simplex

On the simplex machine, the slivers are subjected to the attenuating process, and a small amount of twist is received by slivers and followed by winding on bobbins. This machine produces roving for the ring frame; a simplex-frame in a cotton spinning industry in Uzbekistan is shown in Fig. 8.4. The proper attenuation and twist of fibers are not correctly given in the drawframe. A perfect sliver is produced having proper attenuation and twist in the simplex machine, and the production cost of this machine is also increased, the recent development is going on in the simplex for reducing the cost of yarn.

Several recent developments of the simplex have to be known. The significant progress has been made in the winding system, drafting system, monitoring system, and roving package transport system. The drafting system provides the required drafts and attenuation of fibers in roving. For the wrong drafting and twisting, the different faults could have appeared, and during this process, the operators should be careful.

8.5.1 Flyer Speed

Earlier, the flyer was made up of steel, but recently, they are made up of light alloy. Previously the flyer's speed was usually 1000–1500 rpm, but modern flyer speed is up to 2000 rpm.

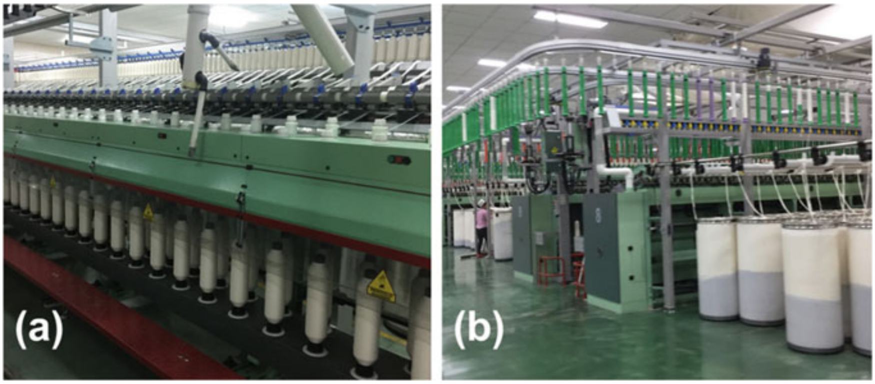

Fig. 8.4 Simplex-frame in a cotton spinning industry in Uzbekistan **a** front view **b** back view

Fig. 8.5 The roving bobbin transport system in a cotton spinning industry in Uzbekistan, **a** roving bobbins automatically being transported from simplex to ring frame, **b** roving bobbins has been installed to ring frame, and **c** empty roving bobbins automatically being shifted from ring-spinning frame to simplex

8.5.2 Roving Bobbin Transport System

From simplex to a ring-spinning machine, the roving bobbins are transported manually from the simplex to ring-spinning machine, often results in the roving damages, This problem is recently solved by the advancement of a roving bobbin transport system, which transport material, saving time and labor cost as compared to manual bobbin transport, as shown in Fig. 8.5.

8.5.3 Roving Stop Motions

The light barriers are used at the delivery of a drafting arrangement. At the delivery of the drafting arrangement, the light barriers are used. The light beam is usually focused straight to flyer tops. As a result of a roving break, the broken roving end spins around the flyer top or so-called 'hoods' form at the flyer top. This interferes with the light beam and causes the machine to be stopped.

8.5.4 Electronic Driving System

The Servomotors are used for driving the bobbin rails, bobbins, flyers. They are synchronized throughout the package built by the control system, this system is more advantageous as compared to the previous system because it requires no need for heavy counterweight for bobbin rail balancing, lower consumption of energy, and maintenance cost is reduced. Toyota uses three servomotors on simplex. One motor for flyer and drafting system and other for bobbin rail and bobbin drive.

8.5.5 Computer Monitoring Device

The Computer monitoring device is a tremendous advantage in the simplex machine. It measures the production rate of the machine. It can display the spindle speed of small to big riving and determines the variation of moving parts.

8.6 Ring-Spinning

In terms of efficiency, production and quality of yarn, the large numbers of improvement occurred in ring-spinning such as in air pipes, air suctions, and air conditioning requirements due to these changes the advantages are taking in terms of fine yarn count, high strength yarn and excellent in yarn evenness. The ring-spinning is conventional technology for yarn spinning, such as from wool, cotton, and synthetic fiber; a ring-spinning frame in a cotton spinning industry is shown in Fig. 8.6. During the

Fig. 8.6 Ring-spinning frame in a cotton spinning industry in Uzbekistan

last decades, there is the recent advancement in ring technology such as the spindle speed was increased up to the 20,000 rpm, for doffing of full bobbin the automation has been introduced, the roving feed stop motion and automatic creel of bobbins are the recent advancements in ring-spinning.

Nowadays, ring-spinning technology is the most widely used technique in terms of short spinning technology. The collective action of ring and traveler is applied for putting in the twist and for winding yarn on cops. However, the primary drawbacks of the twisting system are the friction lies between ring and traveler. This friction generates heat at higher speed and results in decreasing productivity. A magnetic bearing system that is based upon superconducting technology might be employed to overwhelm these limitations. This superconducting magnetic bearing is comprised of a circular superconductor with a durable magnetic ring.

8.6.1 Compact Spinning

The compact spinning is simply considered as the modifications of ring-spinning; without these spinning triangle, the ring yarns, which are spun on the ring frame, are considered as the minimum hairiness and high strength yarns.

8.6.2 Spinning Triangle

The inclinations of the drafting arrangement influence the sizes of the spinning triangle, as presented in Fig. 8.7. A long spinning triangle directs the significant weak point more end break. While the short triangle shows the small weak points and fewer end breaks, if it is short beyond the limit, the fibers are strongly deflected to bind.

8.6.3 Principle of Superconducting Magnetic Bearing

The Superconducting magnetic bearing is the co-operating force between the negotiator system (permanent magnet) and high- temperature superconductor components. These bearings act as self-stabilizing as completely passive devices without any necessity for positioned sensing and control. A permanent magnet is located over a superconductor at a distance of few millimeters. The flux lines of the permanent magnet, which are initiated through superconductors, are restrained by Nanocrystalline shortcomings. This is implemented by cooling the superconductor at −196 ºC with the liquid nitrogen called as the flux pinning effect. The superconducting magnetic bearing system has advantageous over the conventional ring/traveler system that it does not need the extra sensor to run, the construction of

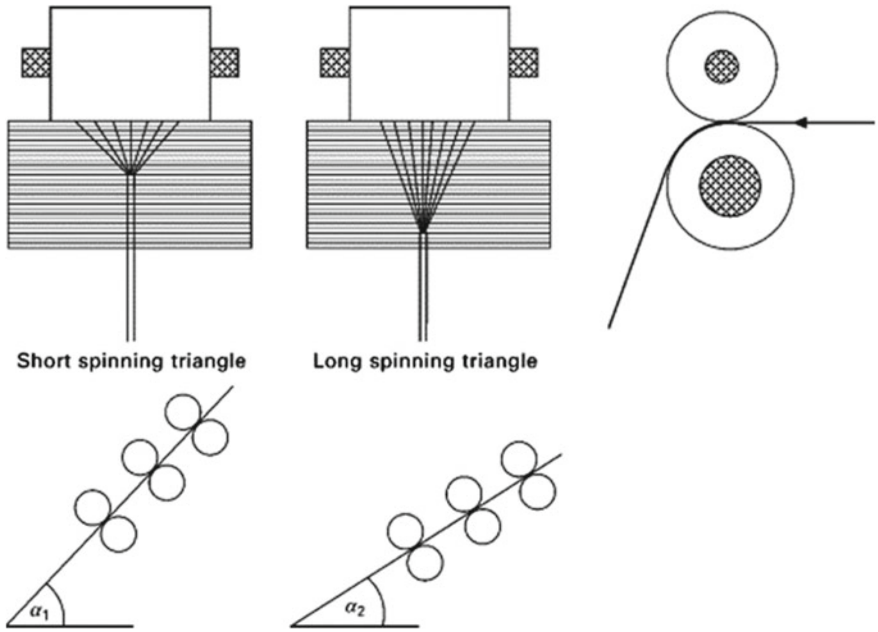

Fig. 8.7 The relation between the inclinations of the drafting arrangement and sizes of the spinning triangle [14] (Fig. 2.8 on page 56) Copyright © 2010 Woodhead Publishing Limited

this kind of bearing is simple, this friction-free magnetic bearing can increase the productivity of ring-spinning machine because of its stable rotation at high speed [15].

8.7 Rotor Spinning

The fully automatic rotor spinning machine sets new standards in terms of its high production, utilization of raw materials with improved methods, and low consumption of energy. At each spinning position technology, the state of art-automation technology increases efficiency and flexibility. Due to the recent advancement of Box S 70 ensures the yarn tenacity and high spinning stability. The uniform yarn quality with yarn-like piecings provides the best results for further processing. The improvement in rotor spinning has increases productivity by 8–10 times of ring-spinning. Due to the recent advancement in rotor spinning, the cost benefits increases and causes a reduction in capital costs. Rotor diameter has to be reduced at high rotor speeds to keep down power consumption. Increased twin disk diameter, magnetic bearing, and automatic evacuation of filter waste and cooling systems for inverter and motor reduce power consumption.

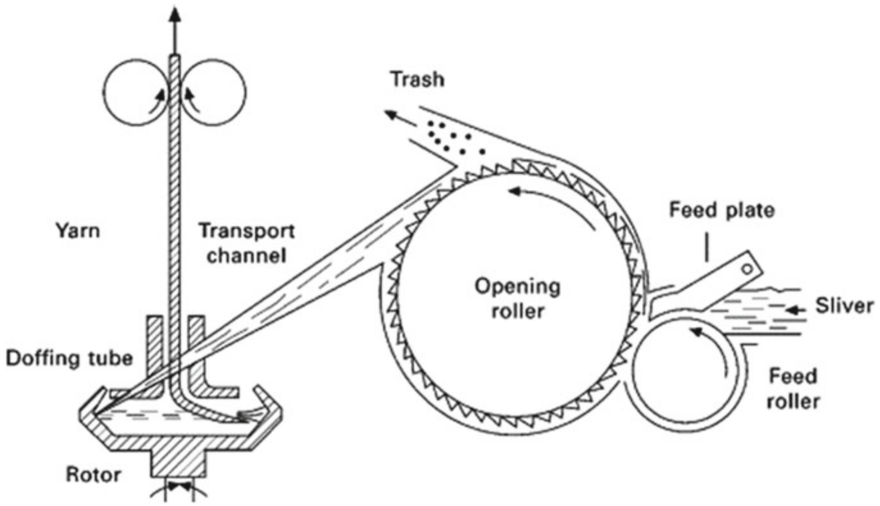

Fig. 8.8 Main features of the rotor spinning system [16] (Fig. 10.1 on page 262) Copyright © 2010 Woodhead Publishing Limited

In the rotor spinning machine, more than 8 million rotors are working out, of which 35–40% yarns are made and used for sports wears, furnishing, fancy fabrics [12]. More than 8 million rotors are currently working, and about 35–40% yarns are made out of rotor spinning. Denim, sportswear, upholstery, furnishings, fancy fabrics, and even knitted goods are made from rotor yarns. Marked improvements in machine features with a high level of automation and computerization make rotor spinning more attractive even in medium to fine counts. See, the main features of the rotor spinning system in Fig. 8.8. Proportions of these machines have gone up by 32–37%. Rotor speeds have been increased by 40–50%, and power consumption has been reduced by 15–20%.

8.7.1 Reduction of Power Consumption

The most power is consumed in rotor spinning during opening roller, winding, and suction systems. The textile sector consumes a tremendous amount of energy during production from the singeing process to final fabric production. The textile sector is always searching for adopting modern and efficient technologies. Today the electricity is needed for mills to operate. The textile industry is using renewable energy sources and contributes mostly to the clean and environmentally friendly atmosphere. With the advancement in the solar system and knowing the advantages of the energy system, the textile sector is adopting the solar system on a large scale. Among all industries, the textile sector is considered as the highest energy consumer, and solar power is much cheaper, and prices are going sustainable throughout the life cycle of solar plants. Most industries have a vast open shaded roof and available places, setting up the solar plants in these areas are a suitable and easy task.

8.7.2 Rotor Speed and Diameter

The diameter of rotor spinning has a significant impact on power consumptions, as compare to 30 mm diameter and 56 mm diameter, the more power is consumed in the 56 mm width, the higher diameter is responsible for more use, to reduce the power consumption and increase of rotor speed recently the diameter of the rotor has been reduced**.** With the addition of computer design, the rotor weight and shape have been optimized for friction reduction in the Coro box SE 12 by Schlafhorst. The decrease in friction causes a significant reduction in power consumption.

8.7.3 Advancement in Rotor Bearings

In place of steel ball, the aero bearings offer the air cushion axial support to the rotor, by compressing the air 6 bar, the air film is produced, which causes the reduction in wear and tears, frictions, and power consumptions. Magnetic rotor positioning system by Schlafhorst contributes to power saving as it dispenses energy consuming steel balls, staggered twin discs, or air nozzles.

8.7.4 Advancement in Suction System

Significant power is consumed in the suction system for the production of vacuum. Autocoro 12 is an electronically controlled system for maintaining the constant suction throughout the spinning process. In some cases, this also permits the reduction of the suction level without any affects to performance. In Reiter R40 model vacuum level in the rotor is kept constant monitored by an electronic sensor for power reductions; the primary fan is also attached to improve its efficiency.

8.7.5 Advancement in the Driving Rotor

The width of the tangential belt was reduced to 20 mm, and the diameter of the twin disc driving rotor increased to 78 mm by Sussen in their new spin box for power reduction. In the R40 model, the pressure on the tangential belt is reduced and will be favorable for power reductions. At the starting time, the pressure is increased to increase the acceleration due to the facilitation of the robot for speeding up the rotor.

8.7.6 Advancement in the Cooling System for Inverter

The power-saving has been obtained in Reiter R40 by better designing cooling systems for motors and inverters.

8.7.7 Advancement in Online Quality Monitoring

Schlafhorst uses energy-saving LEDs and optimized electrically controlled sensors to reduce power in the yarn quality monitoring system.

8.7.8 Advancement in Humidification

Humidification has great importance in on quality and production of cotton yarn, control of humidity is also an essential factor of workers working in the industry when conditions inside are very unfavorable causes the loss of efficiency of the workforce. Some textile raw materials are naturally hygroscopic, and maintenance of humidity is essential; otherwise, the poor quality, low productivity, and high wastages of material will be in process. So for manufacturing high product of yarn in spinning the humidification plants important, and actions are needed to overcome the situations as new spinning machines are very long and staff/workforce available is also very less to bring the case to be normal once disturbed.

8.7.9 Automation and Digitization

Earlier to the recent advancement, the dumpers and water pumps are used to achieve favorable conditions inside; due to recent innovations, all pumps and fans are inverter controlled, The high sensors gives signals to the dampers/pump motors to control the air quality.

8.7.10 Energy Saving

The new fans in the mill are designed in such a way that it consumes less energy and provides better efficiency. Currently, with prefabricated buildings, the humidification plants mostly installed on the ground floor reduce the civil work.

8.8 Conclusion

The inventions discussed in this paper exhibit tremendous potential for the production of yarn. They have an enormous impact on the cost-effective, time-saving, and ensures better quality yarn productions. These technologies will create a significant influence if it is commercialized in the textile sector. In the future, further research is still required to bring the effects of these concepts.

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Chapter 9
Recent Advancements in Cotton Spinning Machineries

Jianping Shi, Wenli Liang, Hua Wang, and Hafeezullah Memon

Abstract There has been significant improvement in the spinning machinery. This chapter aims to present some knowledge about the groundbreaking advancements over the last decade in the spinning machines. This chapter covers the overview of the improvements in the blowroom, carding, drawing, and ring frames only. All the machines have been tried to be illustrated with the help of schematics and simple illustrations to make them understandable to the readers.

Keywords Bloowroom · Carding · Drawframes · Ring frame · Spinning machines

9.1 Introduction

The cotton spinning industry is being developed at a higher pace. The spinning process employed to make fibers may be generally classified as melt spinning, wet spinning, and dry spinning [1]. Most of the latest innovations in spun yarn manufacturing are the alterations of current techniques as well as development in processes and product qualities. A primary downside of existing twisting mechanisms of ring-spinning is the friction between ring and traveler. The implementation of superconducting technology-based twisting tools has remarkably reduced the friction between traveler and rings during production [2].

The Radio Frequency Identification RFID technology is used in spinning technology to trace the bobbin to the spindle during the production process. The targeted

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bobbins are recorded and identified in the spinning frame without touching dual-directional data communications [3]. The latest machine parts of rotor spinning help for the reduction in energy consumptions. Tuft size in the blowroom process is become smaller by using automatic bale opener.

This chapter aims to provide a basic overview of the recent development of textile spinning machinery. The chapter focuses on four primary areas of cotton spinning machines, i.e., blowroom, carding, drawframes, and ring spinning machines. Other areas have been deliberately not discussed to avoid the unnecessary lengthy book chapter.

9.2 Recent Advancements in Blowroom Machines

The blowroom is the first department of the spinning, whose main task is the opening, cleaning, and mixing of fibers. The general flow of the blowroom process is illustrated in Fig. 9.1.

9.2.1 Reciprocating Bale Plucker

The JWF1012 Reciprocating Bale plucker is shown in Fig. 9.2a. The beater adopts the "Unidirectional Plucking" design to ensure less fiber loss, better ingredients evenness, and dispersion. This technology has obtained a national invention patent. The beaters for JWF1018, as shown in Fig. 9.2c, adopt a double-edged blade, and pick the material by tooth tip. After the blade is worn, it can be replaced separately for easy maintenance. Moreover, the length of the cotton-picking arm is increased by 10 cm.

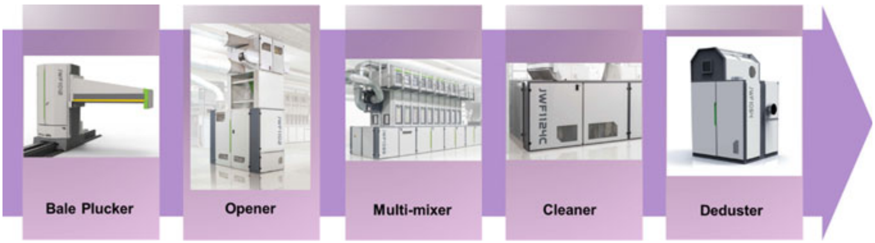

Fig. 9.1 The flow of blowroom machines

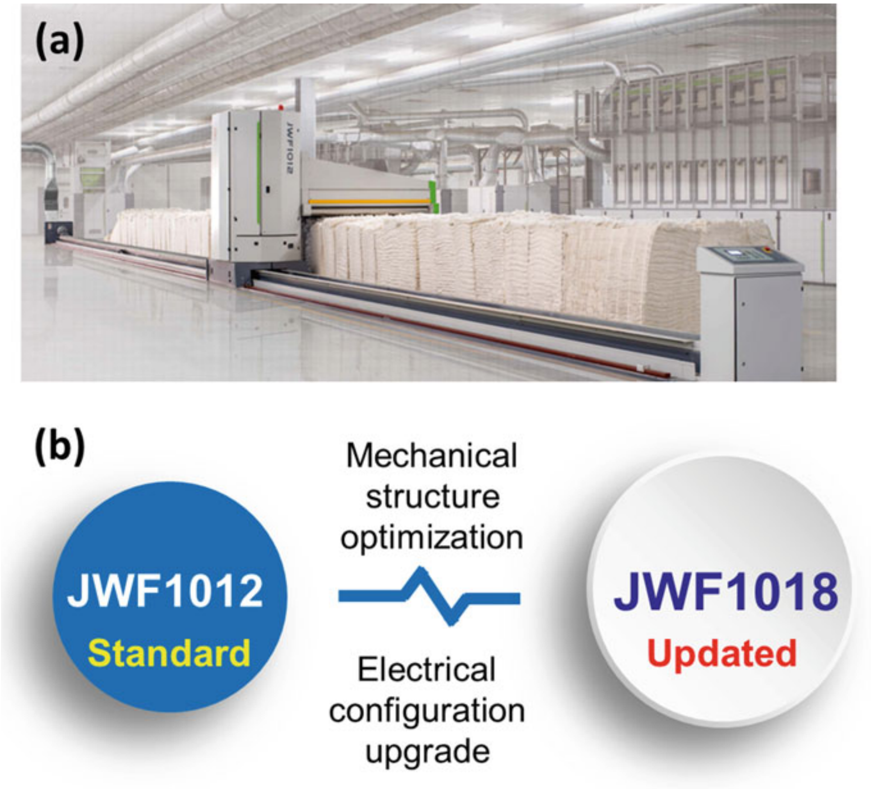

Fig. 9.2 Reciprocating Bale plucker. **a** JF1012 Reciprocating Bale plucker installed in the cotton spinning industry, **b** conventional beater used in JF1012, and **c** double-edged blade and picks beater of JF1018

9.2.2 Heavy Particle Separators

There are different kinds of heavy particle separators, i.e., TF45A, TF50, TF45B, and JWF0001. TF45A removes mass impurities; it tends to be protective. TF50 removes small impurities and fragments; thus, it tends to clean. TF45B removes mass impurities and lint, as well as it balances airflow. JWF0001 multi-functional separator detects and eliminates metal and sparks, removes heavy and foreign particles, impurities, lint, dust, and balances the airflow. This technology has also obtained a national invention patent. The images and working mechanism of all four kinds of heavy particle separators are shown in Fig. 9.3.

Fig. 9.3 Some heavy particle separators and their flow mechanism

9.2.3 Opener

The three openers are well known for a long time, i.e., FA103B, JWF1102, and JWF1104. The FA103B is Double-roll opener, in which fiber is beaten freely and gently by the two spiked-cylinder to loosen cotton tufts. The beater speed can be adjusted at a range of 400–650 rpm by frequency inverter according to different material and technological requirements. The JWF1102 is a Single-roll opener in which a compound beater is adopted for further opening as well as removing impurities while reducing fiber damage and ensuring high production. This technology has obtained a national invention patent, i.e., Patent No. ZL 201010155776.2). There is a diversion trench with a new design of gradually increasing spacing structure, not only beneficial to material opening and cleaning but also avoid fiber deterioration.

Moreover, JWF1104 is known as the high-efficient opener because it adopts a large-hopper structure with a wider working width. The micro dust and lint in raw cotton can be removed efficiently, as well as, "fast feed and thin layer" method is used to increase the cleaning efficiency with less fiber damage. The feed roller and beater are controlled by converter with easy adjustment to meet technological requirements. It adopts grid-bar structure and center suction technology in waste dropping area with no dust accumulation and low energy consumption. All three openers, along with their mechanisms, are shown in Fig. 9.4.

The new double-roll opener (JWF1111) of Qingdao Hongda Co. Ltd, shown in Fig. 9.5, has a good opening degree with high production (3000 kg/h), and it can work with the cotton containing impurities >2.5%. Thus, JWF1111 improves the opening degree and impurities removal capacity of the blowing process. The cleaning efficiency of this new model (JWF1111), is 1.3–1.5 times of previous models

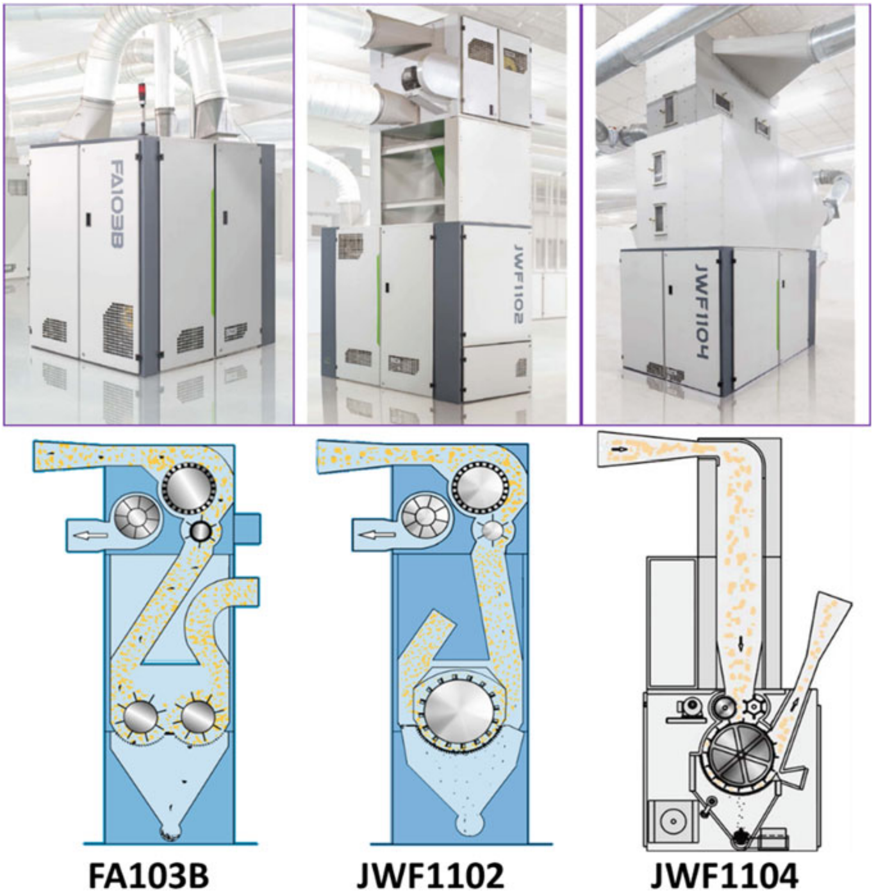

Fig. 9.4 Cotton openers and their flow mechanism

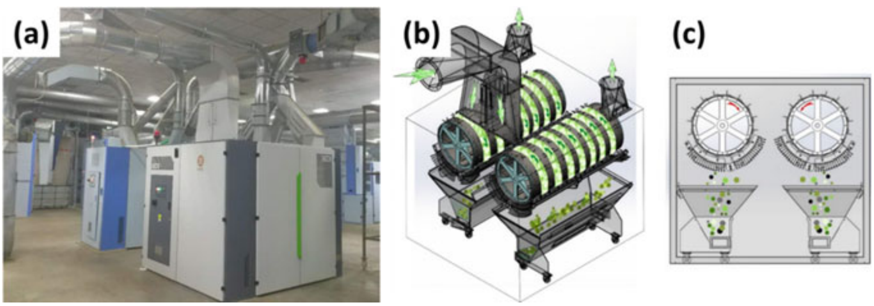

Fig. 9.5 Double-roll opener. **a** JWF1111 double-roll opener installed in the cotton spinning industry, **b** pictorial representation of double-roll opener, and **c** working mechanism of double-roll opener

(JWF1107/09). Compared with two single-roll openers in series, the machine occupies a smaller area by saving a fan and the cotton pipeline between two adjacent single roll openers.

9.2.4 *Multimixer*

The mixing is one the main objective of the blowroom, since changing in some parameters may alter the overall quality of yarn significantly [4]. JWF1024 series multimixer is available in two working widths, i.e., 1200, and 1600 mm only with two specifications: six-chambered or ten-chambered. The mixed fibers are transported into the following process by pneumatic pressure without physical contact with metallic parts. It adopts several new technologies to ensure the operation is stable and reliable. And the blending effect increased by 50% compared with the previous model. Another series, JWF1026 series multimixers are available in four working widths, i.e., 1200, 1600, 1800, and 2000 mm, with similar six-chambered or ten-chambered specifications. However, it uses a leather belt used for conveying the fibers, so the fiber may not be damaged, and energy may also be saved. With several new technologies, the operation is stable and reliable, and the cotton blending effect is mostly improved, i.e., 50–100% comparing with the previous model. JWF1026 holds and conveys the raw material to Cleaner JWF1124C through lattice instantaneously. Thus, the mixing ratio is stable, see Fig. 9.6.

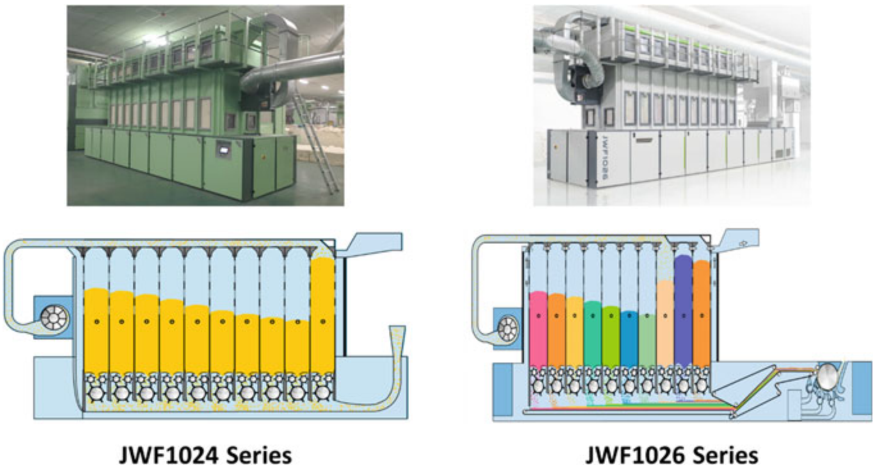

Fig. 9.6 Two different series of multimixer and their flow mechanism

9.2.5 Cleaner

FA109A Series Tri-cylinder Cleaner is connected to multimixer as a combined unit, and available in two working widths, i.e., 1200, and 1600 mm. Three cylinders equipped with the pin, coarse saw-tooth, and fine saw-tooth, respectively, to realize gradual opening and efficient removal. Three beaters and feed-roll are all controlled by frequency inverters. JWF1124C is a single roller cotton cleaning machine series, which is connected to multimixer as a combined unit, available in four working widths, i.e., 1200, 1600, 1800, and 2000 mm. Needle-plate covered beater of large diameter, together with combing-plate and mote-knife structure, ensures flexible opening and high cleaning efficiency of the machine, in which the position of the first mote-knife can be easily adjusted. The speed of the beater controlled by frequency inverter can be adjusted easily. The maximum speed is set at 1000 rpm. JWF1116 Cleaner can be used in polyester, recycled cotton, pure cotton, and other raw materials, with wide application range to feed raw materials.into storage hopper by the aid of a fan, see Fig. 9.7. After the lint and dust are removed through the upper mesh plate, fibers are fed to beater by the gripping of four rolls. The needle-plate beater together with three groups of "combing-plate + mote-knife" structure, ensuring high cleaning efficiency and less fiber damage. Similarly, the beater and feed-roll are controlled by frequency inverter.

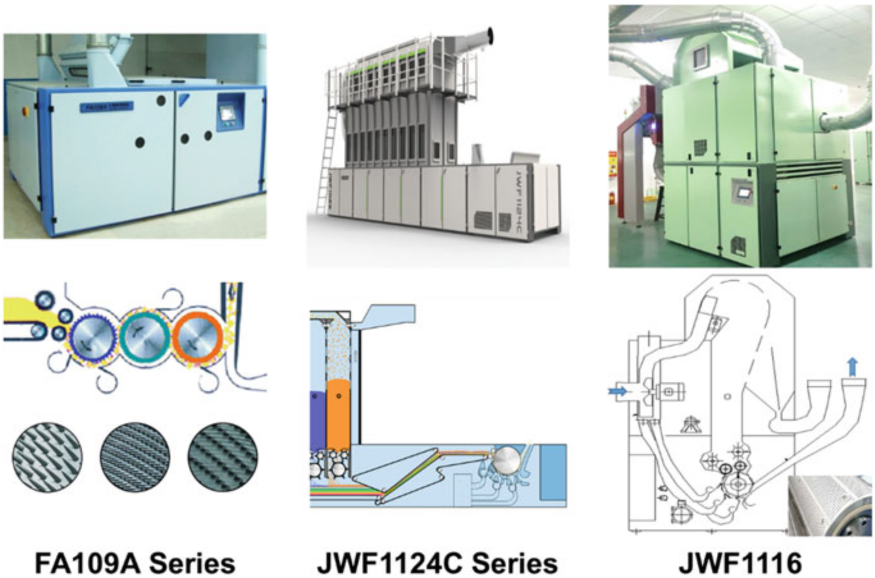

Fig. 9.7 Some common cleaners and their flow mechanism

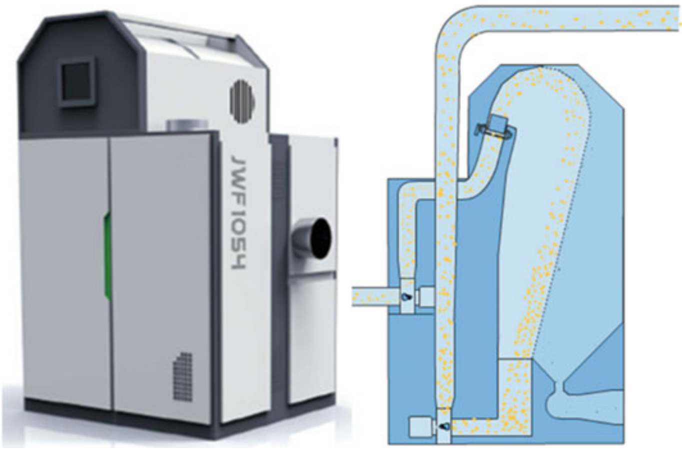

Fig. 9.8 The dedusting machine (JWF1054) and its flow mechanism

9.2.6 Dedusters

In the latest dedusting machine, i.e., JWF1054, see Fig. 9.8, the mesh-plate area increased by 40% compared with traditional dedusters to improve the lint and dust cleaning efficiency with high production. The inlet of fiber distributor widened by 25% to ensure the evenness of fiber distribution. The fan adopts a radial impeller of a large diameter directly connected with motor, and it is controlled by frequency inverter with easy adjustment and low power consumption.

9.3 Recent Advancements in Carding Machine

9.3.1 Chute Feeder

The JWF1173A and 1177A feeding boxes are the latest products with the same feeding structure but different working width, see Fig. 9.9. With an increased storage capacity of cotton box, the machine ensures high production and stability of the cotton layer. The cotton board is spring-loaded, the fiber is elastically held, and the distance between the board and feed roller can be automatically adjusted according to the thickness of the cotton layer.

The inner circulation wind structure is adopted so that the cotton supply is not affected by the number of operating carding machines and the pressure of the dust filter system. In simple words, cotton feeding is more uniform and stable. The first roller with six rows of spiral-arranged combs realizes continuous and softens opening and the seal on both sides of the beater and feed roller to avoid cotton clogging

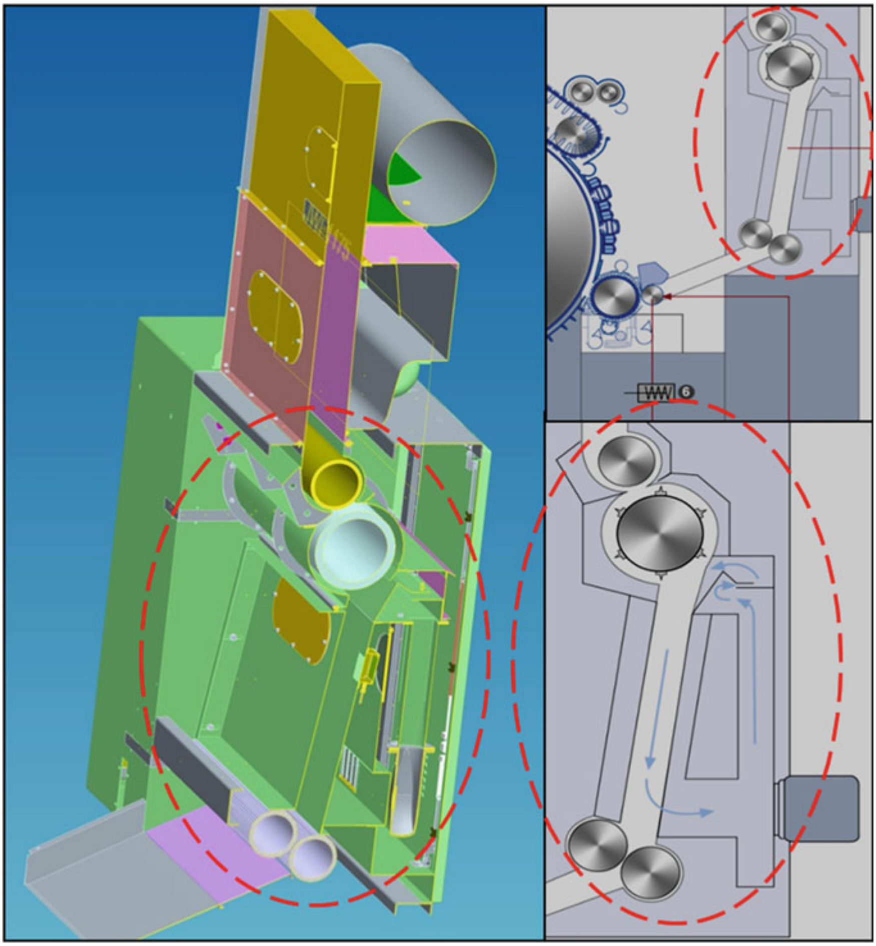

Fig. 9.9 Schematic illustration for the flow of chute feeder (1177A feeding box)

and entanglement. The feed roller cover plate and the front/rear cover plates of the opening roller can be conveniently rotated and opened for cleaning; at the same time, the safety can also be ensured.

9.3.2 Feeding System

The new type of forward cotton-feeding structure makes the feeding smoother and reduces fiber damage effectively. The licker roller is covered with self-locking card clothing, with two dust removing knives are arranged below, and can be adjusted from outside, see in Fig. 9.10a, and the pre-separating plate is combined with the licker

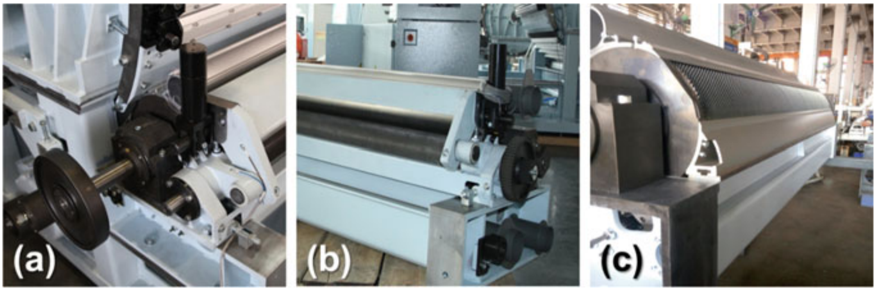

Fig. 9.10 Feeding system **a** the machine can be adjusted outside, **b** forward cotton feeding for transferring fibers to the cylinder as the licker rolls rotate, and **c** back cover is removed for adjustments

roller. It has been observed that the amount of neps per gram in sliver is decreased by the point per square inch in stationary licker-in side flats [5]. The impurities are removed, and the spinnable fibers on the licker roll are subjected to a specific holding action so that they can be smoothly transferred to the cylinder as the licker rolls rotate, see forward cotton feeding in Fig. 9.10b.

Licker-in checks through the first and second dust removing knives and the carding plate spacing according to the gauge map. The back cover can be temporarily removed when adjusting the space of the second dust-removing knife, as shown in Fig. 9.10c.

9.3.3 Carding System

This part includes cylinder, rotating cover flat, front and rear stationary flat, front and back cover plate, and big undercasing. The pre-carded fibers processed by rear stationary flat are transferred in the working area of the cylinder for further fine-carding, in which the cotton flocs are entirely broken down, and the impurities and short fibers can be removed. The relative speed of rotating flats and cylinder has a significant effect on the quality carded sliver and, thus, the final yarn [6]. Before transferring to the doffer area, the cotton fibers are further carded by front stationary flat, so that their straightness can be enhanced and achieve uniform mixing during the carding process. In the latest carding system, the cylinder is raised, and the doffer is lowered so that the angle between barrel, doffer, and licker roller is increased. The carding angle and arc length are increased, i.e., the angle increased from 212° to 247°, and the arc length is increased from 2.4 to 2.8 m, which is 47% more than the traditional machine. Likewise, the working width has also been improved, as shown in Fig. 9.11a.

Extra front/rear stationary flats and the cotton net cleaners are added on the increased area to achieve a finer opening, combing and finishing effect on the fiber layer, and better removing the short fiber, impurities, and dust. The aluminum alloy active flat has the characteristics of lightweight, stable structure and convenient

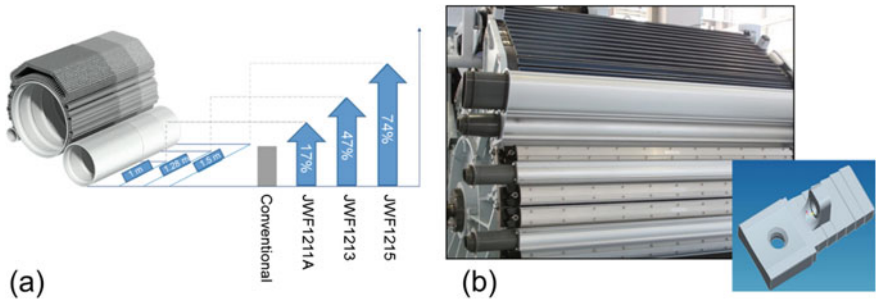

Fig. 9.11 Advancement in carding system, **a** the working width of different carding machines, and **b** aluminum alloy active flats are replacing the fasteners

process adjustment. It is connected and guided by the toothed belts on both sides, as shown in Fig. 9.11b. There is no need for other fasteners, so it is easy to disassemble and install and easy to maintain.

9.3.4 Flat Cleaning System

The brush roll is driven by frequency motor, and its rotational speed can be set individually according to different raw materials and different processes (refer Fig. 9.12a–c). Aluminum alloy suction cover is equipped for smoother dust collection. The cover plate and brush roller are embedded with each other, and the distance is 1 mm. The flat cleaning roller is equipped with under-speed protection. The relative position of the brush roller and the cleaning roller is changed from the previous horizontal arrangement to the oblique arrangement, (refer Fig. 9.12d, e), which is more favorable for the removal of the cover impurities. The distance between the brush roller and the cleaning roller is eccentrically adjustable, i.e., 0–2 mm, (refer Fig. 9.12f), which can effectively avoid the entanglement of the fiber on the surface of the brush roller.

9.3.5 Transfer System

The compact three-roller stripping device peels off the fibrous layer that condensed on the doffer forms it as a cotton web. The upper and lower rollers with spiral grooves on their surfaces guide the web by friction and adhesion. The machine adopts an apron cotton guide device driven by a flat belt to actively collect cotton, which is suitable for different fibers and is conducive to high-speed and high-yield. The newly designed large roller and dual active transmission make the machine easy to install and adjust and meet the needs of high-speed delivery; a dedicated test platform is equipped

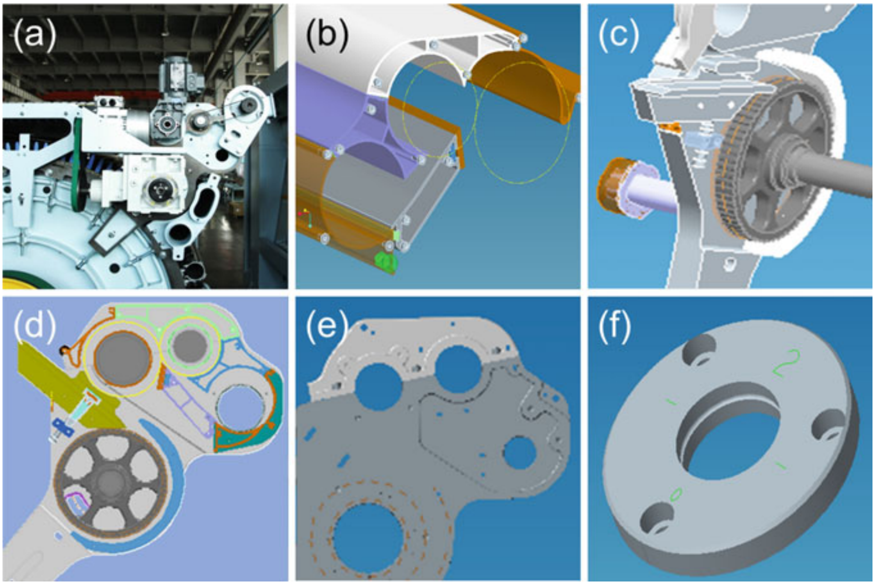

Fig. 9.12 **a** Flat cleaning system, **b** flat cleaning arrangement, **c** flat cleaning driving shaft, **d** oblique arrangement of brush and cleaning roller, **e** oblique spacing for brush and cleaning roller, and **f** cleaning roller is eccentrically adjustable

to reduce the failure rate. The gauge between upper and lower roller is adjusted to 0.25–0.3 mm, and an anti-winding protection device is added. The function of mixed loop auto-leveling is realized by the new close-ring high-precision test mechanism on trumpet cooperating with the rear open loop. The air-pressure must be high enough to avoid the accumulation of short fibers. The leather collar locking system is added to ensure the stable distance of the leather collar and the upper and lower roll. The typical transfer system of the card is shown in Fig. 9.13.

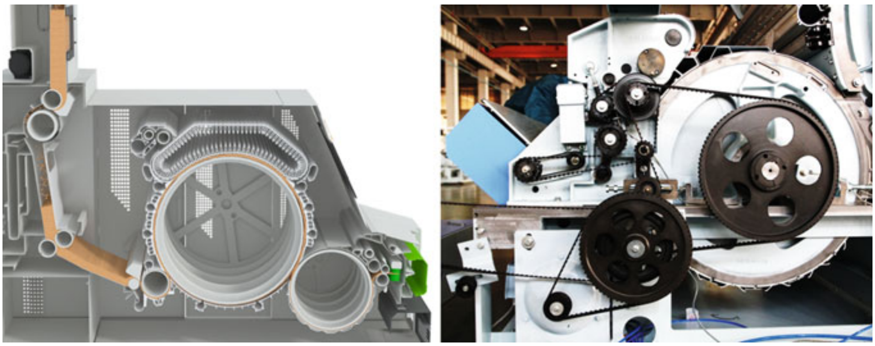

Fig. 9.13 Transfer system of carding machine

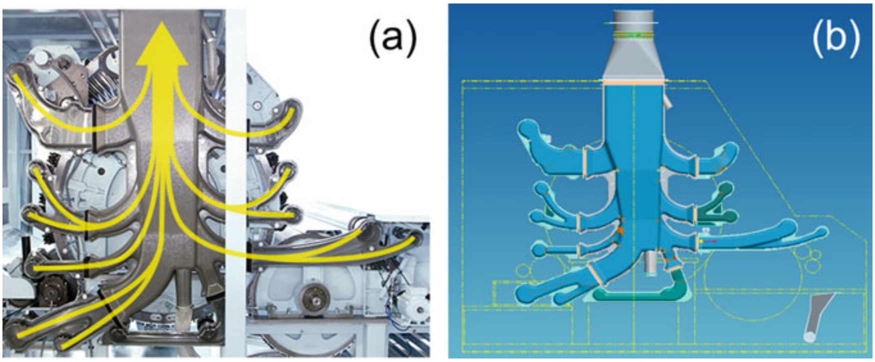

Fig. 9.14 The dust filter system, **a** the airflow trajectory inside the carding machine, and **b** flow of dust to the main pipeline

9.3.6 Dust Filter System

The streamline designed pipe is more accord with the airflow trajectory, see Fig. 9.14a. It helps reducing windage, thus reducing energy consumption. Airflow stratification of each branch in the main pipeline to avoid airflow impact. Increased air speed at suction port reduces the total air volume of the main pipeline, see Fig. 9.14b. There is a difference in the cotton net cleaner when spinning cotton and chemical fiber. Suction ports, branch, and the main pipe are well sealed to ensure the inside of the machine is clean.

9.3.7 Carding Coiler

At present, various types of coilers (serialization of barrel diameter and height, manual or automatic change, on-ground or under-ground configuration, separate motor drive and mechanical drive, the function of pre-draw or leveling) can meet different needs of users. Among them, The FT209A linear automatic change coiler is the most popular, see Fig. 9.15. It has a high-speed sliver cutting mechanism (i.e., the doffer does not need to slow down) without affecting the quality of sliver; also, it saves raw material consumption. As compared with the rotary automatic cylinder changer, this structure is simpler and saves 33% of the floor space.

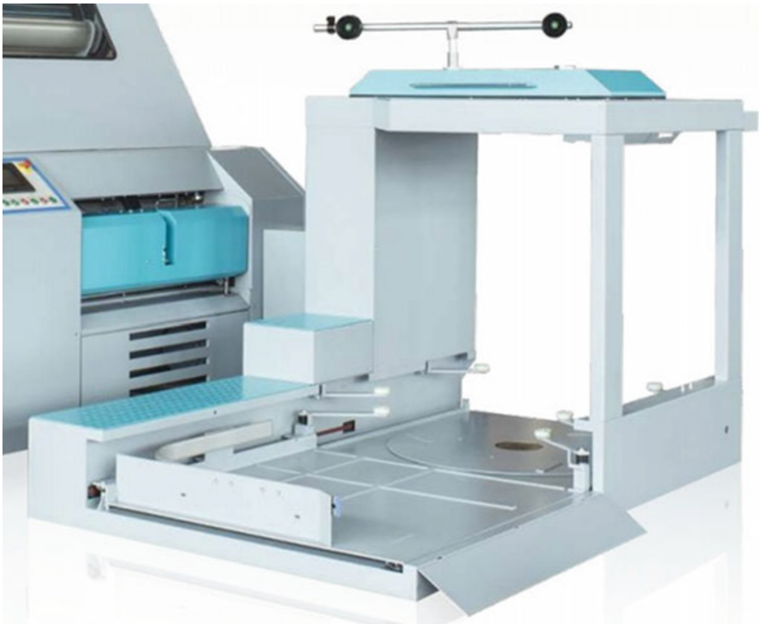

Fig. 9.15 FT209A linear automatic change coiler

9.4 JWF1313—A Well-Developed Drawframe

The drawing machine, i.e., JWF1313, is known as Intelligent Drawframe, see Fig. 9.16. The use of innovative driving form, electronic drafting, l000 mm output diameter, intelligent breaking device, roller monitoring, and independent suction functions make the machine be able to reduce the cost for the user.

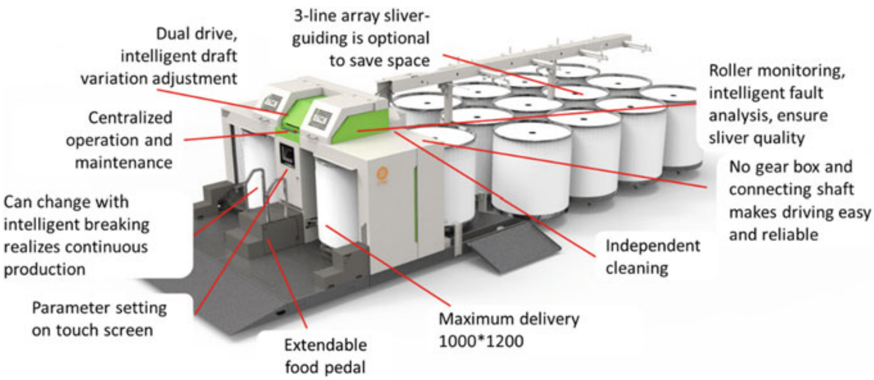

Fig. 9.16 The new experience of delivery 1000 mm and electronic drafting

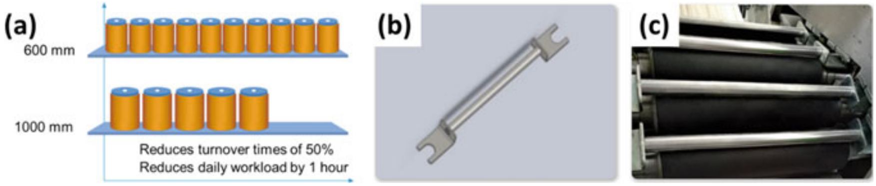

Fig. 9.17 Advancement in drawframe by space and cleaning for JWF1313, **a** comparison of 600 mm versus 1000 mm dia of the can for minimum floor space, **b** steel bar for JWF1313, and **c** high-speed steel bar cleaning mechanism

China's first proven two-head 1000 mm delivery drawframe, Fig. 9.17a. Comparing to those of 600 mm, it has larger storage capacity and can reduce 50% of the sliver-can turnover times at the same output, thus reduces daily workload by 1 h on average. It requires minimum floor space since the feeding sliver can be arranged in 3 arrays (array type $5 + 6 + 5$) or two arrays (array type 2×8, standard) according to the user's workshop space.; The new type of steel bar cleans roller refer, Fig. 9.17b, c ensures a cleaning effect in high-speed production.

9.4.1 The New Experience of Dual-Drive Drafting

The double motors drive draft area realizes draft multiple stepless adjustments and high system response frequency. The control precision of the drafting ratio is 0.001. In the production process, the operator only needs to enter the target weight in the touch screen, whether he wants to adjust the weight or change the process. The system will calculate the draft constant automatically.

9.4.2 A New Braking Device with Auto Can Change

By modifying the broken strength on the touch screen, the auto braking function of different varieties can be realized. It is convenient and straightforward to adjust without manual maintenance. It can adapt to a wide range of types, and achieve continuous production with the use of auto can change mechanism. Thus, the new auto can adjust with an intelligent braking device that realizes continuous production.

All the operations during production are completed in front of the machine. Comparing with other machines, the operators do not need to go around the machine repeatedly any more, which saves time and reduces workload. The touch screen is placed in the middle of the machine; thus, adjustments for both sides' delivery can be realized at the same time. All transmission parts are concentrated in the middle. This structure is simple, which reduces the difficulty of maintenance. With the patent of all-new automatic can change the structure, in which the change arm can be

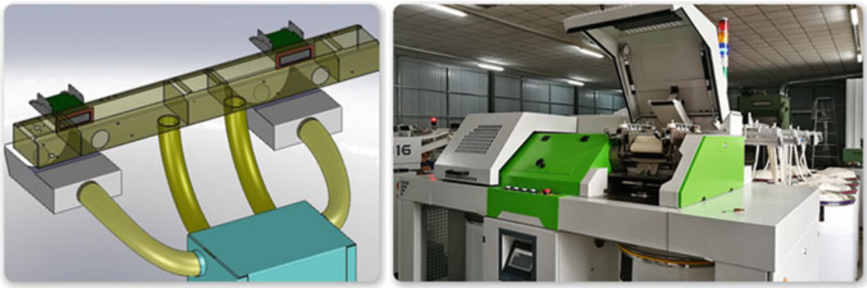

Fig. 9.18 Independent suction system in JWF1313

rotated and folded, the changing distance (area covered) can be reduced by 20%. At the same time, the design of the mechanism is stable and straightforward, and it is more durable and more comfortable to maintain than the traditional way, and the maintenance period can be extended to more than half a year.

9.4.3 Independent Suction System

The left and right draft areas are entirely separated, and the air suction is not disturbed. The independent suction box is located in the middle of the deliveries. The left, right, upper, and lower air suction is independent of each other, and the air tubes do not interfere with each other, see Fig. 9.18. The air volume can be adjusted independently, and the air tubes are reached the cleaning points, respectively, the cleaning efficiency improves by 50% compared with the traditional drawframe. The total suction air volume reaches 1500 m^3/h, and negative pressure is 1.2 kPa.

9.4.4 Cleaning Monitoring to Guarantee Quality

The independent suction box and air tubes, equipped with an under-pressure alarming device, ensure a good suction and cleansing effect, see Fig. 9.19a. This machine is equipped with high precision roller speed monitoring, and real-time monitoring of the drafting area (draft constant) to ensure the stable delivery by right feeding.

If there is failure in the drafting area, the roller monitoring system will determine the location of the problem, thus reducing the difficulty of maintenance work. This machine has a total of thirteen sets of sensors, real-time monitoring on the running state to ensure the high quality of the delivery slivers. All sensors adopt photoelectric or contact type self-stop with high reliability and long service life, see Fig. 9.19b.

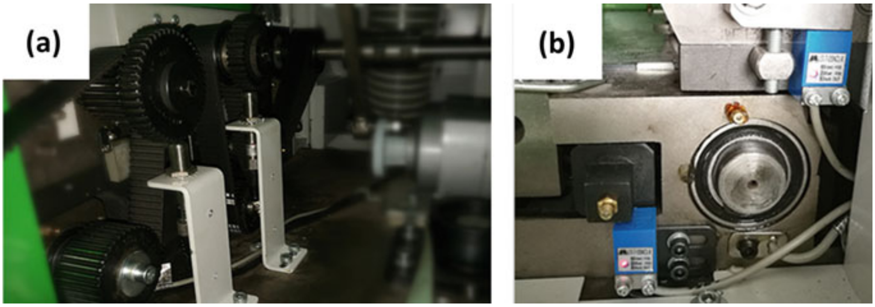

Fig. 9.19 Cleaning monitoring as well as a quality guarantee, **a** high precision roller speed monitoring, and **b** sensors to guarantee quality

9.4.5 Structure Simplification for Energy Conservation and Environmental Protection

New exterior design and I-shaped structure, elimination of transmission box, shortened transmission chain, optimized power consumption, production costs, labor, maintenance, and other aspects. The use of energy-saving motors that meet the national energy efficiency standards, see Fig. 9.20a, realizes high power in low energy consumption. Widely used timing belts in the whole machine, see Fig. 9.20b, reduces transmission power consumption.

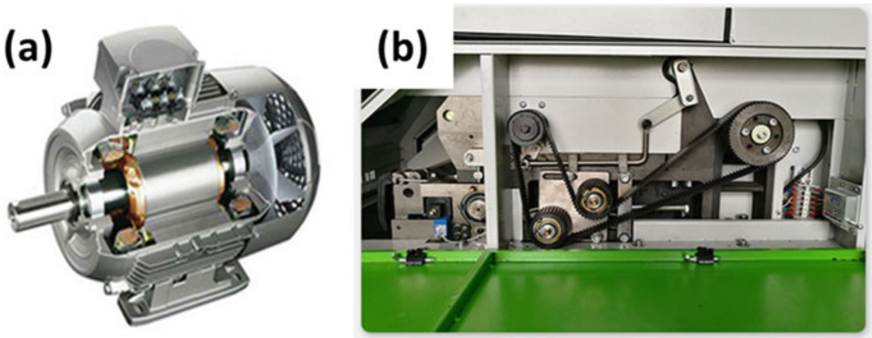

Fig. 9.20 Structure simplification for energy conservation environmental protection, **a** national energy-saving motor, **b** Widely used timing belts

9.5 JWF1316/JWF1316^T—An Example of Advanced Drawframe

JWF1316 series, also known as Auto-leveler Drawframe Series, is developed by Shenyang Hongda Textile Machinery Co., Ltd., according to the development trend of high-speed auto-leveler drawframe, mingling the current internal situation of the cotton spinning enterprise, from the satisfaction of customers for auto-leveler drawframe. With the assurance of high quality, high yield, high stability, less labor, small occupation, easy to maintenance, and low cost, based on Shenyang Hongda's nearly 70 years of experience in draw frame production as well as research and development of technology, and benchmarking with the first-class equipment worldwide, the JWF1316 series has been launched, see the development of the auto-leveling drawframes in Fig. 9.21.

From the view of the machine itself, this draw frame overcomes the traditional design habit and can meet the special requirements of the spinning of different varieties of each unit. The model of one side in operation while other-side under maintenance can also be realized. The overall running efficiency will be 10–15% higher than that of an ordinary two-head drawframe. The series of drawframe include two types, i.e., single unit (JWF1316) and combine-head (JWF1316^T). In the production of the combine-head type, both units can be operated at the same time without leaving the machine. All driving parts are designed in an accessible position when the machine cover is opened to reduce maintenance difficulty. High-speed, high-yield and humanized operation are ensured by the various combinations of software and hardware.

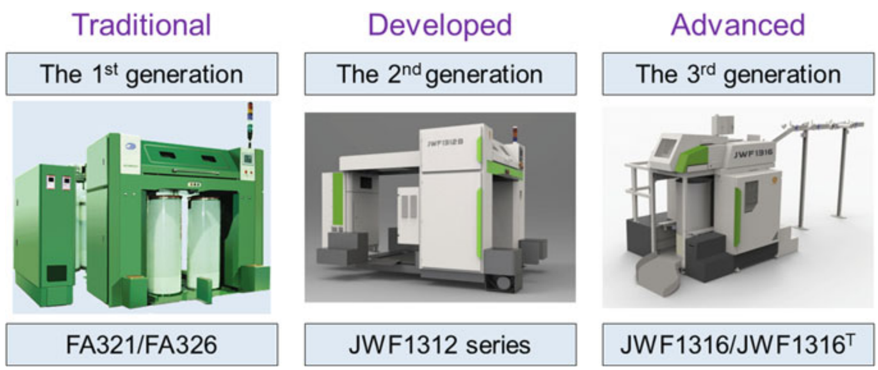

Fig. 9.21 The development of drawframe of Shenyang Hongda Textile Machinery Co., Ltd

9.5.1 Easy Operation

During maintenance, the operator can handle all parts in the front, thus reducing the difficulty of maintenance. The roller lifts and falls with the pendulum arm so that the fluffy flying and winding can be cleaned faster. The new type of sliver-can changing device is integrated with the machine to avoid leaning. All electrical adjustments can be done on the touch screen with easy and convenient operation.

9.5.2 Energy Conservation, Environmental Protection by Low Input and High Efficiency

The production speed of the JWF1316^{T} drawframe can be up to 2 × 1000 m/min. The investing costs can be reduced by 20–30% compared with traditional machines. Combine-head drawframe can save the floor space of nearly 40% compared with conventional single-head types in the arrangement of equipment in a spinning mill.

9.5.3 Simple and Convenient Maintenance

This drawframe adopts a new roller bearing structure, improves lubrication, high speed, heat dissipation, and reduced maintenance workload. All parts are tightly sealed with a new sealing strip to reduce the cleaning frequency. The main components are lubricated by a centralized lubrication mode, which reduces the maintenance workload. All transmission parts are designed to be controlled by a single touch screen to minimize maintenance difficulty. The roller monitoring system can accurately analyze the transmission fault in the drafting area and the actual output of the drafting multiple, which reduces maintenance difficulty and laboratory workload.

9.5.4 Flexible Usage by the Auto-leveler System

Uster UQA auto-leveler system and expert system are available, and the Jingwei NAS auto-leveler system can also be selected. Single head or combine-unit can be freely matched according to the actual situation of spinning mills. A combine-head model can produce different products from different materials at the same time. It can be different in the ration, feeding ends, and delivery speed, and other technologies for the left and right units. Different specifications of sliver cans can be selected under 1000 mm for inlet and under 600 mm for output. When using 1000 mm, sliver can, the 3-array arrangement can be chosen according to factory space, which can reduce up to 3 m of length compared with traditional 2-array. UQA system is an upgraded version

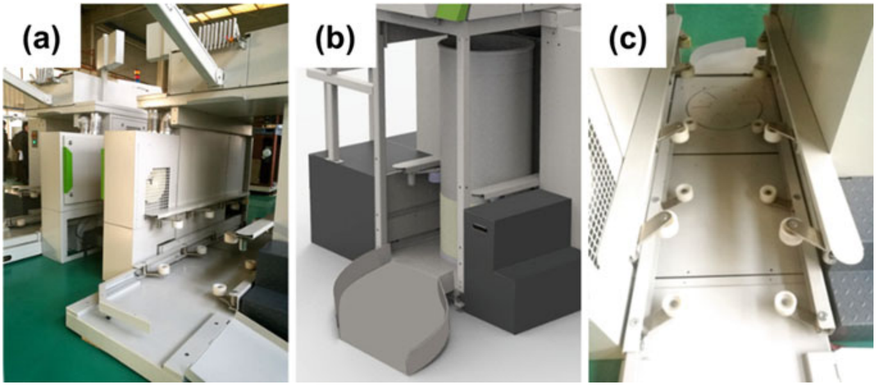

Fig. 9.22 Continuous production without care

of the USG system provided by Uster Switzerland. As an OEM customer of Uster, UQA is the first auto-leveler system in China to adopt digital communication, which is more stable than the analogy system and has more anti-interference capability. NAS system is an "embedded" auto-leveler system independently developed by Jingwei, which is the only domestic auto-leveling system. The Jingwei NAS system is more in line with the operating habits of Chinese operators.

9.5.5 Continuous Production Without Care

All-new structure of automatic can-change equipped with buffer structure and the intelligent braking system makes the machine suitable for continuous production, see Fig. 9.22a. The new structure is stable, reliable, easy to maintain, and designed with sliver can protection devices to improve the service life of and avoid a series of problems like can body deformation, off-track, and changing difficulties. The sloped plate independently innovated by Shenyang Hongda solves the off-track problem so that cans will be regularly placed at the exit of the slope plate after can changing, refer Fig. 9.22b, c. The intelligent braking device realizes its function by electric control without adding any extra mechanical structure.

9.5.6 Highly Efficient and Stable Drafting System

Equipped with a high-precision roller supervision system self-developed by Shenyang Hongda, refer Fig. 9.23a. By monitoring the operation state of each roller, the actual draft ratio and the mechanical faults in the draft area can be monitored in real-time, so that to guarantee sliver quality. The online detection system can track

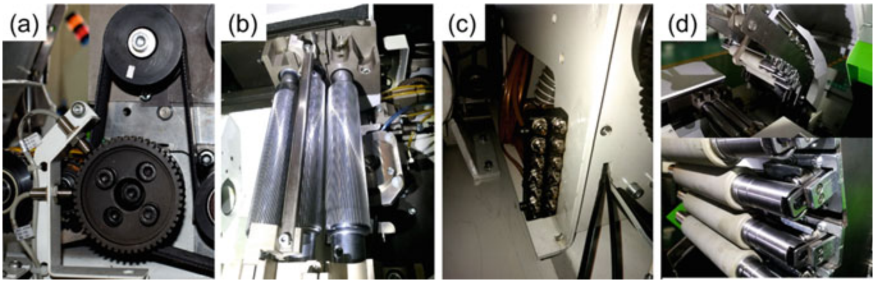

Fig. 9.23 Highly efficient and stable drafting system, **a** sliver quality control, **b** non-disassembly integrated pressure bar device, **c** draft zone lubrication, and **d** simple operation of pendular arm and roller

the sliver quality in real-time, and carry out the quality testing on CV %, A %, thick and thin, spectrogram of sliver, which reduces the workload of quality inspection of sliver in the laboratory. Combined with the use of roller supervision, the sliver quality is doubly protected to ensure more safety and reliability.

It is also equipped with a non-disassembly pressure bar device to realize better control of floating fiber and more convenient operation, see Fig. 9.23b. The gap between the pressure bar and 2nd roller can be adjusted from 2 to 3 mm.

Bearings of the whole draft zone are lubricated centrally to facilitate maintenance, refer Fig. 9.23c. The top roller bearing structure with sealing function can reduce the cleaning and maintenance cycle. The machine adopts uniform upper rollers to simplify the spare parts management and daily operation workload, refer Fig. 9.23d. The upper roller is one of the most frequent dismantled parts in regular operation. This machine adopts a new structure to raise and lower the roller with the pendular arm as a whole, which avoids routine and trivial moves of operators, as well as, simplifies the cleaning of the draft zone.

9.5.7 The Driving System with Reliable Cleaning and Feeding

The main transmission of the draft zone adopts a new type of driving belt with a thin and soft body. It is suitable for the high-speed drive of small belt pulley up to 40 m/s, refer Fig. 9.24a. Compared with the transmission of synchronous tooth-belt, this new belt has less vibration and heat generation, which is conducive to improving transmission reliability, stabilizing drafting quality, and reducing driving interference.

A new type of steel bar cleans roller ensures high-speed production and cleaning effect. Each cleaning point has a separate pipeline in the independent suction system

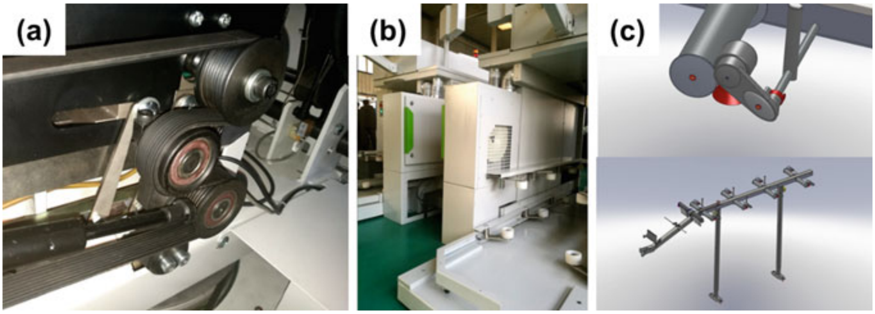

Fig. 9.24 Features of drawframe JWF1316 series, **a** driving system, **b** reliable cleaning, and **c** stable feeding

to ensure the cleaning effect. The left/right side air intake can be adjusted independently when spinning different varieties. The negative pressure alarm system automatically reminds the cleaning time of the filter box to reduce the workload of the operator on inspecting the filter box. The use of a synchronous belt and multi-wedge belt minimizes the consumption of transmission power.

Each unit has an independent suction box and is equipped with an under-pressure alarm device. The operator can clean the cotton box according to the alarm instructions to reduce the workload and ensure good suction cleaning effect. The independent fan has a total air volume of over 1200 m^3/h and negative pressure over 600 Pa. Frequency conversion fans can be selected to adjust suction volume automatically according to the cleaning effect, refer to Fig. 9.24b. The airspeed in each channel can be adjusted separately through the adjusting plate since the upper and lower suction channel is independent.

The new type of sliver guiding creel with a simple structure is more stable and reliable and easy to maintenance. 8-way photoelectric device and calendar roller contact self-stop are equipped to track the feeding state of each sliver and avoid the improper draft Fig. 9.24c. The sliver guiding calendar roller adopts a new type of customized bearing, which is stable, flexible, and free of oil maintenance.

9.6 Recent Advancements in the Ring Frame

In the recent JWF1579 Series Ring Frame, the new series of ring frame has advantages of integral centered wallboard, high-precision, less vibration, thus, it ensures high-speed spinning of 22,000–25,000 rpm, see Fig. 9.25a. Different from the sling belt driving method, the new active lifting mechanism adopts a new form of the driving method, gear transmission, see Fig. 9.25b. The ring plate lifting is smoother, without stagnation, and the yarn tube can be well-formed, which is suitable for high-speed winding. The technological parameters of spinning (spindle speed, highest and lowest

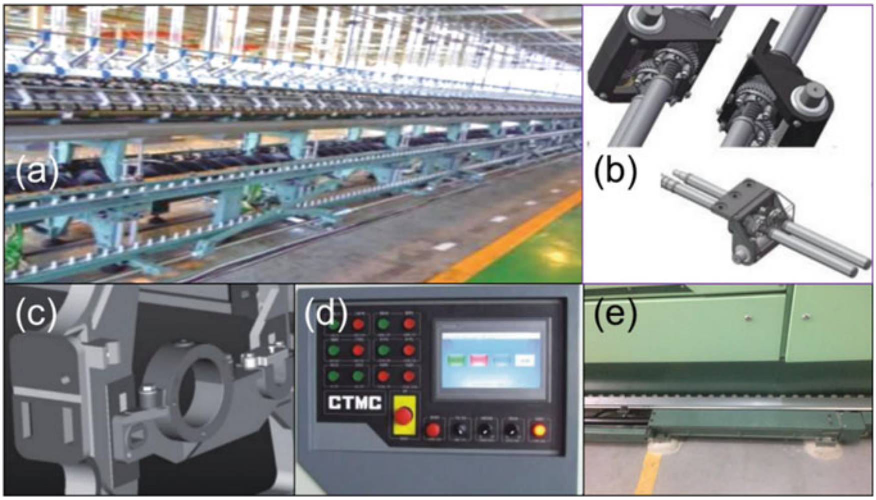

Fig. 9.25 Recent advancements in the ring frame, **a** high-speed spinning, **b** new lifting mechanism with gear transmission, **c** pinhole positioning technology to guarantee precision, **d** intelligent electronic control system, and **e** quick doffing technology

positions of spinning, spinning diameter, winding pitch) can be adjusted on the operation panel.

In this new high-precision ring frame, i.e., JWF1579, the integral centered wallboard (keel bracket and center wallboard are integrated); further type deformation-resistant high-precision keel. The pinhole positioning technology guarantees precision in which the main axle is easy to put in, thus shorten the installation time, see Fig. 9.25c. The intelligent electronic control system is embedded with the spinning process expert system (fault display function), see Fig. 9.25d. Also, the quick doffing technology (ball screw) effectively improves the operation efficiency and output, see Fig. 9.25e.

9.7 Conclusion

In this chapter, we have briefly introduced the latest advancements in the textile machinery industry. With the rapid development of technology, there will be further changes in the coming years. The development of textile machinery depends upon the advancements of other related fields. The manufacturers should pay more attention to the development of other associated areas. While other industries are making progress, Chinese textile machinery manufacturing firms should also keep optimizing and upgrading.

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Chapter 10
Cotton in Weaving Technology

Shamima Akter Smriti, Farial Islam Farha, Fahmida Siddiqa, Md. Jawad Ibn Amin, and Nawshin Farzana

Abstract The significance of cotton as one of the core raw materials in weaving can be realized based on the utility of approximately 75% of annual worldwide produced cotton in the production of woven fabrics. This chapter has mainly emphasized on a brief description of manufacturing processes to produce cotton woven fabrics along with multiple weave structures. Here, the basic weaving processes are described sequentially for the smooth handling of cotton yarn during fabrication. Besides, some particular preparatory processes for cotton weaving have been pointed out as the suitability of cotton yarn in several weave structures are different, so a few key production parameters of weaving differ from conventional loom to modern loom. Herein, this content covers various processing factors of cotton weaving for multiple looms, fundamental weaving calculation, and loom settings related to cotton fabrication.

Keywords Cotton weaving · Preparatory process factor · Weaving production parameter · Loom setting

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10.1 Introduction

Fabrics are mainly textile surfaces. These structures are incredibly long compared to their thickness. Although three methods, namely weaving, knitting, and nonwoven, are basically and commonly used to manufacture different designed fabrics, the term ‘weaving’ comes very first along with the introduction of human civilization itself. Historical evidence confirms that Egyptians made woven fabrics some 6000 years ago, and the Chinese made delicate fabrics from silk over 4000 years ago. Woven fabric is produced by the interlacement of threads placing perpendicular to each other. The yarns that are placed lengthwise or parallel to the selvages (edges) of the cloth are called warp yarns. The yarns that run cross-wise are called weft or filling yarns. There are numerous ways of interlacing yarns to produce a variety of fabric structures.

On the other hand, Cotton, for example, is hardly a “niche” fiber as it owns approximately 40% of the world’s fiber market. Cotton, like other farms, bred fibers like wool, cashmere, alpaca, silk, vicuna, and coir, has performance characteristics that could never be duplicated by synthetics. Degradable natural fibers have an advantage indeed over synthetics when it comes to the environment. Therefore, having eco-friendly features, Cotton is recognized as the most popular choice for several textiles all over the world in terms of its comfortability, easy handling, and cost-effectiveness [1].

When this excellent material is combined with weaving, then obviously, the product becomes a great one, especially in terms of comfortability and availability. However, no particular loom is used to fabricate cotton fabrics, as the basic principle of weaving is obligatory for the fabrication of any kind of fiber. The progress in cotton weaving was also attained with the continuous advancement in weaving technology which expanded this manufacturing process from a cottage to a cottage industry by innovating hand-operated fly shuttle loom in 1733 by John Kay; then developing power loom in 1785 by Edmund Cartwright and eventually, led to electric power loom with introducing increased not only productivity but also more advanced technologies in loom operating system [2].

In this chapter, a brief description of overall weaving processes related to cotton yarn is presented to help readers understand how perfectly cotton individual yarns are made into cloth, maintaining several processing parameters. Moreover, an active effort has also been taken to point out the significant regulations in different sections of weaving to produce a quality cotton fabric.

10.2 Warping

For carrying out a continuous weaving process, the warp and weft yarn needed to be prepared earlier. Though the weft yarn can be delivered directly to the loom. But the supply of a required number of warp yarn having an adequate length on an appropriate package needs some preparation. Warping is one of those preparation stages where a continuous length of hundreds of warp yarns being organized parallel to one another and are arranged on a beam by transferring the required number of yarns according to the width of the fabric from the cones or cheeses [3].

Warping involves developing parallel yarn on a package, which is either called a weaver's beam or warp beam. Weaver's beam can be set up at the back of the weaving machine, whereas warp beams are sent to the next process called sizing. The warp beam or weaver's beam surrounds with several hundreds of warp yarn in parallel form. The number of warp yarn wound at a time depends on the capacity of creels of warping machine [3, 4].

Among different types of warping systems, the most popular types are:

- Direct warping
- Sectional warping.

Both methods can be applied for carded and combed cotton yarn. The selection of the warping process typically depends on the circumstances and type of fabric to be manufactured.

10.2.1 Direct Warping

The procedure of direct warping is straightforward. Usually, this process is applied with the cotton warp of a single color, which requires the application of sizing later. For example, a weaver's beam may need up to 12,000 warp ends, whereas a modern warping machine can produce beams with only 800–1200 warp ends. In such cases, this is common practice to produce several warp beams, which are later combined in the sizing process to produce the weaver's beam. This combining process may involve warp beams of different colors if necessary. Besides, these warp beams can also be combined with an easy beaming procedure if the sizing process is not required. This direct warping process is also known as high-speed warping [5].

10.2.2 Sectional Warping

This type of warping is employed in the cases of small width fabric of complicated color patterns. The beam used in this warping is tapered on either side. Small sections of the same patterns and equal lengths are wound on beginning with the tapered side in the first step. The geometry of this concentrically wound sections of yarns is that one side of the beam is tapered to ensure the stability of the yarns in a section. Then rewinding of all the sections is done on to the weaver's beam.

10.2.3 *Different Sections of Warping Machine*

Both type of warping machines mainly has two sections:

(1) Warping Creel
(2) Headstock

(1) **Warping creel**
Creels are a type of metallic frame, where several yarn packages can be fitted. Ends from each package are drawn towards the headstock unit. This creel is usually operated with sensors to be detected in case of yarn tension variation and yarn breakage. The creel capacity of modern warping machines is generally between 800–1200.

(2) **Headstock**
It is an assembly where all the warp ends are wound on the beam parallel to each other. Constant speed and tension are recommended to be maintained during the process.

10.2.4 *Commonly Used Parameters During Warping*

A data of warping machine creel capacity, speed, and yarn length used in research:

Patil et al. [6], conducting their research on improved productivity of warping, used the parameters shown in Table 10.1 to conduct the study. These parameters may be referred to as the commonly used parameters in industries of this time.

Table 10.1 Machine details selected for study [6]

Warping machine specification	Fabric type 1	Fabric type 2	Fabric type 3	Fabric type 4
Manufacturer: Benninger	Warp end count 60 Ne	Warp end count 20 Ne	Warp end count 40 Ne	Warp end count 100 Ne
Model 2007	Set length—21,000 m	Set length—16,000 m	Set length—19,000 m	Set length—23,000 m
Creel capacity 1088	Cone weight—1.89 kg	Cone weight—2.5 kg	Cone weight—1.8 kg	Cone weight—1.25 kg
Make-Switzerland	No of ends-9816	No of ends-7422	No of ends-7536	No of ends-11028
V shape creel	Supplier—Alok SPG	Supplier—Govind Raja SPG	Supplier—Alok SPG	Supplier—Jayjoti SPG
Machine speed: max 1200	Beam length—3500 m	Beam length—2666 m	Beam length—3166 m	Beam length—3833 m

10.3 Technical Discussion on Cotton Warping

The modern weaving machines are now equipped with the latest weft insertion devices with much higher speed. For coinciding with speed, warp yarn must have improved and uniform quality, confirming sufficient strength to withstand the mechanical stress and friction. The minimum the number of yarn breakage and knots, the higher will be the quality. The knots must be of standard size and type to pass through the heddle eyes and reed dents.

10.3.1 Maintaining the Mechanical and Physical Properties of Cotton Yarn

The distance of yarn packages, even considering the package position in the dedicated creel plays a vital role in maintaining the cotton yarn properties. The tensile strength, elongation %, must not be changed and be well maintained for better weaving efficiency. From lower to higher, any count cotton yarn; these properties are maintained best when the yarn package is at the nearest position from the warping beam. A decrease in yarn strength can be occurred due to the long way and mechanical friction that the yarn has to pass when it is fixed further away from the warping beam or if it is fixed in a longer distance creel [7].

For keeping yarn breakages lower, it is recommended to maintain a single yarn strength of about Rkm (Reisskilomter) 15 for yarn from 7 to 20 Ne (coarser yarn), Rkm 20 for yarn from 22 to 40 Ne and Rkm 25 for finer yarns. Also, splicing portion strength should be kept 80% more than the regular area. It is also recommended to keep the cotton yarn under appropriate moisture regain state. The breakage rate of a quality warp beam should be within the limit of 0.5–2 per million meters [8].

A yarn breakage data has been published in a technical report by J. H. Majumder. It is observed from the data that, card ring compact yarn (KWC) breakage rate is comparatively better than the combed ring compact yarn (CWC). Whereas the open end yarn (OE) has a maximum breakage rate than other ring yarns [8] (Table 10.2).

10.3.2 Maintaining Uniform Tension

Tension during unwinding of a full package is much more than that of an empty package. In the beginning, tension over the yarn is high as the yarn comes under frictional forces and also due to a large balloon formation. The high tension due to a full package is somehow balanced by the balloon formation tension towards the finishing of the bobbin when the yarns are unwounded from a large balloon.

Table 10.2 Warp yarn breakage rate recorded in a reputed textile mill of Bangladesh [8]

Count of yarn	Average CSP (Count Strength Product)	Approximate Rkm	Average U %	IPI (Imperfection Index in 1000 m)	Breakage rate per million meter
40 CWC	3057	21.4	9.44	102	1.01
40 KWC	2768	19.4	11.89	661	1.9
30 CWC	3147	22	8.5	41	1.37
30 CWC	2848	19.9	10.5	328	1.45
20 KWC	2833	19.8	9.15	62	1.66
20 OE	1806	12.6	10.5	50	1.6

10.3.3 Circular Shape of the Warping Creel

A new concept of arranging the warping creels was registered in the US patent in 2003. Where the warping creels are arranged in a circular shape. This helps to maintain an equal distance among the warp yarns. Also, it requires a similar force to pull the yarn from the creel to the headstock that is shown in Fig. 10.1 [9].

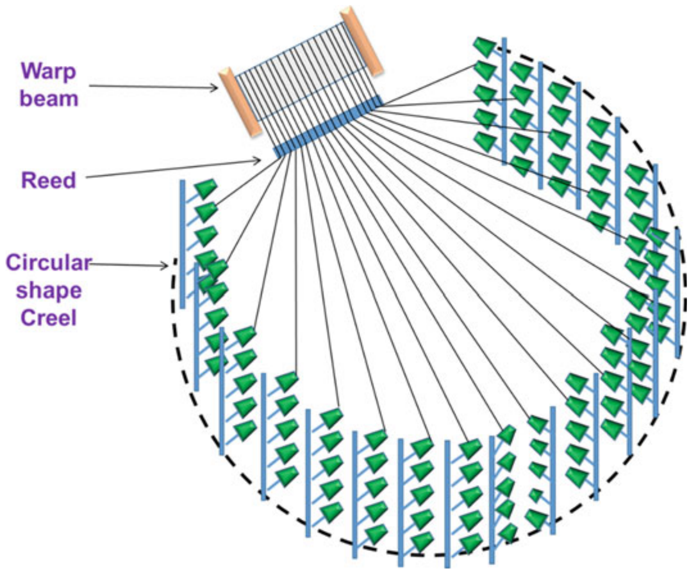

Fig. 10.1 The circular shape of the warping creel

10.3.4 Optimum Warping Speed

Warping speed can be considered as one of the variable parameters to obtain minimum yarn breakage and enhanced efficiency as well. There is an optimum warping speed coinciding with the characteristics of cotton yarn. Both higher and lower speeds than this optimum value can increase the breakage rate.

An increase in warping speed increases the ends breakage rate. For courser count, a rise in speed increases the breakage rate rapidly as compared with the medium count. This is due to the breakages of weak places and splices in the yarn. In the case of the finer count, an increase in speed shows an increment in the end breakage rate linearly [6].

10.3.5 Beam Drum Pressure

In modern high-speed warping machines, a drum pressure is applied to construct a compact, and cylindrical warp beam of parallel warp ends. The beam drum pressure has a significant effect on the cotton yarn breakage and yarn hairiness. The amount of increase in the beam drum pressure associated with elongation property of cotton yarn when it was wound on beam bracket.

Lower the beam drum pressure, lower the number of cut cotton yarns will be. A higher drum pressure can affect the elongation and strength of the cotton yarn, imposing a higher tension. This can increase the breakage rate considerably. In a study of recent developments of warping, Vashi et al. [10] found that 40 Ne cotton (commercial name Giza 83) yarn in a direct warping machine has 6 to 8 yarn cuts at 29.42 MPa beam drum pressure, whereas yarn cuts increase to 23–25 at 39.22 MPa beam drum pressure. Also, rubbing on the yarn of a warp beam by the drum, which stops it abruptly, is a potential hazard to all the ends, causing a hairy yarn.

An increase in beam drum pressure increases the hardness of the beam, therefore, increases the tension on the warp yarn, which causes yarn breakage. In recent research on improved productivity of warping by Patil et al. [6] observed that in the case of coarser yarn, growth in the beam drum pressure increases the yarn breakage to a small extent, further enhancement in the drum pressure increases the end breakage significantly. Whereas in the case of finer yarn counts, higher beam drum pressure increases the warp yarn breakage rate to a small extent. A graphical presentation developed according to the mentioned research is in Fig. 10.2.

10.3.6 Density of Warp

Either a large number of warp ends, or a very long length of warp sheet can increase the density of the warp beam. Both can increase the yarn breakage rate. The warp

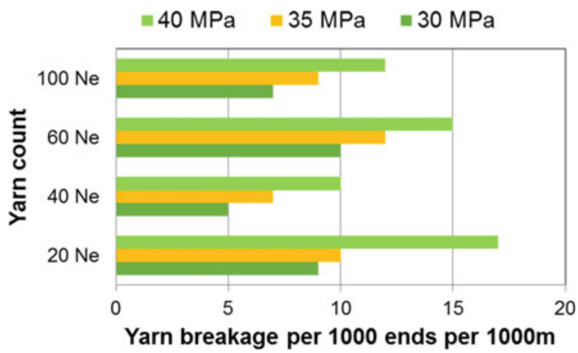

Fig. 10.2 The number of yarn breakage per 1000 ends per 1000 m of different beam drum pressure concerning different count [6]

beam has to be sufficiently compact to obtain satisfactory results in density. This compactness should be achieved by creating pressure by the drum rather should not be achieved by increasing tension.

10.4 Sizing

In weaving, the warp yarns are subjected to some degradative actions such as continuous rubbing, cyclic strain, and flexing action, inter yarn friction, and abrasion with different parts of the loom. For this, the warp yarn disintegrates, which ultimately leads to warp breakage, loom stoppage, efficiency loss, and several fabric faults. Sizing is required to increase the tolerance limit of weaving resistance.

Sizing is the application of a protective adhesive coating to the warp yarn to enable it to withstand the degradative action during the weaving process. The main objectives of sizing process are to coat warp yarns with a polymeric film-forming agent (size) and bind fibers of yarn to protect weak places in the warp yarns from destruction, to increase strength as well as to reduce fluff or hairiness so that they can prevent the mechanical strain in the weaving process.

10.4.1 Requisite Properties of Size Material Used for Cotton

The desirable properties of size material can be varied according to the type of fibers, yarn, loom, or fabric construction. Size materials used for cotton yarn sizing must possess some desirable properties so that a highly wear-resistant and efficient weave able sized yarn can be obtained. As cotton is cellulosic fiber, cellulose unit is essential to select an appropriate size material because if size material and fiber have similar chemical construction, good bonding will be achieved, which is required to hold the protruding fibers. An ideal size material for cotton has to be one with the following characteristics:

- The good film-forming property, i.e., must form a smooth and uniform coating on the yarn surface.
- Good adhesiveness can be derived by the type and number of bonds formed in-between size material and fibrous material. For this, a large number of –OH groups are required in size materials for cotton sizing so that the number of bonding points of the sizing material with fiber would be high.
- Quick and optimum penetration is required as excess penetration reduces yarn flexibility.
- Easy removability of size materials. For this, the low bond length between cotton and size material is required as strong bonds like covalent; electro covalent bond creates problems during desizing.
- Enough flexible and elastic sized film is required to cope with the flexing or bending of yarns around the back-rest, heald eyes and other loom components.
- Stable viscosity of size solution as it varies due to different reasons throughout the process.
- Lubrication and Softness so that the film can bend easily without forming cracks and yarn can pass easily through machine parts.
- Non-polluting.
- Relatively cheap as sizing is not a value-added process in woven fabric manufacturing, the cost of sizing should be minimized.

10.4.2 Basic Size Ingredients

The basic elements of sizing recipe are film formers or adhesive, lubricant, an antimicrobial agent. Chemical Structure of different adhesive materials are shown in Fig. 10.3 and comparative analysis of their properties are given in Table 10.3.

10.4.3 Lubricant Used for Cotton Yarn Sizing

Application of lubricant in size solution reduces the stiffness of the yarn surface and increases its abrasion resistance, smoothness, flexibility. Different types of lubricants are used for cotton yarn sizings such as tallow based wax, based on hydrogenated tallow glycerides and bleached tallow. Some synthetic tallow such as polyethylene glycol and polypropylene glycol are used. Wax should be added 3–5% of total size ingredients in size solution used for cotton to achieve smoothness and avoid stickiness.

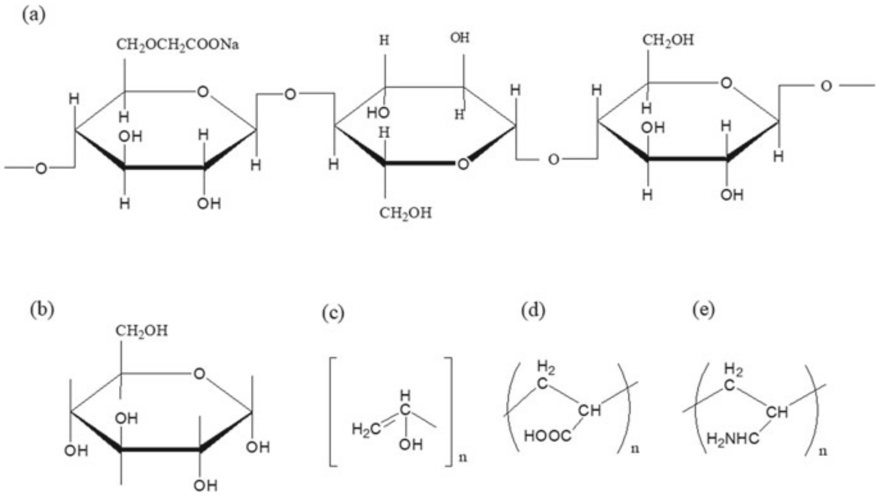

Fig. 10.3 Chemical structure of **a** carboxymethyl cellulose (CMC); **b** α-D glucose; **c** polyvinyl alcohol **d** polyacrylic acid **e** polyacrylamide [11, 12]

10.4.4 Gelatinization Process of Starch Solution

Gelatinization can be defined as the process in which the starch granules are heated in water, swell until its maximum swelling accomplished, then they burst and form a gel. The temperature at which the granules begin to swell rapidly and lose their property of birefringence is called gelatinization temperature. However, the gelatinization temperature is not a single temperature; it is a range of temperatures where the crystallinity of starch solution is lost. In pure water, this temperature is between 57 to 72 °C. In Fig. 10.4; gelatinization starts at point A, this temperature is called as pasting temperature. As the temperature increases, starch granules absorb more water, and viscosity of the solution increases from point B to C. At point C, maximum viscosity is reached; this is called the intensity of gelatinization. Then the super-swollen granule burst like a balloon under the influence of shear force applied by heating and stirring. As a consequence of that, the chain molecules of amylose and amylopectin come out within the solution, which causes viscosity reduction in size solution (C to D). The viscosity of the solution becomes stabilized at point E; this is called level viscosity (E). In this situation, the size paste is best suitable for the coating yarn surface. On storage and with decreasing temperature, starch pastes are solidified to a pulpy mass. This process is known as recrystallization or retrogradation of starch (at point F). It is determined by measuring the viscosity when the starch paste is cooled from 95 to 50 °C. This retrogradation has detrimental effects on the sizing agent, leading to poor storage properties, skin formation, the formation of deposits on the rollers, and reduced adhesive strength. Therefore, natural starches are increasingly being replaced by starch derivatives [11].

Table 10.3 Comparative analysis of different film formers properties used for cotton yarn sizing [11–13]

Key points of properties	Starch	Modified starch	Carboxymethyl cellulose (CMC)	Poly vinyl alcohol (PVA)	Acrylic sizing agent
Chemical composition	Monomer:α-D glucose, composed of amylose and amylopectin	Modified starch by physical, chemical or enzymatic treatment	Sodium carboxymethyl cellulose made by reacting mono chloroacetic acid or its sodium salt with alkaline cellulose	PVA prepared by hydrolyzing polyvinyl acetate, four types: super hydrolyzed, fully hydrolyzed, intermediate hydrolyzed, partially hydrolyzed	Three types: polyacrylate, polyacrylamide, and polymethyl acrylate
Film-forming property	Stiff	Soft but short film strength	Uniform and soft film, moderate film strength	Soft and high film strength	Soft with lower film strength
Viscosity stability	Very poor	Poor to excellent	Excellent stability over a range of temperature	Excellent, different viscosity available (from 5 to 65 cP)	Good
Fluidity	Low	Very high	High	Low to high	
Adhesion force to cotton (kp)	3.6	Similar to starch, but when acetyl and hydrophobic ester group were induced into acetate starch, its adhesion to cotton fiber was enhanced	3.9	4.9	3.5
Retrogradation or congealing	Very high	High to very low	Low	Low	High

(continued)

Table 10.3 (continued)

Key points of properties	Starch	Modified starch	Carboxymethyl cellulose (CMC)	Poly vinyl alcohol (PVA)	Acrylic sizing agent
Elongation (%)	8–12	Ester modified starch has high elongation property	10–25	100–150	100–600
Tensile strength (PSI)	600–900		2000–4000	7000–15,000	1000–2000
Pollution	Higher BOD, high pollution	Green size material	Low BOD, less polluted	High pollution	Most environment friendly
Resistance to microorganism	Very poor	Poor	High	High	–
Moisture content at 65% RH	15–20	–	15–20	8–9[a]	–
Cost	Cheap	Cheap ($0.69/kg)	Relatively high ($1.56/kg)	Expensive ($3.4/kg)	Relatively cheap than CMC ($1.112/kg)
Water solubility	Not soluble in normal temperature	Paste form at a lower temperature than Starch	Both soluble in hot and cold water	Both soluble in hot and cold water depending upon the extent of hydrolysis	Both soluble in hot and cold water
Flexibility	None	Medium to Excellent	Excellent	More flexible than CMC	Good
Removability	Easy de-sizing	Required hot water to remove	Easily removed by cold water	Easily removed by hot water	Easy desizing

(continued)

Table 10.3 (continued)

Key points of properties	Starch	Modified starch	Carboxymethyl cellulose (CMC)	Poly vinyl alcohol (PVA)	Acrylic sizing agent
Application	widely used in cotton fiber	Acid treatment starch (thin boiling starch) are used in warp sizing of cotton and cellulosic based fibers as well as some cotton or synthetic blends	Low or medium viscosity grade CMC in blends with starch is used for cotton warp yarn sizing	Because of short film-forming properties, PVA can be used as a good binder with Modified starch in cotton yarn sizing. Fully Hydrolyzed PVA suitable for cotton sizing	Poly acrylate and polyacrylamide have excellent adhesion to hydrophilic fiber like cotton. Combination of acrylic size and modified starch was applied in the sizing process of thin cotton fabric entirely instead of PVA

[a] At 70 °F and 65% RH, depending upon the degree of hydrolysis

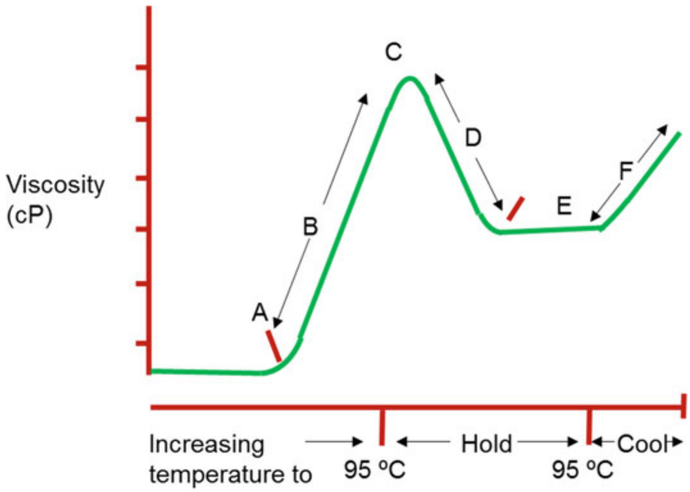

Fig. 10.4 Gelatinization behavior of starch, **A** gelatinization temperature or pasting temperature; **B** granules hydrate and swell; **C** intensity of gelatinization, **D** continue rupture of starch granules; **E** level viscosity; **F** retrogradation

10.4.5 The Innovation of Biodegradable Textile Sizing Agent

Due to environmental causes recently, PVA is substituted by other materials such as acetate or grafted starch. Zhang and his co-workers [14] had invented an easily permeable grafted starch size material by grafting polyacrylic acid, which has excellent sizing performance and the full capability of complete use in the sizing process of polyester/cotton instead of PVA. Although several pieces of research are being conducted to substitute PVA, yet it could not be replaced due to its excellent film-forming property. For example, starch derivatives applied at present could not completely substitute PVA. To fully utilize more excellency in the performance of grafted starch should be incorporated by overcoming the restrictions of high cost and low market share. On the other hand, re viscosity after moisture absorption along with high cost still does not let Acrylic sizing agents to be exploited for substitution of PVA. Whereas pure exploitation and low transport cost enable Solid acrylic sizing agents as one of the right choices for researchers. However, current investigation on this aspect is mainly based on two phenomena, firstly, to impart biodegradability in PVA by modification and secondly, to degrade PVA by developing strains. In a word, the development of real green textile size material is still possible if continuous efforts can be monitored along with higher quality, more function, fewer compositions, seriation, less or no consumption of PVA, or developing biodegradable PVA [15].

10.5 Sizing Machine

The sizing machine can be divided into five zones, which are shown in the block diagram in Fig. 10.5.

10.5.1 Creel Zone

This is the input section of the sizing machine where a large number of warper's beam can be placed differently. According to design, this zone can be named as over and under creel, equi-tension creel, vertical creel, and inclined creel. In over and under the creel system, the warp sheet in the rearmost beam may suffer more stretch

Fig. 10.5 Block diagram of sizing machine

and tension than the front-most beam close to the size box. This problem can be compensated by using an equi-tension beam where the warp sheets are subjected to equal tension and stretch irrespective of the position of the warper's beam. In the inclined creel, a constant inclination can be maintained in the path of the warp sheet by changing the height of the beam. But creel systems, as mentioned above, may require significant floor space, which can be minimized by using a vertical creel system. For maintaining uniform and adequate tension upon the warp sheet during the sizing process, this section plays an important role. As the radius of the warper's beam decreases, tension and stretch upon the warp sheet also increase. For adjusting warp tension on beam, dead weight with rope is suspended over the ruffles of the warper's beam (conventional sizing machine), or pneumatic pressure is applied on the bearing region of warper's beam. In the sizing process, the allowable stretch is 1–1.5% for cotton.

10.5.2 Size Box Zone

This is the most important zone in sizing machine where the warp sheet is immersed into the size paste and then squeezed under high pressure so that uniform coating of size film forms over the yarn surface. The major controlling points that effect on the size pick up % in size box zone for cotton yarn sizing are given in Table 10.4.

10.5.3 Drying Zone

After the size box, the warp yarn passes through the drying zone, where 75–80% energy of the complete sizing process is consumed to evaporate the water from size paste. The sized yarn can be dried in various ways such as cylinder drying, infrared radiation, and hot air drying. Among them, multi-cylinder drying is commercially more successful and used for cotton sized yarn drying. The surface speed of the cylinder is tried to keep similar with the translational speed of the yarn sheet coming from size box so that abrasion between these two can be avoided. The maximum proposed machine speed is 120 m/min. The number of the dry cylinders (Teflon coated) may vary from 2 to 32 with four or more size box depending upon the amount of water to be evaporated in unit time. Drying cylinders come in diameters of 76–86 cm, with working widths of 1.5–1.8 m.

The drying temperature for cotton yarn sizing is 100–150 °C. The temperature of each dry cylinder can be controlled by fitting a unique pressure regulating valve as an overheated cylinder could produce harsh and brittle yarn whereas under heated cylinder would give sticky yarn. All modern sizing machine is equipped with moisture measuring tools so that moisture regains of sized yarn can be controlled. For cotton sized yarn, 6–7% moisture regain is recommended.

Table 10.4 The major controlling point in size box [4, 11]

Temperature control in the size box	The ideal temperature of the size box should not be less than 90 °C. For cotton yarn sizing, size box temperature should be kept 85–95 °C
Wet pick up % for cotton	120–130%
The viscosity of size paste	It depends on the cotton yarn count and warp density A high viscosity size solution is required for finer yarn count and higher ends per cm
Weight of squeezing roller	The weight of the squeezing roller should be 200 kgs with an extra loading facility. The amount of size added to the yarn can be decreased by increasing the weight of the squeezing roller. If the speed is more than 25 m/min, then weight should be higher and around 400 kg. An increase in roller weight from 90–227 kg reduces the percentage of the size required in pure sizing by about one-fifth
The hardness of the squeezing roller	Shore hardness of the rubber-coated roller should be between 46° and 55°
Depth of immersion roller	In modern sizing machine, the depth of immersion roller can be adjusted with the speed of the yarn sheet. The depth of immersion in size solution and the speed of the machine governs actual time that yarn takes to pass through the size box. The longer the yarn is in contact with the size solution, the more size material it will absorb
The density of warp yarns in the size box	High warp density in size box affects yarn hairiness, size pick up %, and drying. So, Size box occupation % can be used to determine the number of yarns accumulated in the size box. It can be determined by Eq. 10.1 $\text{Occupation}\ \% = \frac{Number\ of\ ends\ being\ run}{Yarns\ per\ unit\ length\ at\ 100\% \times section\ beam\ distance\ between\ flange} \times 100$ (10.1) Here, yarns per unit length at 100% means several yarns placed side by side in specified unit length, and section beam distance between flanges means the width of the yarn sheet in the size box. From expertise knowledge, a range of maximum Ends per cm in size box for different cotton yarn 10–20 Ne > EPcm 12–20 30–50 Ne > EPcm 22–31 The maximum EPcm in size box depends on yarn type and count

(continued)

Table 10.4 (continued)

Temperature control in the size box	The ideal temperature of the size box should not be less than 90 °C. For cotton yarn sizing, size box temperature should be kept 85–95 °C		
Squeeze roller pressure	The desired amount of size penetration can be achieved by controlling the pressure of the squeeze roller. Excess size penetration decreases yarn flexibility, whereas lower penetration flake off size coating easily. An effective combination of squeeze rollers such as rubber-coated and steel rollers could generate around 1–5 tones pressure per linear meter. Hari and Behera [16] studied the weaving performance, and physical properties of cotton yarn (40 Ne) sized with thin boiling starch at high (2500 kPa) and low squeezing pressure (500 kPa). It was observed that high pressure sized yarn exhibits better weaving performance than low pressure sized yarn, and it also causes no yarn flattening and gives high penetration. The properties of high pressure sized (HPS) yarn and low pressure sized (LPS) cotton yarn are given below:		
		HPS	LPS
	Breaking strength (g)	335	355
	Breaking elongation (%)	3.4	3.3
	Film thickness (mm)	0.008	0.014
	Size penetration (mm)	0.020	0.080
	Packing density	0.618	0.593
	From the above table, it is cleared that HPS film becomes thinner, but better penetration occurs, which facilitates more inter-fiber bonding and better anchoring of size film to yarn surface. This increases weaving performance		
Tension on the size box	In modern sizing machines, yarn tension in size box is maintained by using servo meter		

10.5.4 Splitting Zone

Due to the nature of sizing, the warp yarn sheets may adhere together when coming out from the dryer zone. So they need to be separated, which is done by using well-polished bust rods (lease rod). The total number of lease rod should be one less than the total number of warp beams used in the creel zone. The lease rod must occupy the full width of the machine and split the yarn sheet evenly so that each sheet represents the warp beams from which they came.

10.5.5 Beaming Zone

This zone consists of two guide rollers, one drag roller, and an expandable comb that supports to adjust varying width of weaver's beam. The yarns are passed through the adjustable comb, then guided by drag roller to wrap on weaver's beam.

10.5.6 Stretch of Cotton Yarn During Sizing

Warp yarns are kept in tension during sizing, which causes a permanent stretch in yarn. It leads to a decrease in extensibility or elongation at the break of sized yarn, which results in a high warp breakage in the loom. If the stretch of cotton is kept 2% or less, then the extensibility of sized yarn could be controlled; otherwise, loom performance would be deteriorated significantly. MT. Devare et al. [17] studied the effect of different stretch % on elongation at break % and loom breakage rate of cotton yarn. It was found that if the yarn undergoes through the higher stretch, the breakage rate in the loom is increased, which is described in Table 10.5.

Table 10.5 Effect of stretch % of cotton yarn in sizing on elongation and loom performance [17]

Stretch %	32 Ne cotton yarn with 4.3% elongation of the original yarn		60 Ne cotton yarn with 4.49% elongation of the original yarn	
	Elongation % of sized yarn	Breakage/Shift on the loom	Elongation % of sized yarn	Breakage/Shift on the loom
0.4	3.86	9.8	3.8	9.39
0.6	3.57	12.7	3.64	13.25
0.9	3.45	16.3	3.51	16.57

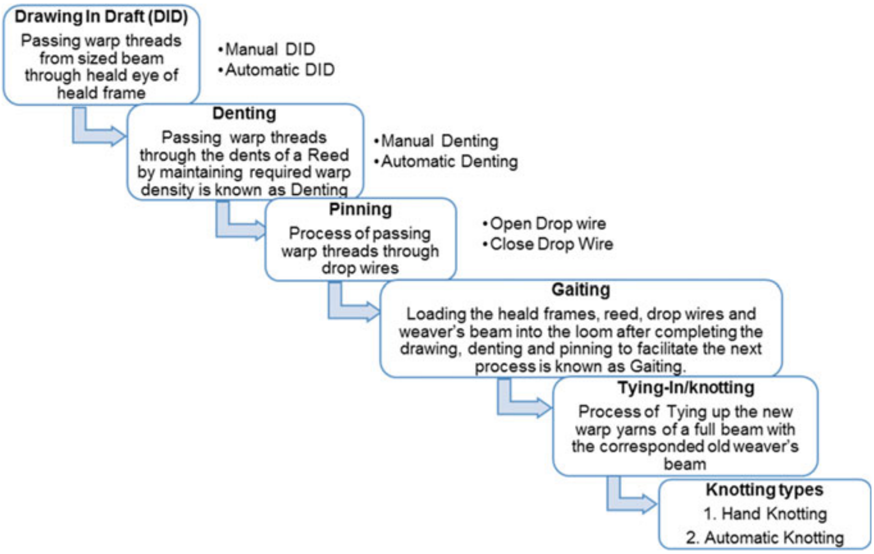

Fig. 10.6 Description of looming process sequence

10.6 Looming

The process of preparing a loom before starting the weaving process is commonly known as looming. It includes Drawing in Draft (DID), Denting, Pinning, Gaiting, and knotting of warp threads by using different looming elements (drawing hook, denting plate). The sequence of the looming process for cotton fabric production is displayed in Fig. 10.6, while the basic looming process is shown in Fig. 10.7.

10.7 The Relation Between the Drop Wire Densities and Yarn Count

A drop wire is a lightweight narrow metallic sheet that is hung in the air by the tensioned warp end. Drop wires are available in stainless steel, or oxidation resistant galvanized design, and the thickness varies from 0.15 to 1.15 mm. Drop wire rails can be fitted upto 8 in a loom.

According to ISO 1150, specification of drop wires for electrical warp stop motion that is suitable for automatic drawing-in of cotton weaving is—Length = 145–165 mm, width = 11 mm, and weight range from 1.9 to 6.6 g (according to the thickness variation from 0.2 to 0.6 mm). However, for a particular range of cotton yarn count, drop wire weights are varied. A typical weight range followed by Groz-Beckert company for a different count of cotton yarn is given in Table 10.6.

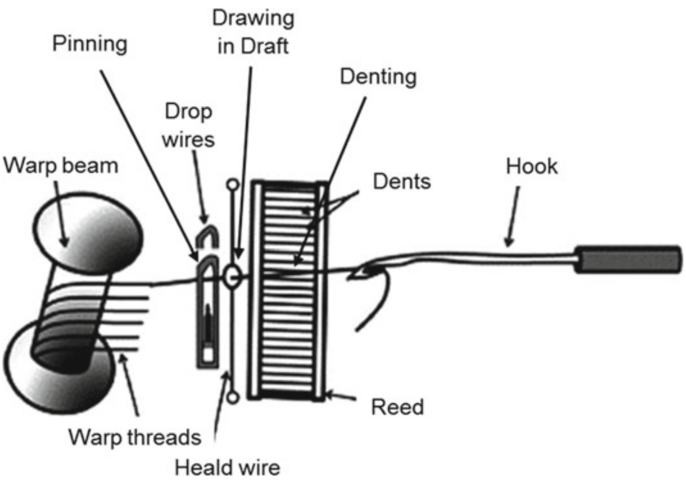

Fig. 10.7 Diagram of looming process [18], reprinted with permission © Elsevier

Table 10.6 The relation between warp yarn count and dropper weight [19]

English count (Cotton) Ne	Weight in gram
>66	<1.3
66–42	1.3–1.9
42–30	1.9–2.6
30–24	2.6–3.2
24–18	3.2–3.9
18–10	3.9–5.2
10–6	5.2–7.8
6–4	7.8–13.0
4–3	13.0–18.2
<3	18.2–22.7

Maximum drop wire densities for cotton yarn depend on warp yarn specifications. For cotton spun yarns and high-speed weaving machines, heavier drop wires are recommended to ensure proper warp stop motion function. It varies 50–5 drop wires per cm on each rail according to the thickness from 0.2 to 1.0 mm of each drop wire.

10.8 Shedding

Shedding is the act of dividing the warp threads according to design into two parts to allow the passage of shuttle/weft inserting elements from one side of the loom to the other side. From the very beginning of the weaving process, paddle/treadle shedding had been used in handloom. With time, several shedding mechanisms are being introduced and accepted by the weavers to produce a wide range of designed fabrics. The most commonly used shedding mechanisms in conventional loom are Tappet, Dobby, Jacquard shedding, or combinations of these. Although, Cam shedding is the widely used shed formation technique in most of the modern loom.

10.8.1 Cam Shedding

The shedding mechanism is operated by two shedding cams. The shedding cams are mounted on the bottom shaft in the case of plain weave design, which needs to employ only two heald frames. However, wherever the design requires operating more than two heald frames, separate tappet shafts fitted to the bottom shaft are used. The shedding cams are mounted on the tappet shafts. Plain simple twill and simple satin designs can be produced by the cam shedding mechanism, which can handle weave patterns that utilize up to as many as 14 different heald frames. This system is simple, inexpensive to design, and reliable for producing fault-free fabric. Also, it does not restrict the weaving machine speed. The main disadvantage of the cam shedding mechanism, however, is their restricted pattern possibilities. To overcome this constraint, more versatile shedding mechanisms, namely, dobby and jacquard, are utilized [2].

10.8.2 Dobby Shedding

Dobby mechanism can control up to 30 heald frames. For cotton weaving, a maximum of 24 heald frames can be used due to the staggering problem of heald frames. As more number of cotton warp yarns increase the number of heald frames, thus enhance the applied tension on the cotton yarn with an increased angle. But cotton yarn has only a 6% extension, which is justified only within the use of 24 heald frames. This phenomenon has been explained in the shed geometry section (Fig. 10.8).

However, two types of dobby mechanisms, the negative dobby, and the positive dobby, are mainly used. In negative dobby shedding, the dobby lifts the heald frames, which are lowered by a spring motion. In positive dobby shedding, the dobby raises and lowers the heald frames, and the springs are eliminated. Negative or positive dobbies are further classified as single lift and double lift. The double lift dobby's cycle occupies two picks, and therefore, most of its motions occur at half of the loom speed, which allows higher running speed. All modern negative dobbies are double lift dobbies. Although this type of dobby has been primarily replaced by positive dobby. The need for higher speed to improve productivity coupled with the demand for heavier lifts, particularly on wider looms, has led to the more widespread use of the positive dobby. In this system of shedding, heald frames are both raised and lowered by dobby mechanism, and springs are eliminated. A later development

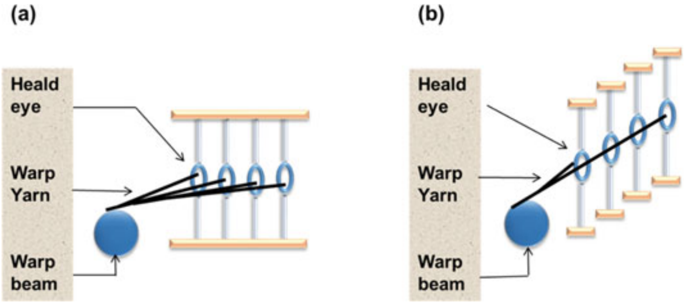

Fig. 10.8 Staggering of heald frame. **a** Different position of warp yarn due to the same position of heald frame; **b** Same line of warp yarns due to staggering of the heald frame

employs a rotary, instead of reciprocating action, to generate the lift given to the heald frame.

10.8.3 Jacquard Shedding

The Jacquard machine was invented by Joseph Marie Jacquard served as the prototype for a very wide range of weaving and knitting machines in the textile industry as well as those in lace making. When a big or complicated design is to be made in weaving, jacquard shedding is used. In this shedding, the warp ends are controlled individually by harness cords, and there are no heald frames. There will be as many cords as there are ends in the warp, which enables unlimited patterns to be woven. Jacquard machines can be mechanical or electronic with single or double lift mechanism. One of the simplest of these is the single lift single cylinder.

Jacquard, with one needle and one hook for every end in the repeat is called single lift single cylinder jacquard. Standard configurations have 200, 400, or 600 needles. For example, 600-needle jacquard generally has 12 horizontal rows of needles, with each row having at least 50-needles plus a few extra needles. Each needle is kinked around a vertical hook, which controls each end [2].

As most of the fancy fabrics are produced from delicate yarns, so cotton yarns are rarely operated by Dobby and jacquard shedding mechanisms. Also, to avoid the heavyweight of shedding along with more cotton yarns, these shedding techniques are not recommended for cotton weaving. However, to produce specially designed fabrics of sophisticated cotton yarns, there has not a very good alternative of dobby and jacquard loom. Although most common weave structures of cotton yarn, for example, plain, twill, and rib are produced by cam shedding.

10.8.4 Pneumatic Shedding

Apart from the above basic shedding mechanisms, modern looms are also incorporated with some advanced shedding mechanisms, which are modified shedding with the variable power source. Among those, Pneumatic shedding is used to a great extent due to its fruitful advantages. Pneumatic shedding is generally based on the pneumatic power, which is referred to the Fluid power indeed. Fluid power is a term covering both pneumatic and hydraulic power. Pneumatic deal with the use of compressed air as the fluid, while hydraulic power covers the use of oil and other liquids. Pneumatic systems are widespread and have much in common with hydraulic systems, with a few key differences. Pneumatic systems respond very quickly and are commonly used for low force applications in many locations on the factory floor. In Pneumatic shedding, the air pressure is used to transmit power to divide the warp threads into two layers. This new shedding mechanism can drastically increase the productivity being incorporated into a local weaving loom along with reduced time cost, labor cost, and space often needed by the operators of the local weaving machines. One report showed that through this shedding mechanism, the fabric having a 500–900 mm width could be weaved at a maximum of 172 weft cycles per minute. Maximum 24 heald frames can be controlled. It has also eliminated the need for complicated system of gears, cams, and levers leading to less noise pollution at weaving shed. The sample loom that is manufactured with pneumatic shedding is ideal for use in any space-limited environment such as office, design studio, and R&D center [20].

10.9 Shed Geometry

On a weaving loom, the warp yarn is divided into two half to make up a shed. This division makes up a specific geometry of divided warp yarns, called “Shed Geometry.” Shed geometry plays a vital role in controlling warp yarns’ tension, elongation, and friction between them. Resultantly, this helps in adjusting the weft density of fabric by controlling pick penetration, warp, and weft yarn breakages, and loom stoppages, hence machine efficiency, and also helps to control/avoid fabric faults produced due to these. Shed geometry is mainly classified based on different weave structure and types of fabrics shown in Fig. 10.9.

Each shed type has its setting and adjusting parameters as shed geometry includes some particular components of a loom like a frame height, frame depth, cloth support (front rest) height, back-rest (and deflecting roller) height, and depth, virtual shed dividing line, dropper box adjustment and dropper’s movement, top shed line, bottom shed line, front shed, rare/back shed. Although different shed style has different impacts on the tension of warp yarn and weave structures. For weighty fabrics with high warp densities, such as denim, sailcloth, or awning fabrics poplins on account of appearance, the strongest asymmetric shed is maintained in the loom. So, how to avoid warp yarn breakage controlling proper tension and elongation % of cotton yarn by

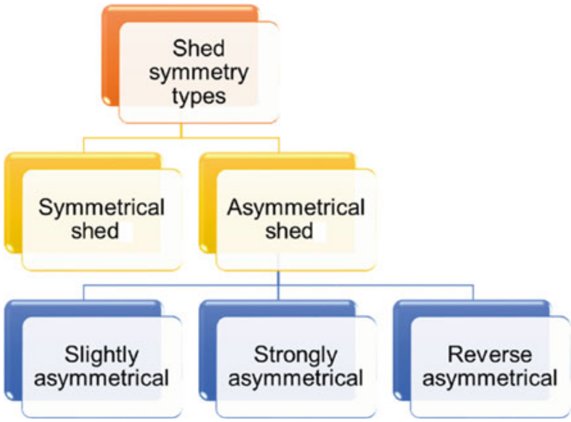

Fig. 10.9 Classification of shed geometry

appropriate shed geometry is of great significance. Figure 10.10 is a simple example of the strongest asymmetric shed for a better understanding of this phenomenon [21, 22].

Here, A weaving zone is assumed where A is the position of fell of cloth, and PQ is the reference line. For producing the strongest asymmetric shed, the height of the front rest roller's position is lifted 3 mm from 0 mm (in back-rest height scale), and the back-rest roller's position is lifted to 30 mm.

Weaving zone length, AG = 1000 mm.

Front shed zone length, AB = 250 mm.

Back shed zone length = 750 mm.

Shed height from reference line = 40 mm.

Shed depth from reference line = 40 mm.

Fell of the cloth from reference line = 3 mm.

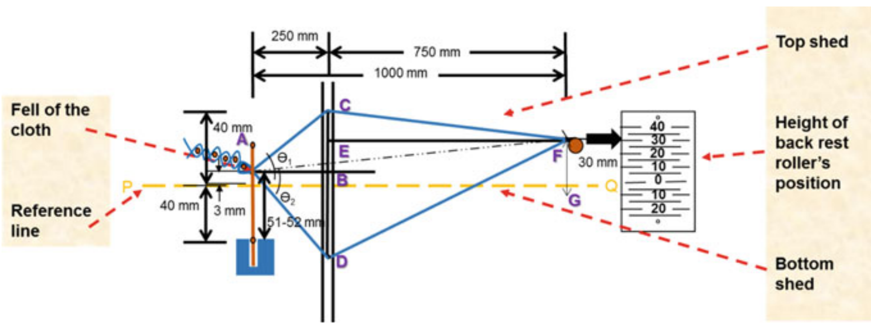

Fig. 10.10 Calculation of warp strain from shed geometry

Initial length of yarn = AF.

Extended length of yarn for top sheet = AC + CF.

Extended length of yarn for bottom sheet = AD + DF.

Strain of top sheet = (AC + CF) − AF.

Strain of bottom sheet = (AD + DF) − AF.

Let's calculate the value of [(AC + CF) − AF] & [(AD + DF) – AF].

Calculation of Strain on the top sheet

$$\begin{aligned} AC &= \sqrt{AB^2 + BC^2} \\ &= \sqrt{250^2 + (40 - 3)^2} \\ &= \sqrt{62500 + 1369} \\ &= \sqrt{63,869} \\ &= 252.723\,\text{mm} \end{aligned}$$

$$\begin{aligned} CF &= \sqrt{EF^2 + EC^2} \\ &= \sqrt{750^2 + (40 - 30)^2} \\ &= \sqrt{562,500 + 100} \\ &= \sqrt{562,600} \\ &= 750.066\,\text{mm} \end{aligned}$$

$$\begin{aligned} AF &= \sqrt{AG^2 + GF^2} \\ &= \sqrt{1000^2 + (30)^2} \\ &= \sqrt{1000000 + 900} \\ &= \sqrt{1000900} \\ &= 1,000.449\,\text{mm.} \end{aligned}$$

Strain of top sheet of warp = (AC + CF) – AF.

= (252.723 + 750.066) – 1,000.449.

= 1,002.789 – 1,000.449.

= 2.34 mm.

Percentages of Strain on top sheet of warp $= \frac{2.34}{1{,}000.449} \times 100\%$
$= 0.234\%$

Calculation of Strain on the bottom sheet:

$$\begin{aligned} AD &= \sqrt{AB^2 + BD^2} \\ &= \sqrt{250^2 + (40 + 3)^2} \\ &= \sqrt{62500 + 1849} \\ &= \sqrt{64,349} \\ &= 253.671\,\text{mm.} \end{aligned}$$

$$\begin{aligned} DF &= \sqrt{EF^2 + ED^2} \\ &= \sqrt{750^2 + (40 + 30)^2} \end{aligned}$$

$$= \sqrt{562,500 + 4900}$$
$$= \sqrt{567,400}$$
$$= 753.259\,\text{mm.}$$

$$\text{AF} = 1,000.449\,\text{mm.}$$

The strain of the bottom sheet of warp = (AC + CF) – AF.

= (253.671 + 753.259) − 1,000.449.

= 1,006.93 − 1,000.449.

= 6.481 mm.

Percentage of Strain on bottom sheet = $\frac{6.481}{1,000.449} \times 100\%$

= 0.648%.

Thus, the 6% elongation of cotton yarn is controlled during the shedding of any kind of weave structure. If the same weaving zone is used for the remaining shed types with individual setting parameters, then strain percentage on warp yarn will be changed, which is summarized in Table 10.7.

From Table 10.7, it has observed that if the Back-rest lift from the reference line, then strain decreases in the top sheet and increases in the bottom sheet and vice versa.

Table 10.7 The relation between shed type and strain on the warp sheet of various fabrics based on Fig. 10.10 calculation

Shed type	The strain on top sheet (%)	The strain on bottom sheet (%)	Front rest lift from the reference line (mm)	Back-rest lift from the reference line (mm)	Suitable fabrics for each shed
Strongly asymmetric shed	0.23	0.65	3	30	High warp density fabric such as denim, sailcloth, awning fabrics, poplins on account of the appearance
Slightly asymmetric shed	0.36	0.46	1	10	All light to medium weight fabrics
Symmetric shed	0.30	0.30	0	0	Very light fabric such as voile, gauze
Symmetric shed for special cloths	0.71	0.35	0	−15	Mostly satin, Jacquard fabrics, dobby fabric

10.10 Picking

The process of propelling the weft yarn through the open shed by a weft insertion element continuously across the width of the loom is called picking. It is the second primary motion of loom, which is mainly classified according to the weft insertion system. In early manual looms, weft yarn was inserted by an oblong-shaped wooden element called a shuttle. Over pick or an under pick mechanism is used in conventional shuttle loom. But this picking system suffers many drawbacks such as low speed, high power consumption, high noise level, and low-quality fabric. A lot of researches have been conducted to avoid the use of shuttle in picking system to overcome this problem. The result of this is the innovation of air-jet, projectile, rapier, water jet, multiphase weft insertion system, which are also called the shuttleless loom. By using a picking mechanism, different types of yarns can be selected one after another. For making delicate cotton fabric, the conventional picking mechanism is still used with air-jet, rapier and projectile picking mechanism.

10.10.1 Classification of Picking Mechanism

See Fig. 10.11.

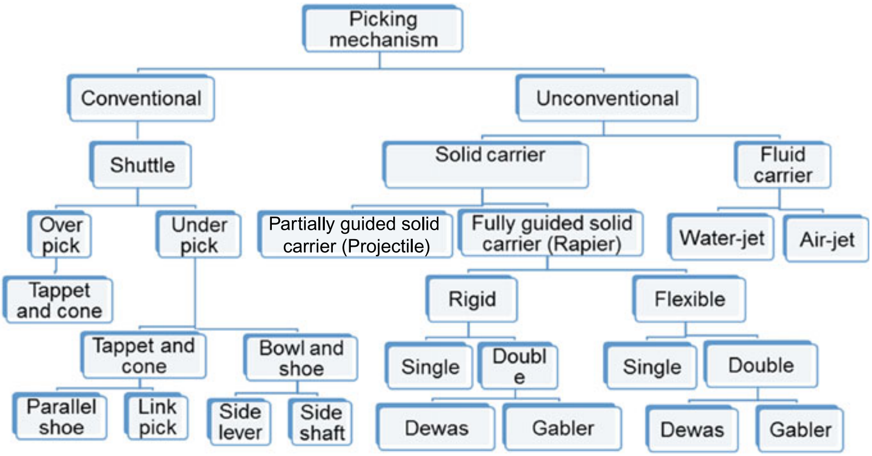

Fig. 10.11 Classification of picking mechanism

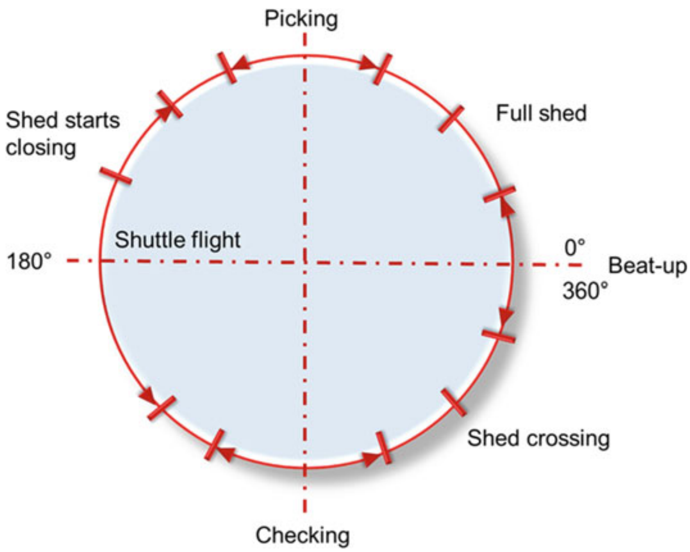

Fig. 10.12 The timing diagram of shuttle loom

10.10.2 Loom Timing

When relative chronological sequences of various primary and secondary motions are expressed in terms of the angular position of the crank, then it is called loom timing. The crankshaft angle of 0° on the crank circle is taken at the front center or beat-up the position of the sley. Usually, in cotton weaving loom, the shedding motion is set in such a way that when the crank reaches 270°, the heald frames are leveled. The timing diagram of two cotton-weaving looms, i.e., shuttle loom with over and under picking mechanism and air-jet weaving machine, are shown in Figs. 10.12 and 10.13.

A comparative analysis for picking motion through loom timing diagram of Shuttle loom (over & under picking) and modern loom (air-jet picking) used for cotton is given in Table 10.8.

10.10.3 Conventional Picking Mechanism for Cotton

In cotton-weaving, a shuttle of 30 cm length and 3.81 cm dia. in the center has been used for carrying the weft yarn. This weft carrier (450 g in weight for cotton weft yarn) plays mainly three functions.

- Housing a weft yarn package in the form of pirn inside its hollow.
- Propelling of this pirn package across a warp shed.

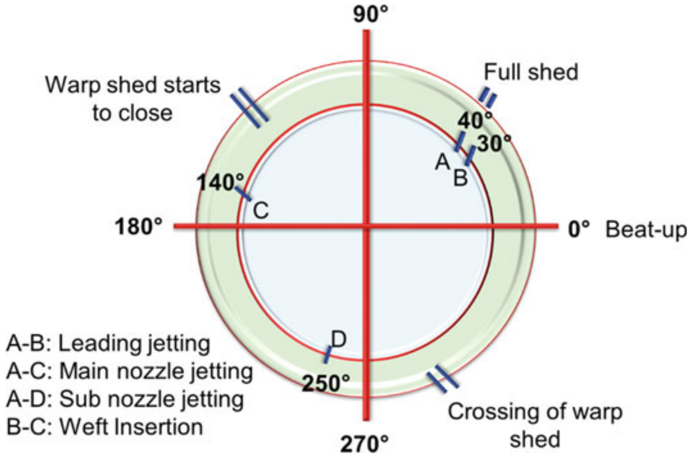

Fig. 10.13 The timing diagram of air-jet loom [23]

- The smooth unwinding of the desired length of weft yarn from the static pirn package.

Actually, in conventional picking mechanisms, picks have been moved by some negative action such as over pick and under pick mechanism, which is the arrangement of picking arm, picking cone, picking cam, picking strap, picking stick, and bottom shaft. In over pick, the position of picking arm fulcrum is above the shuttle box, whereas in under pick, it is situated entirely under the shuttle box. For cotton weaving, over pick motion is extensively used for preparing light and medium weight cotton fabric [24].

10.10.4 Unconventional Picking Mechanism

The multitasking shuttle in a conventional picking mechanism is replaced by a lightweight solid or fluid carrier whose flight may be controlled positively, partially, or free. Here, the weft carrier performs only the function of propelling the pick through comparatively small shed depth from the weft storage package such as cone placed stationary on out of the loom.

The partial guided solid weft carrier known as projectile or gripper or missile, made of steel with a dimension of 90 mm $\times$ 14 mm $\times$ 6 mm, measuring between 40 and 60 g in mass [4]. Projectile grips the tip of weft by its clamp and flies with minimum air resistance through a set of steel rakes, which precludes the possibility of the projectile from flying out of a warp shed and also rubbing action between warp yarns and projectile. The torsion bar picking mechanism is the heart of the projectile propulsion system. This torsional rod preserves torsional energy, which is used for releasing the projectile through the warp shed. So, the speed of the projectile depends

Table 10.8 Picking motion through loom timing diagram of shuttle loom (over & under picking) and modern loom (air-jet picking) used for cotton [23, 24]

Crank angle (degree)	Picking and checking of the shuttle	Crank angle (degree)	Weft insertion by air-jetting
80–110°	The shuttle leaves the box and enters in to the warp shed	30–40° (A to B)	Leading jet angle range where the air-jet from the central nozzle is blown before the pick is released from the solenoid pin. It is required for straightening the tip of the weft yarn before insertion
105–110°	The shuttle moves in the box in under pick loom	30–140° (A to C)	Leading jet angle of the main nozzle jetting
240–250°	The shuttle leaves the warp shed	30–250° (A to D)	Leading jet angle range of sub nozzle where air-jet from sub nozzle is blown before the tip of pick fed into the guide channel reaches the first sub nozzle. It has the advantage that when the tip of pick yarn reaches sub nozzles earlier than set timing, the tip of the pick is straightened out preventing the tip from losing its speed
110–240°	Shuttle flight and Pick insertion range	40–140° (B to C)	Pick runs freely between its releasing and stopping position done by the solenoid pin
270°	Shuttle strikes the swell in the shuttlebox		
300°	The shuttle comes to rest		

on the torsional angle of the bar, not on the machine speed. In this system, the torsion rod is twisted through an angle φ radian, the picking energy, or the torque generated by this is given in Eq. 10.2 [25].

$$M_t = K_t \varphi = \frac{\pi d^4 G \varphi}{32 l} \tag{10.2}$$

Table 10.9 Picking points of projectile looms according to their width [25]

Loom width (cm)	545,393	367	333	283	220,189
Picking point	110°	110°	120°	135°	150°

where K_t = torsional rigidity of rod in N-m.

d = diameter of torsion rod (m).

G = shear modulus of torsion rod (N/m^2).

l = Length of torsion rod (m).

The distance traveled by the projectile can be modified in the loom by moving the receiving unit of the projectile across the width. For this, more than one width of fabric can be woven at a time. The typical width of a projectile loom is 330–540 cm. Picking points of different Sulzer Ruti Projectile looms according to its width are shown in Table 10.9.

10.10.5 Cotton Fabric Density in Projectile

The square set plain weave curve for the 330 cm machine is a longitudinal curve by

$$S = 99.43C^{-0.4023} \tag{10.3}$$

where S is the square set in ends and picks per cm, C is tex count of warp and weft. Thus, for the 40 tex square cotton fabric, the critical range commences at 22.5 threads/cm [25].

10.10.6 Fully Guided Solid Carrier

This picking system consists of a solid carrier (Dewas or Gabler), a source of oscillating motion, and a link (rigid or flexible) between them. Here the picking carrier is guided by a link across the warp shed very gently, which leads to minimum weft breakage. This is called the rapier system of weft insertion. The overall speed of this type of weft insertion remains lower than the projectile or air-jet, which results in the lower stretch on a weft. But today the rapier picking mechanism has become very fast and competitive for air-jet through production rate as it can be run from 600 to 800 rpm. Now, the versatile rapier head can be available with very lightweight, smaller size, including free-flying, which makes it faster in the weft insertion process. It can handle a variety of weft yarn ranging from 0.77 to 3333 Tex. In this mechanism, up to 16 weft colored yarns can be used and for this versatile style and design in fabric can be produced [10, 26].

10.10.7 Fluid Carrier

In this system, fluid like air or water is used as weft carried for propelling the weft yarn across the warp shed. For cotton weaving, air-jet is used where the air is compressed to get potential energy for propelling the weft yarn. Here, main nozzles with some sub or relay nozzles are used for weft insertion. The nozzles are designed based on a venture tube where the potential energy of compressed air is converted to kinetic energy. The main nozzle can insert weft up to nearly 165 cm, after which the air current is scattered so that the weft cannot be carried further. This problem was solved by using supplementary jets called 'relay nozzles'. A jet of air creates a drag force on the yarn body for dragging a pick from one end of selvage to the other. This propelling force largely depends on yarn structure and dimension, the difference between air and yarn velocity [23]. The drag force dF on the small yarn element of dx is given by following Eq. 10.4.

$$dF_1 = \frac{1}{2} C_f \pi \rho d (U - V)^2 dx \tag{10.4}$$

where ρ = Air density.

d = Effective weft yarn diameter,

C_f = Coefficient of friction between air and yarn.

U = Air velocity and.

V = The weft yarn velocity.

dx = Filling yarn length subject to air.

The propulsive force is increased with a more significant difference between air and yarn velocity and an increase in airspeed. The finer the weft yarn, the smaller the force is. The air consumption for finer and highly twisted yarn will be lower as they would offer a lower surface area with the air stream, and air consumption becomes high for the higher surface area of yarn with an air stream. The air consumption requirements for various yarn count (Ne) is given in Table 10.10 according to the author's practical experience.

Weft yarn tension is the total force of hindering the filling motion which is the sum of air resistance, balloon tension and guide friction, given in Eq. (10.5)

$$T = \frac{1}{2} V^2 (m + \pi \rho d C_f l_b dx) e^{\mu\theta} \tag{10.5}$$

Table 10.10 Air consumption of different weft yarn according to the author's practical experience

Weft count (Ne)	Air consumption (m^3/h/loom)
45	19
22	21.5
20	30.5
7	34

where l_b is the balloon length, μ is the coefficient of friction between the yarn and guide, θ is wrap angle.

Research has been conducted to find the relationship between yarn characteristics with weft yarn tension for cotton twill fabric in the air-jet loom. It was found that the higher the yarn count, the higher the weft yarn tension per cycle. Moreover, with an increase in yarn hairiness, weft yarn tension is increased as high friction force is developed. But twist multiplier of cotton yarn has a reverse effect on filling yarn tension. As high twist multiplier reduces yarn diameter, which results in a smooth yarn surface. This consequence ultimately leads to lower filling tension as the friction between the yarn surface and the air becomes less [23].

10.10.8 Energy Consumption of Different Picking Mechanism

The shuttle picking mechanism consumes high energy per pick as the weft carrier has heavy mass. But in unconventional picking mechanism, the mass and size of the weft carrier are drastically reduced, which leads to reduce consumption of energy per pick and enables the carrier to travel a longer distance.

The kinetic energy absorbed in the projectile picking mechanism per pick is 10.84 J, which is lower than that of the shuttle loom (36.60 J). In the case of the shuttle loom, 89% of energy is absorbed in the receiving side, while only 10% of energy is absorbed in the receiving side of the projectile loom.

Of course, 60% of energy is absorbed in the hydraulic system of the projectile picking system. The width of the projectile is nearly three to four times that of the shuttle. Therefore, the weaving cost of a projectile loom is much lower than that of the shuttle loom.

Power for picking—for shuttle 201.34 W at 230 picks per minute (PPM), for projectile required 268.45 W at 220 ppm. Note that the width of a projectile loom is nearly 3–4 times than that of the shuttle loom.

Air-jet looms consume the highest power (3.2 KWh/kg), whereas rapier (2.5 KWh/kg) and projectile (gripper) (1.3 KWh/kg) are considered as the second and third ones, respectively. Air compressor of an air-jet loom that supplies air to a large number of jets consumes most of the 3.2 units. Rapier machines require high power consumption to overcome the inertia as well as to pass through repeated phases of acceleration and deceleration of rapier heads and their driving systems within each cycle of machine operation. The comparatively less inertia, along with the gripper's frequent acceleration and deceleration after completion of its free flight, leads to much lower power consumption. Moreover, the lower mass of gripper leads to lower power consumption, which is lower than that of a shuttle loom. Gripper looms and the latest generation air-jet looms can work at about 5.5 m reed width, whereas monophase rapier looms with an intermediate rank can suit reed width of 4 m or slightly higher.

10.11 Beat-up

Beating or beat-up is the process of pushing the weft thread that has been inserted across the warp ends during picking by reed, up to the cloth fell. It is one of the primary motions of weaving. The main objective of beat-up is to maintain the proper tension of the overall fabric by letting the inserted weft yarn proceed forward with the progress of the weaving cycle.

Beat-up includes several portions of the loom, including mainly race board and sley. The lower portion of the warp yarns is in between the race board and the shuttle. The reed and race board are assembled, and it is called a sley.

10.11.1 Types of Beat-up

There are different types of beat-up mechanism, depending on several factors. But mainly, two types of beating is considered in general based on the operating element. One is crank and crank-arm beat-up (used in shuttle loom), and another is cam best up (mostly used in the shuttleless loom). However, the related parts of the beating process remain constant irrespective of whether the main motion comes from crank or cam. The basic difference in between this is the source of motion of the sley, whereas this sley motion ultimately controls the overall parameters of beat-up.

10.11.2 Crank Beat-up

The sley is mounted on two sley swords, which are two levers that oscillate the sley to and fro (the combination of forward and backward movement) (Fig. 10.14). The sley receives its motion from a crank on the crankshaft. The crank-arm connects the crank to sley by a sword pin mounted in the rear of sley, so that rotating action of the crankshaft is converted to oscillating action of sley on its rocking shaft. The sley is operated once every weaving cycle for beating-up the weft yarn by the reed and performs a continuous harmonic motion.

10.11.3 Factors Affecting the Motion of the Sley

The motion of the sley is the vital factor for the proper beat-up process. As the tension of both warp and weft yarn is related to the force of beating, several factors need to be considered for maintaining sley motion accurately; ultimately resulting under appropriate tension on yarns, which are varied for the count as well as materials of yarn. As the sley is operated by crank and crank-arm and its motion approximates to

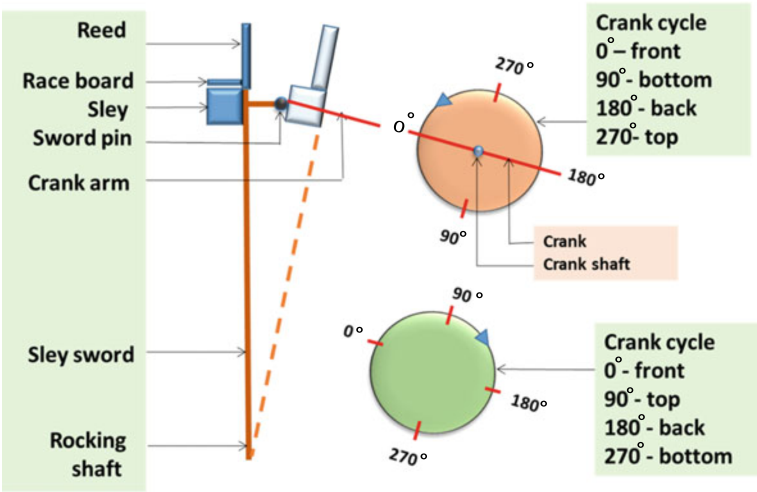

Fig. 10.14 Principle of crank beat-up mechanism [27]

simple harmonic (Fig. 10.14), the extent to which it deviates from simple harmonic motion is governed by three factors: firstly, the radius of the arc along which the axis of the sword pin reciprocates. This mainly points out the traveling of sword pin along an arc of a circle centered upon the rocking shaft, which ultimately modifies the movement of both sword and reed. Although, this effect is small enough to be neglected because of a larger radius of arc (length of sley sword) indeed.

Secondly, relative heights of sword pin and crankshaft, which focuses on the significant impact of raising or lowering of the crankshaft from its normal position over the extent and nature of the motion of sword pin. In practical cases, it was obtained that only 10 cm upward or downward movement of the crankshaft from its normal position could increase the distance passed by the sword pin about 8% and hence the velocity; which in together lead to enhanced effectiveness of beat-up to allow more time for the passage of the weft carrier. Finally, the length of the crank with that of the crank-arm that is called ‘sley eccentricity ratio’ plays a challenging role in irrespective of yarn type and tension.

10.11.4 Sley Eccentricity Ratio

The ratio r/l, where r is the radius of the crank circle and l is the length of the crank-arm, is called the sley eccentricity ratio, e. The more value of ‘e’ causes more deviation of sley from harmonic motion. If this ratio is increased more time is offered to weft carrier to pass over the race board as the sley could remain longer time near its most backward position and thus more active beat-up is occurred with better beat-up force due to the increment of the maximum possible velocity of the sley

Table 10.11 Values of eccentric ratio for different loom [25]

Loom maker	Loom type	r (cm)	l (cm)	e = r/l
Saurer	Cotton, Tappet	6.25	15	0.42
Ruti	Cotton, Dobby	6.99	27.94	0.25
CIMMCO	Cotton, Tappet	6.67	29.53	0.126
Picanol	Cotton, Dobby	7.2	32.4	0.225

around beat-up. However, a higher sley eccentricity ratio offers some elementary disadvantages of the loom. A high value causes rapid acceleration and deceleration of the sley around beat-up which results in a higher acting force on the sword pins, crankpins, cranks, crank-arms, crankshaft, and their bearings; leading to the demand of more robust and heavy looms for consuming this excessive vibration and wear and thus increase the cost.

For these reasons, most of the loom makers avoid keeping a higher sley eccentricity ratio in particular, not more than about 0.3. However, there are exceptions, especially for cotton weaving. Some value of 'e' for different looms are shown in Table 10.11.

10.11.5 Cam Beat-up Mechanism

Cam beat-up is mostly used in the modern loom that is shuttleless loom to achieve high speed by reducing both the mass of the sley and the distance through which it reciprocates. In Cam beat-up, to minimize the weight of the sley, heavy parts related to picking mechanism are fixed with the loom frame. Therefore, the sley can dwell in its most backward position during the total time required for weft insertion. Only this technique operated by cam can precisely ensure the dwell period within the range of 220–250°. The whole mechanism is positively controlled. This mechanism includes several pairs of matched cams, as shown in Fig. 10.15, positioning at intervals across the width of the sley. From the cam, motion is transferred to rockers containing anti-friction rollers to pass the final motion to the sley. One pair of rollers being in contact with the pair of the matched cam, works alternately providing forward and backward movement to the sley and thus to reed [27].

10.12 Let-off

For a continuous and efficient weaving process, it is essential to ensure unremitting releasing of warp ends. The mechanism which continuously releases these warp end from the weaver's beam to the weaving zone is let-off. This let-off mechanism has a dual function of delivering the warp sheet to the weaving zone at the rate corresponding to the weaving speed and of maintaining the warp tension uniform.

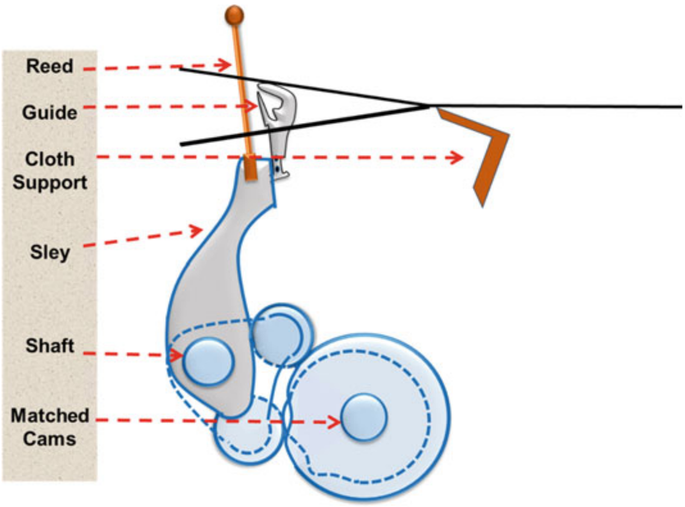

Fig. 10.15 Cam beat-up mechanism in a modern (Projectile) loom; cross-sectional view of motion transferring for the final beat-up [27]

It is essential to have synchronization between the rate of warp yarn unwinding and the rate of fabric winding just after the weaving. Uniform tension is maintained during letting off the yarn to control this rate of flow of unwinding the warp yarn, which is considered as a significant parameter of the let-off mechanism. Let-off can significantly affect the crimp percentage of both the warp and weft and the fabric structure as well [13, 28].

The let-off motions can be classified mainly into three types.

(1) Negative let-off,
(2) Semi positive let-off and
(3) Positive let-off

Also, the historical development of the let-off mechanism can be found within the classification, as mentioned earlier in let-off motion.

10.12.1 Negative Let-off

The developments of let-off motions started from the days of the handloom weavings. At that time, after weaving a small length of fabric, a sufficient amount of warp yarn was unwound to provide yarn supply for the next fabrication. This caused a clear slackening of the warp yarn and the fabric, which is somehow overcome by rotating the take-up roller forward. Thus, the tension on warp was controlled by the take-up motion rather than the let-off motions. The next leading development was the negative let-off motion, where controlling the warp tension to become the primary function. Negative let-off motion is a conventional mechanism and generally used in the nonautomatic weaving machines. In this motion, the warp yarn itself rotates the warp beam, and the warp tension is controlled through the braking torque applied to the warp beam. As the warp beam diameter diminishes simultaneously with the fabric formation, the breaking torque is reduced through adjusting weights to keep the warp tension uniform [13, 28].

10.12.2 Semi Positive Let-off

In the semi-positive let-off motion, the rate of warp yarn unwinding and tension over them is controlled by a tension sensing roller named back-rest. This motion is not using the warp yarn tension itself anymore to rotate the warp beam. Whereas it aims to keep the warp tension constant neither knowing nor caring about the rate of unwinding. This type of let-off motion is prevalent in weaving industries [28].

10.12.3 Positive Let-off

In recent developments, a fact came out that controlling the warp tension cannot be the only principle of let-off motion. Thus positive let-off is designed to control directly the warp yarn supply and separate mechanism to ensure constant tension with the gradual depletion of warp. Here the unwinding rate of warp yarn depends on the length of yarn from the warp beam to the fell of the cloth. Positive let-off can be either mechanical or electronic. In positive let-off motion, an oscillating back-rest is used to control the warp tension. It can be equipped with a pulley mechanism or a reduction gear mechanism [13].

10.12.4 Mechanically Controlled Let-off System

Research has been done by Jeddi et al. [29] on a comparative study on the performance of electronically and mechanically controlled warp let-off systems. The mechanically controlled let-off system used in the mentioned research is presented below. In the mechanical control system, the displacements of back-rest correspond to the difference between the actual tension on warp yarn and desired tension on warp yarn, which is raised from weight and spring-loaded tension. These differences are then transferred to the PIV controller, which takes action to move the warp beam to a suitable position corresponding to minimize the differences of the tensions mentioned above.

In Fig. 10.16, a block diagram of a closed-loop warp let-off system has been shown that P1 and P2 are the cyclic and disturbance tension, respectively. Spring and

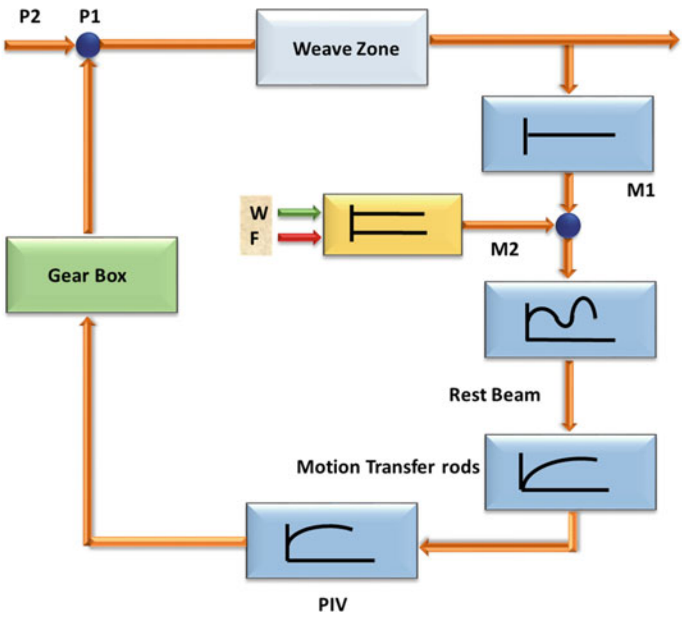

Fig. 10.16 Block diagram of a closed-loop warp let-off system [29]

weight loaded tension F and W, are to displace the back-rest position in M2 value. Actual warp yarn tension displaces the same in M1 value. However, the final position of the back-rest roller is the resultant values of these two displacements.

10.12.5 Electronically Controlled Let-off System

In electronically controlled let-off the system, the back-rest roller displacement movements are continuously measured by a linear inductive analog sensor and are transmitted to an A/D card. These measured values are then processed by a processor computer, and the output signal is transmitted by the D/A card, amplifier, and motor controller to a DC motor to the let-off control unit as a compensating system. However, it is necessary to determine the relationship between the automatic control system output and the actuating error signal [29] Comparison between electronically and mechanically controlled warp let-off system is depicted in Table 10.12.

Table 10.12 Comparison between electronically and mechanically controlled warp let-off system [29]

Factors considered for comparison	Mechanically controlled system	Electronically controlled system	Comments
Setting time	Nearly after 220 weaving cycle	Nearly after 110 weaving cycle	Setting time of electronic controller is nearly half of the mechanical one
Compensation for a sudden increase in warp tension	Take more time to adjust the tension	Take less time to adjust the tension	In an experiment, it is seen that mechanically controlled system take double time than an electronically controlled system to compensate the variation
Compensation for a sudden decrease in warp tension	Take more time to adjust the tension	Take less time to adjust the tension	In an experiment, it is seen that mechanically controlled system take double time than the electronically controlled system to compensate the variation

10.12.6 Mechatronic Let-off

In some cases, let-off motion uses a mechatronic solution, which is a combination of servo drives. Here warp beam gets to drive by servo motor. As the diameter of the beam changes gradually, the rpm of the beam is controlled by the load cell. It is predictable to maintain a higher speed of let-off than that of the take-up, considering the warp crimp [28].

10.12.7 Back-Rest and Dropper Position and Its Effect on Warp Tension

It is a challenge to keep the warp tension uniform, and the main reason behind this is the continuously changing diameter of the warp beam. Keeping the warp tension constant is an important factor as variation in tension can be led to irregular crimp, weft density, and physical properties. An oscillating back-rest has an influencing effect on the variation of the tension of the warp sheet. The swinging motion of back-rest can surely minimize the variation in tension. Both the back-rest position and height effect on warp tension. If the back-rest roller is moved backward or the back-rest roller height is decreased, the tension on warp yarn is reduced, considering the dropper position unchanged. But if the dropper line comes forward due to the change of back-rest position, tension will increase. The dropper position and height also influence the warp tension. When the distance between the back-rest and the dropper line is increased, the tension on warp also increased. Also, if we lower the height of the dropper line, the tension will increase, assuming the dropper line position in the middle of the warp yarn. However, if the dropper is placed closer to the harness, the effect of dropper height will be substituted by the effect of dropper position [13, 30].

10.12.8 Eliminating Stop Marks or Startup Marks by Using Positive Let-off Motion

While producing cotton fabric, stop marks can be eliminated by applying positive let-off motion. The stop mark or the startup mark types can be either thin mark or thick mark. At the time of starting the loom, the thin mark may appear if warp tension becomes less somehow, and thick marks will appear if the warp tension becomes high. The electronic positive let-off motion is equipped with a programmable movement of back-rest with a tenth of pick accuracy. It is capable of relaxing the warp yarn tension at the time of the machine stoppage and recovering it at the time of starting by ranging from one-tenth of a pick to fifty picks. This is how the overstretching of warp yarn can be prevented, which is responsible for the defect during stoppage time. Also, the motion is capable of following both the forward, slow motion, and pick finding motion [13, 31].

10.12.9 Effect of Let-off Type on Fell of the Cloth and Crimp

Synchronization between the let-off and take-up is critical as it can make displacement of the fell of the cloth and crimp as well. If the tension in the warp yarn is more than the tension in the fabric, the variation in the fell of the cloth position will always be higher with a let-off motion equipped with a deadweight than a let-off motion equipped with a brake system. However, it is advantageous as well as not depended on the type of fabric is being woven. Weaving a lighter weight fabric with less crimp percentage requires a very complicated position of fell of the cloth and therefore break type let-off motion is preferable [32].

10.12.10 Let-off Motion Can Even Affect the Color

During let-off motion, the back-rest position can change the color of the fabric. It is found that the higher position of the back-rest can make the fabric darker experimenting with different back-rest heights. This may be explained as if the back-rest position is increased; tension on warp also increased, which reduce crimp and increase density as well. However, this increased yarn density can develop a darker shade in the fabric. Again thinking alternatively, the tension variation from a faulty let-off motion can end up with a fabric of shade variation [30].

10.12.11 Let-off Motion for Pile Fabric

Pile fabrics contain two warp systems, including a beam for the ground warp and another for the pile warp. Thus both the beams are equipped with separate let-off motions that run simultaneously. For the ground fabric weaving, the length of yarn unwound and the length of fabric has been woven are not very different. So the let-off motion for ground fabric runs slowly with higher tension whereas the let-off motion for pile warp beam runs quickly and loosely considering the yarn delivery required for the pile height. Two different independent motors running with two different rpm are required for this fabric [33].

10.13 Take-up

The motion by which the anew woven fabric is withdrawn or pulled up from the weaving area just after beating up of newly inserted pick is take-up. Maintaining a constant rate which will ensure the required pick spacing or pick density and keeping a stable position of the fell of the cloth are the main target of take-up motion. After completing a beating up, reed starts moving backward while the fell of the cloth starts moving forward towards the reed. Thus an appropriate pulling mechanism is needed to take-up the fabric [25, 34].

Pulling the fabric continuously and winding it on the cloth roller keeping uniform tension are done simultaneously in a take-up motion. Different types of take-up rollers, including pin roller, sand roller, and emery roller, are used for pulling the fabric. The fabric moves forward by frictional contact with the mentioned rollers. These rollers are usually driven by gear and wheels, providing a uniform winding rate. One or two pressure rollers are used to avoid the slippage between the fabric and roller. In the delivery zone, fabric passes over front rest, around take-up roller, over a smooth bar and down to cloth roller [25, 34].

Fig. 10.17 Different cloth take-down system for cotton fabric [35]

10.13.1 Different Arrangements of Take-up Rollers to Avoid Slippage

Usually, in cotton weaving, the cloth moves forward by frictional contact between the take-up roller and cloth roller. However, slippage may occur and can cause severe variations in pick spacing. Also, a random formation of thick places may be observed. The take-up roller is covered with a material that provides a high coefficient of friction to avoid this kind of faults and slippage. It is a common practice to use perforated still fillet for cotton fabric weaving as they are unlikely to be damaged by the rough surface. Slippage is further discouraged by setting up the roller arrangements in such a way that the cloth remains in contact with a large part of the circumference of the take-up roller [27].

Figure 10.17 shows a typical roller setting arrangement used in cotton weaving. The breast beam A is adjustable and made up of either a smooth metal bar or a non-rotating roller. B is the driven take-up roller, and C is a small roller usually covered with felt, which is forced against the take-up roller through springs and acts as a nip roller. D is the cloth roller. It is driven by either frictional contact with take-up roller or by chain and sprockets connected with the take-up roller. Sometimes a slipping clutch is attached on the cloth roller shaft, which slows down the rate of winding of the cloth roller as it gradually builds up. Simultaneously it also keeps the fabric in uniform tension to discourage slippage and crease. Sometimes the creasing can be further discouraged by using a slightly curved anti-crease bar E [25, 27].

10.13.2 Types of Take-up Motion

Two types of take-up motion are found. One is negative take-up motion, and another is a positive take-up motion. The use of negative take-up motion was mostly found in conventional looms, and the use of this motion becomes limited these days. As in this motion, it was found difficult to control the pick spacing precisely.

Table 10.13 Weaving performance of cotton woven fabric depending on different weft density [36]

Weft count	No of pick wheel teeth = 42		No of pick wheel teeth = 52		No of pick wheel teeth = 66	
	On the loom	At relax stage	On the loom	At relax stage	On the loom	At relax stage
EPcm	29	32	30	32	31	32
PPcm	17	17	20	21	26	27
	Warp	Weft	Warp	Weft	Warp	Weft
Yarn breakage	Medium	High	Medium	Medium	Medium	Low
Crimp (%)	3.53	7.1	4.66	7.33	5.78	8
Cover factor	17.44	9.61	17.91	11.62	18.38	14.75
Extension %	10.62	14.45	11.09	15.4	12.17	16.31
Breaking strength	786.87	383.56	794.15	487.92	772.03	607.57

A positive take-up motion may be classified as either a continuous (equipped with worm and worm wheel drive) or an intermittent (equipped with pawl and ratchet wheel drive) motion. Positive take-up motion is of various types; 5 wheel take-up motion, 6 wheel take-up motion, 7 wheel take-up motion, Sulzer Ruti take-up mechanism, and worm wheel take-up motion. Research has been done by Md. Mahbubul Haque on the performance of cotton fabric using different weft density. A loom equipped with a six-wheel take-up motion was used where the numbers of change wheel teeth were 42, 52, and 66. Data for fabric performance has been given in Table 10.13. The count of the weft yarn was 20 Ne [36].

10.13.3 Electronic Take-up Motion

In recent modern weaving, take-up motion is controlled electronically and also synchronized with let-off motions. Maintaining a required pick density is one of the core tasks of take-up motion. In different positive take-up, the required pick density is achieved by changing the single or a series of change wheels which is found time-consuming. Whereas in the case of electronically controlled take-up motion, changing pick density is a matter of just pressing a finger. Either in a jacquard control unit or on a microprocessor keyboard, the required pick density can be programmed. Here two separate motors are employed for driving the take-up and let-off. Both the motions are identical in construction and are connected in a control circuit with sensors. This connection makes them a resolver to each other, considering the measuring system. This new synchronized motion is not only controlling and reacting accordingly but also acting about the future [26, 37].

10.13.4 Role of Take-up Motion in Keeping a Constant Cloth Fell

A critical relationship lies between the take-up motion and fell of the cloth position. After a while of weaving get started, the take-up motion helps the cloth fell, to find out it's position impulsively. After beating up the woven fabric is increased to an amount equal to the desired pick spacing. However, to ensure the same position of cloth fell, the take-up motion must pull that amount of fabric. A mathematical expression relating the rate of take-up to the position of fell of cloth was developed by Greenwood. According to his concept, during weaving, if the very new pick spacing having a value S fluctuates from the take-up rate P, the symmetry between the lengths of newly woven fabric and taken up fabric will be interrupted. In such cases, a net increase in the free length of fabric will take place, S-P = (a), when take-up has done, and the fell of the cloth distance L will have changed by an amount a. A relation has been presumed dL/dn = P-S = −a, where n is the number of picks woven and referred to this relation as the take-up equation. Therefore the take-up motion has a direct effect on maintaining the correct position of the fell of the cloth and pick density as well [37].

10.14 Creating Fancy Effects by Variable Pick Density

However, the variation in pick density is considered as a fault in weaving, but at ITMA 2011 types of machinery with variable pick density control system has been demonstrated. Intentionally created variation in the pick density can become a tool for the fabric designers to create fancy effects along the weft direction. It is possible to program a predetermined variation in the pick density by controlling an electronic let-off and take-up mechanisms via microprocessors [38].

10.15 Weaving Parameters

For producing woven fabrics, proper settings of several parameters are one of the most vital parts for achieving expected fabric quality. Different settings of a loom are adjusted to a wide variety of materials and design patterns for an optimum weaving.

For the cotton-weaving process, there are some important parameters for a specific loom.

10.16 Controlling Parameters of the Loom

(1) Warp Tension
(2) Loom RPM
(3) Shed Angle
(4) Back-rest position and height
(5) Dropper Bar position and height
(6) Fabric width
(7) Easing motion
(8) Weft density (PPI).

10.16.1 Warp Tension

For achieving higher loom efficiency, the warp end breakages need to be minimized. The high warp tension is mainly responsible for the yarn breakages during cotton weaving. For the cotton-weaving process, when the total number of warp yarns (W) are increased, or coarser warp yarn count (NE) is used, then it is required to increase the warp tension (TE) and vice versa. There is a formula of calculating the proper warp tension value which is used in TOYOTA Air jet loom [39]

$$\mathrm{TE} = \frac{\mathrm{W}}{\mathrm{NE}} \times \mathrm{Coefficient} \tag{10.6}$$

where, TE = Warp tension (kgf)
W = Total number of warp yarns
NE = English cotton count.

By using the above formula, some coefficient values for an Air-jet loom are given below in Table 10.14.

10.16.2 Loom RPM

The weft insertion rate (WIR), warp breakages, fabric quality, as well as the productivity of a loom mostly depend on the RPM of the loom. Higher loom speed increases the warp yarn tension. Some properties, in particular, warp contraction percentage, shrinkage, elasticity, GSM, are varied with the change of loom RPM. For cotton, spun yarn can be run comparatively at less speed than polyester or PC fabric. For

Table 10.14 The coefficient values for different cotton weave structure [39]

Fabric structure and yarn count (Ne)	The coefficient for cotton spun yarn
Plain fabric ($\frac{1}{1}$)	1.0
Top weave ($\frac{2}{1}$, $\frac{3}{1}$)	
≤10 (for thick yarn)	0.55
11–20	0.6
21–30	0.7
30< (for thin yarn)	0.8
Back weave, Twill or sateen weave ($\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$)	
≤10 (for thick yarn)	0.6
11–20	0.7
21–30	0.8
30< (for thin yarn)	0.9
For Dobby and Jacquard	
Dobby weave	0.9
Jacquard weave	0.8

air-jet loom, average loom ppm ranges 700–1100. For Rapier it is 450–700 and for projectile 260–600.

10.16.3 Shed Angle

In a loom, the warp yarns are divided into two sheet lines to make up a shed. Air-jet picking system requires a larger shed angle compared to rapier picking because of compressed air passing. The typical shed angle of an air-jet loom for cotton spun yarn ranges from 24° to 36°. For free Flight (FF) and guided by C-hook (GC), both types of grippers of the Rapier loom of symmetric cam motions shed angle varies from 22° to 30° [40] (Fig. 10.18).

10.16.4 Back-Rest Position and Height

Back-rest is one of the most important controlling points of a loom for cotton fabric production. The back-rest position varies for different weave structures. The graduation* on the back brackets depends on the fabric structure. The back-rest height will be maximum for Warp face twill/satin weave, and it will be at the lowest position when weaving a weft face twill/sateen fabric (Fig. 10.19). The graduation on the back brackets for different cotton weave structures are given in Table 10.15.

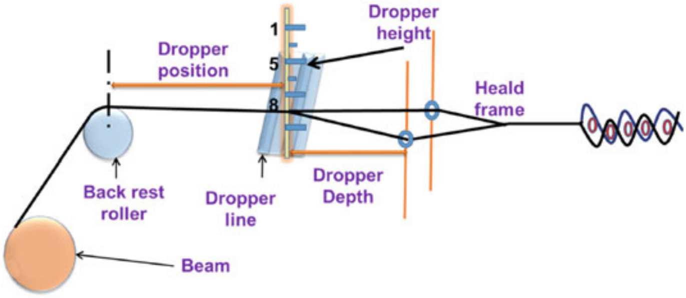

Fig. 10.18 Dropper bar height position and height

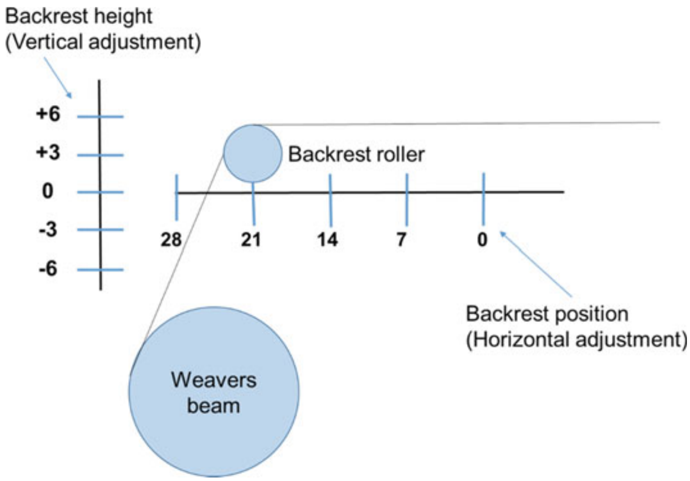

Fig. 10.19 Back-rest position and height [30]

Table 10.15 The graduation on the back brackets for different cotton weave structures [39]

Fabric type	Graduation[a] on the back brackets
Plain weave ($\frac{1}{1}$), Twill ($\frac{2}{2}$)	0
Twill/Satin ($\frac{2}{1}$), ($\frac{3}{1}$), ($\frac{4}{1}$)	+1
Twill/Satin ($\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$)	−2
Dobby	0

[a]Graduation—the positive or negative scale position or height of the back-rest roller

Table 10.16 The horizontal adjustment of the dropper bar (L) for different types of shedding mechanism [41]

Shedding type		L (mm)[a]
Negative cam		240
Positive cam, crank		310
Dobby, electronic shedding	Up to 10 frames	270
	More than 10 frames	340

[a]L = Difference between the heald frame support stand (cloth formation side) and the front side of the dropper bar (beam side) in a loom

Table 10.17 Recommended values of dropper bar height of an air-jet loom for different cotton weave structures (as shown in Fig. 10.18) [41]

Fabric structure	Dropper bar height (graduation)
Plain weave ($\frac{1}{1}$) and Twill ($\frac{2}{2}$)	−1
Twill/Satin ($\frac{2}{1}$), ($\frac{3}{1}$) and ($\frac{4}{1}$)	0
Twill/Satin ($\frac{1}{2}$, $\frac{1}{3}$ and $\frac{1}{4}$)	−3
Dobby	−1

10.16.5 Dropper Bar Position and Height

Starting marks deteriorate the cotton fabric quality depending on the position and height of the back-rest as well as the dropper bar. Two types of adjustment proceeds in a dropper bar setting, one is a horizontal adjustment, and the other is a vertical adjustment, shown in Fig. 10.18.

Sometimes it is required to change the position of dropper line horizontally either nearer to heald frame or rear to the frame that means closer to the back-rest for the optimization of the loom settings for reducing yarn breakages (Table 10.16).

There are some recommended values for the cotton fabric of different weave structures, given in Table 10.17. For the solution of thick mark problem of the plain weave of cotton fabric, it is needed to lift the back-rest and dropper; for thin places, lowering is done.

10.16.6 Fabric Width Control

The Cotton fabric width is controlled by the amount of weft wise crimp percentage, and it relies upon various factors, including warp tension, temple type, pressing tension of fabric take-up, and reed width of a loom. A temple is a metallic device that keeps the fabric stretched by applying a force along the filling direction. Controlled fabric width could be achieved by using medium temple type and intense take-up pressing tension at relatively lower warp tension, and smaller loom working width. There are various types of temple used in cotton weaving. For example,

- Ring temples are used for light, medium and heavy fabrics,
- Rubber temples are temples without spikes and are used for delicate fabrics and on water-jet looms,
- Steel roller temples do not have rings but are covered with short spikes that are suitable for light and medium fabrics [4].

10.16.7 Easing Motion

The motion of correcting the warp tension difference caused during shed opening and closing is known as easing motion or whip roller movement of a loom (Fig. 10.20).

The most important effect of easing motion is to maintain uniform and required warp tension by changing its position. For plain weave, the timing is more advanced than shed close timing due to compact weave structure with maximum interlacement of yarn, but for twill and satin weave, it remains the same, an example is shown in Table 10.18.

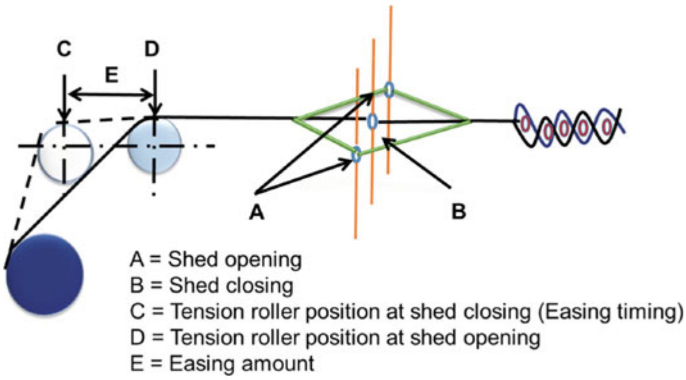

Fig. 10.20 The easing motion of a loom [39]

Table 10.18 Easing timing according to the weave, shed close timing, and the size of the shed of a modern Air-jet loom [39]

Material	Items	Cam shedding motion		Crank shedding motion	Dobby
Cotton spun yarn	Shed size	32°		32°	30°
	Shed close timing	Plain weave	Twill or satin weave	310°	300°
		310°	290°		
	Easing timing	290°	290°	290°	300°

Table 10.19 The relation between the loom speed of Toyota JAT 810 and minimum weft density [39]

	RPM of loom	Minimum weft density (Std. density fabric)	Minimum weft density (Low density fabric)
Machine speed (rpm)	650	24	10
	700	24	11
	750	24	12
	800	26	13
	850	27	13
	900	28	14
	950	30	15

10.16.8 Weft Density (PPI)

Several picks per inch (PPI) of woven fabric are known as pick density or weft density of that fabric. In the conventional loom, minimum PPI depends on the minimum take-up rate. In modern looms, minimum warp withdrawal depends on the diameter of the barrel and flange of weavers beam and the number of teeth on beam gear. Two types of density are measured for woven fabrics in modern loom.

- Standard density woven fabric: From the number of minimum weft density to 240 picks per inch.
- Low density fabric: From the number of minimum weft density to 100 picks per inch.

The relation between loom speed and minimum weft density at 1000 mm warp beam flange dia, 178 mm barrel dia and 136 teeth on beam gear is shown in Table 10.19.

Although for any fabrics, either cotton or synthetics, to properly select weft density is intensely related to loom speed, this relation is shown in Table 10.19.

Here, Tables 10.20 and 10.21 show some examples of loom settings according to the above-described settings that are followed by the industry for the same and different fabric specifications.

Table 10.20 Different loom settings for cotton weaving of different shedding mechanism on the same loom according to the expertise of authors

Sl	Parameters	CAM shedding (Toyota JAT 810)	Crank shedding (Toyota JAT 810)
1	Fabric specification	$\frac{40 \times 40}{130 \times 80} \times 57''$ plain	$\frac{40 \times 40}{130 \times 80} \times 57''$ plain
2	Warp tension	190 Kgf	191 Kgf
3	Total ends	7670	7670
4	Loom RPM	750	780
5	Shed angle	30°	30°
6	Shed cross timing	300°	300°
7	Back-rest height	+40 mm	+40 mm
8	Dropper bar height	0 mm	0 mm
9	Easing amount	15 mm	15 mm
10	Easing timing	300°	300°
11	No. of heald frame	4	4
12	Reed count	120/2	120/2
13	Beat-up type	Crank beat-up	Crank beat-up

Table 10.21 Different loom settings for cotton weaving on a different loom according to the expertise of authors

Sl	Parameters	CAM shedding (Toyota JAT 710)	CAM shedding (Toyota JAT 810)
1	Fabric specification	$\frac{50 \times 50}{150 \times 90} \times 56''$ satin	$\frac{30 \times 40}{82 \times 80} \times 58''$ 2/2 Z twill
2	Warp tension	160 kgf	190 kgf
3	Total ends	8400	4950
4	Loom RPM	800	750
5	Shed angle	32°	32°
6	Shed cross TIMING	280°	300°
7	Back-rest height	+36 mm	+20 mm
8	Dropper bar height	0 mm	0 mm
9	Easing amount	10 mm	6 mm
10	No. of heald frame	6	4
11	Reed count	134/2	74/2
12	Grey fabric width	62 inches	61 inches
13	Beat-up type	Crank beat-up	Crank beat-up

10.17 Conclusion

Weaving process developed from a very ancient technique to high–tech methods likely computer-aided production and design along with electronic jacquard. Since the last three decades, the continuous progress in electronic control of weaving loom to surpass existing fundamental problems regarding weaving is being more advanced and attainable to be incorporated into many of the weaving operations. Although several fiber types, in particular, cotton, polyester, wool, acrylic, and viscose can be utilized in weaving for the production of versatile apparels; the proportional consumption of cotton and cotton blend yarn for the apparel industry is beyond any measure for the manufacturing of several basic wearing ranging from basic shirts to household items including curtains even towels due to their outstanding comfort and healthy properties. The advancement of cotton in weaving technology has been diversified and expanded by a continuous broadening of textiles.

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Chapter 11
Role of Cotton Fiber in Knitting Industry

Nilufar Rahimovna Khankhadjaeva

Abstract This chapter provides information about the use of cotton fiber and its main role in the knitting industry. Modern knitting industry covers a wide range of technologies and methods; therefore, this chapter describes fundamental principles of knitting technology; knitting processes on a single bed and double bed knitting machines of two familiar knitting group: weft and warp knitting are depicted by separate knitting actions. Also, this chapter discusses the classification of knitted fabric structures and their properties. The knitted structures can be classified into the basic, derivative, cardigan patterned, and combined groups. Depending on the knit structures and properties of raw material, knitted fabrics obtain different physical-mechanical properties and aesthetic effects. Cotton knitted fabrics can be produced in a variety of structures, qualities, and dimensions. Their possible application lies in various fields, such as home textiles, sport wears, underwear, outerwear, and medical textiles.

Keywords Cotton fiber · Knitting processes · Knitting elements · Single bed knitting machine · Double bed knitting machine · Warp knitting · Weft knitting · Knit structures · Basic group · Derivative group · Patterned and combined group of knit structures · Properties of knit structure

11.1 Introduction

Cotton fiber is the most important strategic commodity of world trade, as well as the main resource for the textile industry. Cotton accounts for nearly 50% of the world's textile fiber consumption. China, Japan, the United States, the Russian Federation, and India are the major cotton-consuming countries. Annual cotton production worldwide is 80 to 90 million bales (17.4–19.6 billion kg) [1]. China, the United States,

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India, Pakistan, and Uzbekistan are major cotton-producing countries, accounting for more than 70% of global cotton production. The remainder is in the other 75 countries.

According to the ICAC International Advisory Committee on Cotton (ICAC), global cotton fiber production is recovering from the global financial crisis of 2007–2009. World production in the 2014/15 season almost reached pre-crisis indicators—26.2 million tons [2]. Information on cotton fiber production and consumption by country is presented in Table 11.1.

Table 11.1 Information on the state of the world cotton market in the context of countries (Cotton fiber, thousands of tons)

Worldwide cotton fiber production, thousands of tons					
Country	2010/11	2011/12	2012/13	2013/14	2014/15
India	5865	6239	6205	6766	6804.5
China	6400	7400	7300	6928.9	6436.1
USA	3941.7	3390.6	3769.9	2810.6	3539.1
Pakistan	1948.2	2311.2	2002	2075.7	2103.3
Brazil	1959.8	1877.3	1310.3	1704.5	1507.1
Uzbekistan	910	880	1000	940	940
Turkey	594	733.1	659.3	639.2	724.2
Australia	898	1198	1002.4	897	651.3
Others	2891.3	3692.8	3341.1	3357.1	3510.4
In total	25,408	27,722	26,590	26,119	26,216
Worldwide cotton fiber consumption, thousands of tons					
Country	2010/11	2011/12	2012/13	2013/14	2014/15
China	9580	8635	8290	7531	7934
India	4470	4231	4817	5042	5269
Pakistan	2100	2217	2416	2271	2308
Turkey	1300	1300	1365	1406	1448
Bangladesh	843	700	765	900	954
Brazil	958	897	890	889	893
USA	849	718	751	803	827
Vietnam	350	410	492	664	697
Others	4029	3628	3796	3992	4061
In total	24,479	22,736	23,582	23,498	24,391

11.2 What Is the Knitting Industry, and What Is the Role of Cotton Fiber in the Industry?

The knitting industry is the largest in the world. The reasons for its dynamic development are valuable consumer properties of the manufactured products and highly technical and economic indicators of production.

One of the main tasks of the industry is to increase the production of competitive cotton underwear, sports products of light outer knitwear based on the use of high-quality cotton-type yarn, to equip enterprises with circular knitting machines of high (24–34) gauge, including for knitting highly elastic fabrics, with lines for high-quality low-shrinkage finishing of cotton fabrics.

In the structure of the assortment of domestic knitted products, the main share (about 80%) is occupied by cotton yarn products, and mainly by the underwear group (65–70%) [3].

Knitted cotton product has all the advantages of natural basis: safety in use, hypoallergenic, ease of care. At the same time, cotton knitwear has a loose loop structure, to the touch is rather soft and pleasant, and sufficiently well absorbs moisture, as well as heat-resistant. At the same time, those skilled in the art recommend the choice of combination options, because the use of additional synthetic fibers allows the product to have better operational characteristics.

For example, the plain knitted fabric can be made of 100% cotton or with the addition of Lycra yarn, the content of which must be from 5 to 10%. The addition of Lycra yarn to cotton fiber increases the wear resistance, shape stability, and elasticity of the fabric [4].

Knitted fabric rib 2 × 2 is an elastic knitted fabric with production into a large band. It is produced from 100% cotton fiber mixed with synthetic fibers, with and without a nap, with and without Lycra. Knitted fabric rib 2 × 2 has good elongation, does not poorly hold the shape. Rib 2 × 2 natural material passes air well and allows the skin to breathe.

Knitted cotton and other types of textiles from knitted fabric are usually characterized by breaking strength, extensibility (elongation), unraveling, and the orientation of loops, surface density, and curling the edges [5, 6].

Before characterizing the knitted fabric, the basic concepts and definitions about the structure of the knitted fabric should be known.

11.3 Basic Concepts and Definitions

Knitted fabric is a flexible textile fabric or garment of various shapes made by knitting, which consists of forming one or more yarn(s) into loops. The structure of knitwear, like any textile material, is determined by the size, shape, and mutual arrangement of its constituent elements.

The **element of the knitted fabric structure** is taken as intermeshing sections of curved yarn having different shapes depending on the type of interloping [7]. Sections of curved yarn in the knitted fabric may have the form of:

−loop, −tuck loop, −float loop.

The knit stitch is a section of the curved yarn of the closed-loop. In some types of knitwear, along with knit stitch, tuck, and float stitches, the structure can be supplemented by sections of yarn that do not form loop, tuck loop, or float loop.

By meshing elements of the loop structure in a certain sequence forms a knit fabric, and the type of intermeshing, i.e., the relationship of these elements, is characterized by the knit structure. Along with the kind of yarns used to make knitwear, the knit structure is the most important quality characteristic and defines the basic properties of knitwear.

Depending on the method of interloping, the weft knitting and warp knitting are distinguished (Figs. 11.1, 11.2).

In the weft knitting, loops are connected to each other in a row or in a certain sequence along a horizontal line (across the knitted fabric), forming a loop line (course) (Figs. 11.1a, d, e; 11.2a).

In the warp knitting, loops from each warp thread are connected together in different loop rows (wales), in the lengthwise direction of fabric (Figs. 11.1b, f; 11.2b, d). The yarn forms loops simultaneously first in one loop row, then in the next loop row. A thread system called a warp is needed to form a single loop.

The loops 1 in the weft and warp knitting are shown in Fig. 11.1a, b. Distinguished sections of a loop. Each loop contains two side limbs or legs 3 (Fig. 11.1b–d), head and feet 2 and 4. A head that connects two side limbs or legs from above is called a needle loop; feet which connect the side limbs or legs from below (in one loop row in a weft-knitted, in various loop rows in a warp knitted) is called the sinker loop or **float loop**. The two side limbs or legs connected by a needle loop form a frame of the loop. Float loops in knit fabric with different knit structure can connect a loop not only in adjacent loop wales or courses (see Fig. 11.1a, b, d), but also in others (see Fig. 11.1e, f).

Loops predominantly knitted one on another along with the knitting fabric (vertically), form loop wales.

In Fig. 11.2a, b. the elements of loops structure—**tuck loops** T_0, T_1, T_2, T_3 are shown. The tuck loops can be intermeshed with the loops (see Fig. 11.2a, tuck loop T_0) or **float loops** (see Fig. 11.2a, b, tuck loops T_1, T_2, T_3). The float loops which connect the upright noose or tuck loop, may or may not be crossed. The knit stitch (or tuck stitch) with crossing float stitches are called closed (see Figs. 11.1b, f; 11.2b); Knit stitches without crossing float stitches are called open (see Fig. 11.1a, d, e).

Figure 11.2 shows the elements of the knitting fabric structure in the form of additional yarn knitted in the knit fabric. These yarns do not form a knit stitch and can be extracted from the knit fabric, and the structure of the knit fabric is not broken generally. Additional yarns that are knitted in the knit fabric and forming only tuck stitch and float stitch are called fleecy (see Fig. 11.2a, b); yarns forming one float stitch are called inlay (see Fig. 11.2 c, d). Inlay yarns can be knitted in several loop wales (see Fig. 11.2c, d) or over the entire width of the fabric.

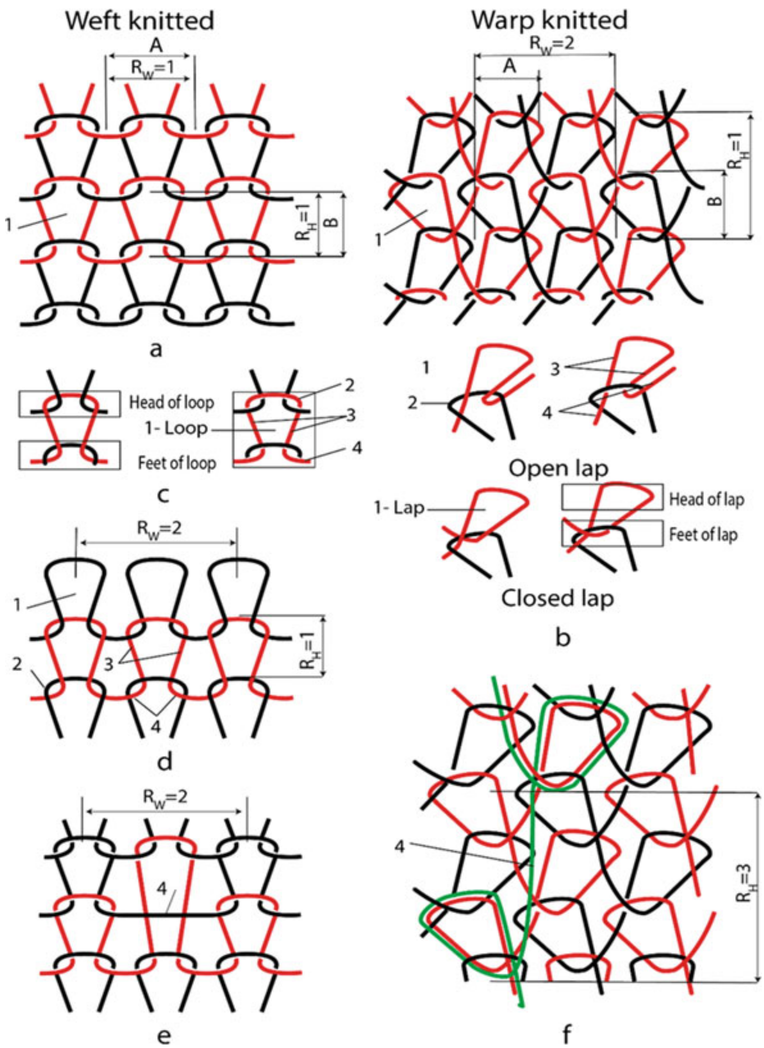


Fig. 11.1 Elements of knitwear structure: **a**, **d**, **e** weft knitting; **b**, **f** warp knitting, **b**, **c** elements of the knit stitch. I-head of the loop, II-feet of the loop

Face and reverse loop stitches are distinguished (see Fig. 11.1b, c). Legs of loops are visible on the face side, and on the reverse side—their sinker loops or float stitches are visible.

The difference between weft and warp knitting is described in Fig. 11.3.

The most important quantitative characteristics of knit fabric (knitwear) are as follows:

Interloping rapport (repeat unit)—This is the smallest number of course (repeat unit by height R_H) or loop wales (repeat unit by width R_W), after which the order of

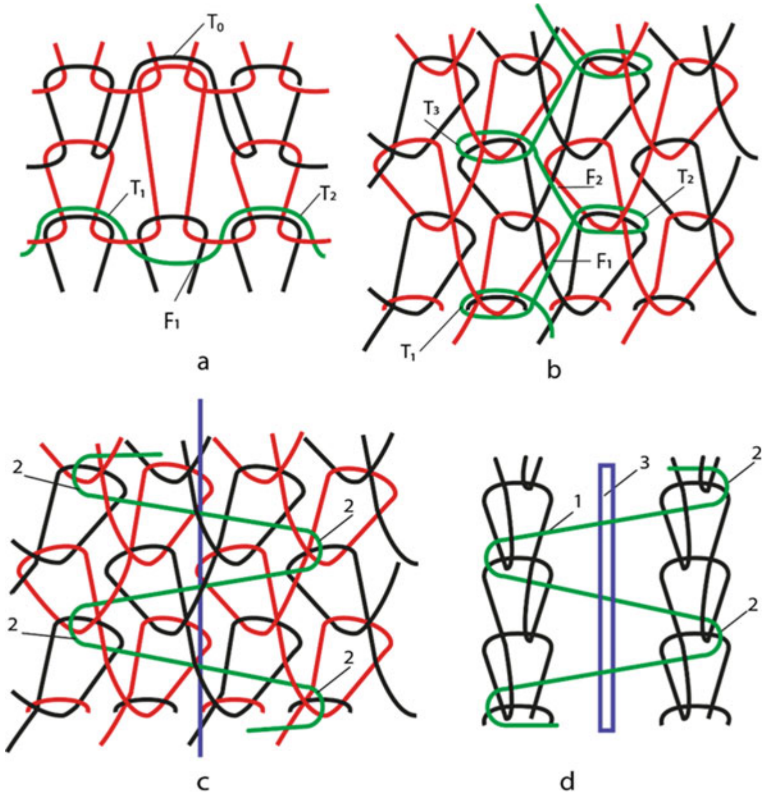


Fig. 11.2 Elements of different knit structures: **a**, **b** elements of cardigan and fleecy structure; **c**, **d** elements of inlay structure

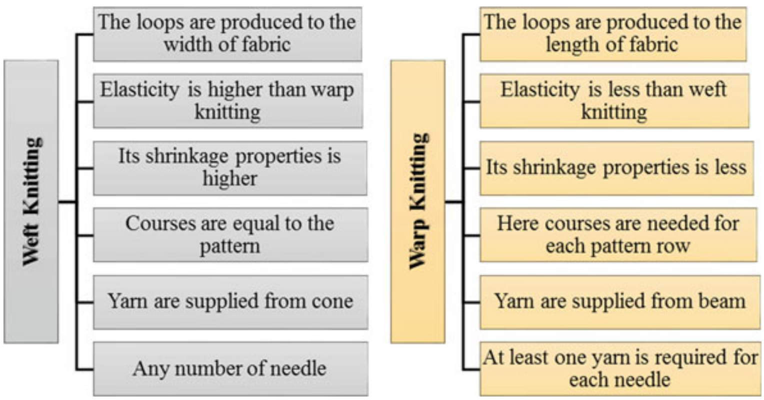


Fig. 11.3 The difference between weft and warp knitting

alternating th~P_{G} read segments as knit, float or tuck stitch in the knit structure is repeated. The rapport of the knit is expressed by integers.

The width of loop A and **the height of loop course B** (see Fig. 11.1) is usually calculated using indirect characteristics: horizontal densities P_G and vertical densities P_V.

The horizontal density is expressed by the number of loop wales per unit width of the fabric. For density determination, 100 mm is taken per unit length:

$$P_G = \frac{100}{A} \tag{11.1}$$

The vertical density is expressed by the number of loop courses per unit length of fabric:

$$P_V = \frac{100}{B} \tag{11.2}$$

Taking into account formulas (11.1) and (11.2)

$$A = \frac{100}{P_G};\ B = \frac{100}{P_V} \tag{11.3}$$

where A and B are, respectively, the width of the loop, mm, and the height of the loop, mm.

Stitch length—the average length of the yarn, mm, used to form a single knitted stitch. This characteristic is determined experimentally by knitting and analysis of knitted samples or by calculation methods.

The thickness of the yarn is characterized by its linear density T, tex (g/km).

The thickness of the knitted fabric M, mm, is determined by measuring it under certain conditions (pressure) on the thickness meter or cross-sections on the measuring optical instruments (microscopes or cathetometers).

The above-mentioned quantities can be determined by directly counting or measuring on knitted samples. They are usually referred to as the most important geometric characteristics.

11.4 Principles of Interlooping (Knitting) Technology

11.4.1 Principles of Hand Knitting

Weaving and knitting are the genius inventions of humanity. The first knitted products found during excavations date from the 6th century.

The first methods of loop formation were implemented by obtaining knit loops from one Y_1 yarn on two pins (Fig. 11.4a, b). In order to perform knitting, a series

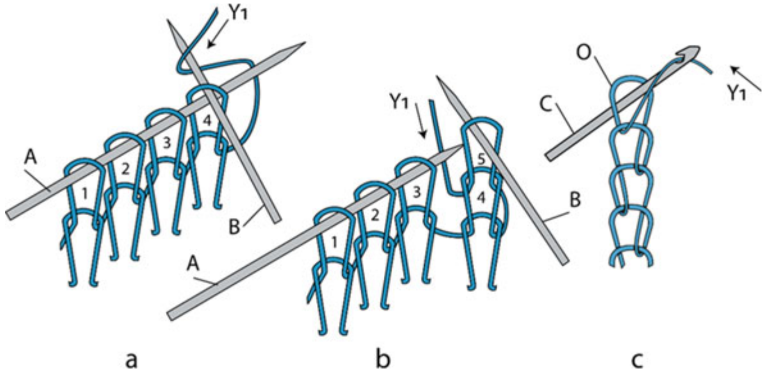


Fig. 11.4 Principles of hand knitting: **a**, **b** on pins; **c** using crochet

of loops (1, 2, 3, 4, etc.) from the N_1 yarn must be pre-fitted or formed on one of the pins (A).

The principle of loop formation is that the other pin (B) is first fed through the last loop 4 of the course, the yarn Y_1 is laid onto the pin B, pulled by the pin through the loop 4, and a new loop 5 is formed, and after the formation of the new loop 5, the loop 4 is throw down from the pin A. The first newly formed loop 5 is placed on the pin B. Then, the knitting process is repeated until all the remaining loops (1, 2, 3) on the pin A are sequentially extended by the yarn Y_1 and the new loops formed from it are placed on the pin B. Further in the same way loops are formed with the pin A, drawing off the thread N_1 through the loops on pin B. Knitting on the pins with the method described above, the knitted loops are formed sequentially in a loop course.

Another method of manually forming loops is performed with crochet C (Fig. 11.4c). In its implementation, as in the case of knitting on pins, loop O must be put on the hook (formed by kinking the yarn). The yarn Y_1 is laid onto the hook so that it falls into its notch and is drawn with a hook through the loop O, by forming a new loop. It is not difficult to see that when the loops are formed by the hook, the loops are arranged sequentially one to the other along the loop wales.

Successive loop formation along the loop course (see Fig. 11.4a, b) results in the production of a weft knitting, and loop formation along the loop wale (see Fig. 11.4c) results in warp knitting.

When considering loop forming methods, loops worn on a pin or hook are conventionally referred to as old loops, and newly formed loops are referred to as new loops.

11.4.2 Principles of Machine Knitting

In 1589 in England V. Lee invented needles with flexible hooks and built the first-hand knitting machine. The principle of operation of the hand knitting machine is given on Fig. 11.5a. Bearded needles N_1, N_2, N_3, etc., are fixed in needle bar. The needles are fitted with a course of old loops O. The yarn N_1 is laid on the needles in the direction of arrow A and kinked sequentially on each needle by special plates—sinkers (not shown) in open loops L_1, L_2, L_3, etc. These loops, when the needles move simultaneously along arrow B, fall under the flexible hooks of the needles; Flexible hooks are closed due to pressing of special sinkers on them in direction of arrow B, their ends enter grooves (cups) of needles, and loops O are landed onto the outside of closed hooks of needles. In the further movement of the needles, the open loops L_1, L_2, L_3, etc. drawn simultaneously through the old loops O, to form a new loops course. The received number of new loops is cleared from hooks on the stem of needles, then the new cycle of looping begins, which differs from previous in the fact that yarn is laid on needles and is sequentially kinked in an opposite direction (the reverse direction of arrow A).

In 1768, Crane invented a hand the knitting machine for warp knitting in England. Its operation is shown in Fig. 11.5b. On needles with flexible hooks (bearded needle), warp yarn Y_1, Y_2, Y_3, etc. are laid simultaneously with the warp yarn guide YG_1, YG_2, YG_3, etc. The warp yarn guides (with holes) are selected and fixed in the guide bar. In order to threading warp on the needle stem, warp guide bars make two motion (swinging and shogging) around the needles, and then return to the initial position. During this movement of the warp guide bar, the warp yarn is feed on the stem of

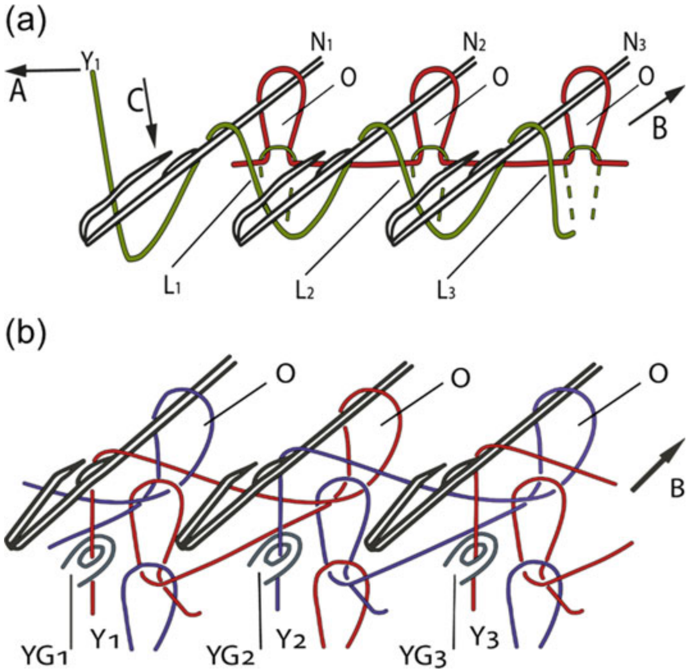


Fig. 11.5 Principles of machine knitting on bearded needles: **a** weft knitting; **b** warp knitting

each needle (see Fig. 11.5b). When needles N_1, N_2, N_3, etc., move along arrow B, sections of warp yarns feed on their stems, fall under needles hooks, flexible hooks of needles are closed (pressed), and knit stitches O, held from movement together with needles land first onto outside of closed hooks of needles, and they are cleared from them; In the following the warp yarns are drawn off into the knit stitch and knit locked, a new lap course of knitwear are formed. This ends the loop formation cycle.

11.4.3 Interloping (Knitting) Elements

Tools that, in the process of forming knitted loops, interact with knitted yarns or loops are referred to as knitting (loop-forming) elements. Knitting elements include: needles, sinkers, hooks, warp guides, cams, as well as verge, yarn feeders and yarn carriers [8].

The needles may be bearded, latch, compound and slide depending on their construction.

The latch needle has nine main features (Fig. 11.6a):

(1) The *hook*, which draws and retains the new loop.
(2) The *slot* or *saw cut*, which receives the latch-blade (not illustrated).
(3) The *cheeks* or *slot walls*, which are either punched or riveted to fulcrum the latch-blade (not illustrated).
(4) The *rivet*, which may be plain or threaded. This has been dispensed with on most plate metal needles, by pinching in the slot walls to retain the latch blade.
(5) The *latch-blade*, which locates the latch in the needle.
(6) The *latch spoon*, which is an extension of the blade, and bridges the gap between the hook and the stem covering the hook when closed, as shown in broken lines.
(7) The *stem*, which carries the loop in the clearing or rest position.
(8) The *butt*, which enables the needle to be reciprocated when contacted by cam profiles on either side of it, forming a track. Double-ended purl type needles have a hook at each end; whilst one hook knits, the inactive hook is controlled as a butt by a cam-reciprocated element called a slider.
(9) The *tail*, which is an extension below the butt, giving additional support to the needle and keeping the needle in its trick.

There are five main parts of the **bearded needle** (Fig. 11.6b):

(1) The *stem*, around which the needle loop is formed.
(2) The *head*, where the stem is turned into a hook to draw the new loop through the old loop.
(3) The *beard*, which is the curved downwards continuation of the hook that is used to separate the trapped new loop inside from the old loop as it slides off the needle beard.
(4) The *eye*, or *groove*, cut in the stem to receive the pointed tip of the beard when it is pressed, thus enclosing the new loop.

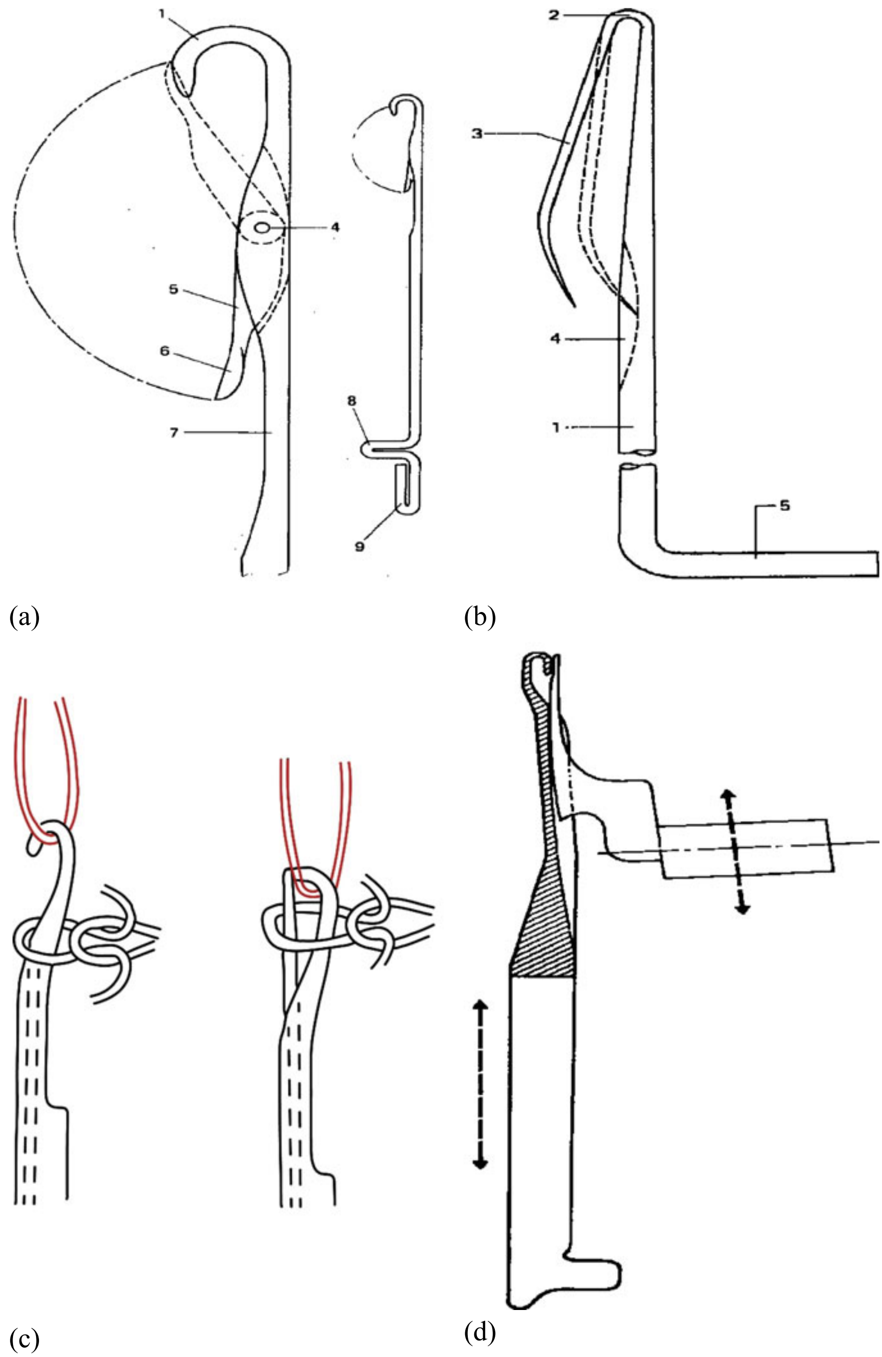


Fig. 11.6 Main features of needles: **a** latch needle, **b** bearded needle, **c** compound needle, **d** slide needle, Reprinted from Ref. [8] Chapter 2, General terms and principles of knitting technology, Pages No. 21-27, copyright 2001, with permission from Elsevier

(5) The *shank*, which may be bent for individual location in the machine or cast with others in a metal ‘lead’.

Compound needles (Fig. 11.6c) consist of two separately-controlled parts—the open hook and the sliding closing element (tongue, latch, piston, plunger). The two parts rise and fall as a single unit but, at the top of the rise, the hook moves faster to open the hook and at the start of the fall the hook descends faster to close the hook. It is easier to drive the hooks and tongues collectively from two separate bars in warp knitting than to move each hook and tongue individually, as in weft knitting.

The **open-stem ‘pusher type’** or **slide needle** (Fig. 11.6d) has a closing wire or tongue that slides externally along a groove on the edge of the flat hook member. This needle is now preferred because it is simpler, cheaper, more compact and each of the two parts can be separately replaced.

Cams are the second primary knitting element. Cams are the devices, which convert the rotary machine drive into a suitable reciprocating action for the needles and other elements. In general, there are two types of cams.

1. Engineering cam.
2. Knitting cam.

Engineering cam: These are of circular type and indirectly control the motions of bares of elements. They are attached to a rotary drive shaft situated parallel to and bellow the needle bar, a number of independent cams correctly aligned movement. The drive is transmitted and adapted cam-followers, levers and rocker shafts. One complete 360-degree revolution of the drive shaft is equivalent to one knitting cycle.

In warp knitting machines four types of cam have been employed.

1. Single acting cams.
2. Cam and counter cam.
3. Box cam or enclosed cam.
4. Counter cam/ring cam/pot cam.

Knitting Cam (Fig. 11.7): The knitting cam is of angular type and acts directly on to the butt of needles or other elements to produce individual movement in the tricks of needle weft knitting machine as the butts pass through the stationary cam system or the cams pass across the stationary tricks.

Knitting cams are attached either individually or in unit form to a cam plate and depending upon the machine design, are fixed exchangeable or adjustable. At each of at least a raising cam, a stitch cam and an up throw cam whose combined effect is required. Usually four main types of knitting cams are used.

(1) Raising cam: The raising cam causes the needle to be lifted to either tuck, clearing loop transfer or needle transfer depending upon machine design.
(2) Stitch cam: The stitch cam controls the depth to which the needle descends thus controlling the amount of yarn drawn into the needle loop. It also a knock-over cam.

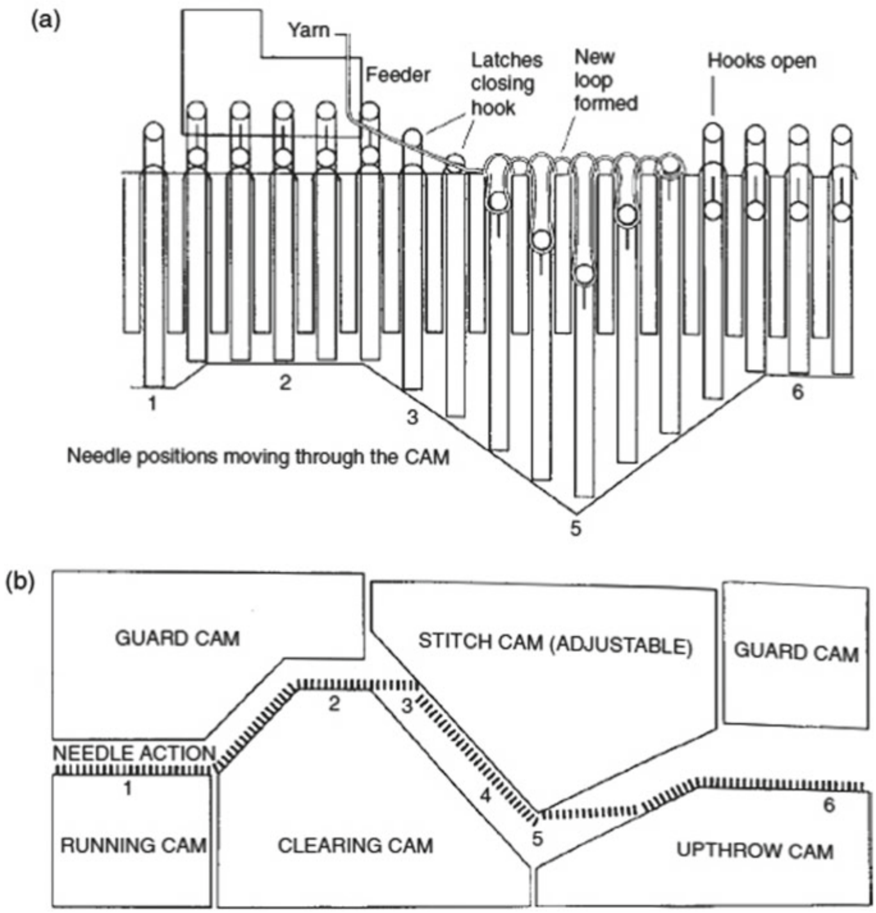


Fig. 11.7 Knitting CAM and needle positions moving through the CAM. **a** Loop formation; **b** typical cam system on a latch needle machine. Reprinted from Ref. [9] Chapter 5, Technical fabric structures 2. Knitted fabrics, Pages No. 100, copyright 2000, with permission from Elsevier

(3) Up throw or counter cam: The up throw or counter cam takes the needles back to the rest position and allows the formed loops to relax.
(4) Guard cam: The guard cam is often placed on the butts and to prevent needles from falling out of track.

Function of Cam: The functions of cam are as follows:

(1) To produce motion to needles.
(2) To drive the needles.
(3) Formation of loops.

The sinkers (Fig. 11.8), participated in the loop formation process, has different uses and can be movable and stationary relative to its bed. Sinkers are stamped from

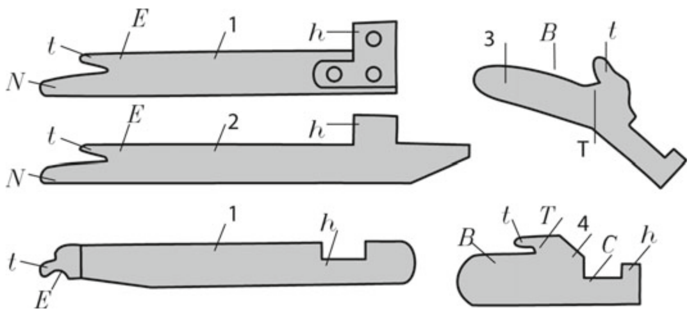


Fig. 11.8 Sinkers

the thin metal plate and differ in configuration. It may perform one or more of the following functions, dependent upon the machine's knitting action and consequent sinker shape and movement.

(1) loop formation,
(2) holding down,
(3), (4) knocking over.

The sinkers 1 perform loop formation, has an edge or catch E, which sinks or kinks the newly laid yarn into a loop, a heel h or a notch n, with which sinkers move, toes t and the nib or nose N. The sinker 2 performs holding down function and it has the same characteristic section as loop formation sinkers. Knocking over sinkers 3 is immovable relative to the bed, have a belly (or upper surface) B, throat (or slot) T and toes t. On some machines, the knock over surface moves on opposition to the descent of needle-sinker 4, contains the same sections as the sinker 3 but moves with the heel h and the notch n.

Various shapes and purposes of **Hooks** are shown on Fig. 11.9. They are used to transfer the loops when the width of the knitwear changes (Fig. 11.9a), to selvage and to seam the edges (Fig. 11.9b–d). The hooks are shown on Fig. 11.9a–c, are stationary relative to their bed and are called deckers; they have a groove G, toes T and heel H. These hooks interact with the bearded needles, in which the hooks of the needle are settled in the groove of these hooks. The hooks shown in Fig. 11.9d are movable relative to their bed, have toe T, heel H and right Br or left Bl bends.

Warp yarn guide of the warp knitting machine is shown on Fig. 11.10. Warp yarn guides 1 are fixed to special bar 2. The holes of the warp yarn guide of the knitting machine are feed with warp yarn.

11.4.4 The Methods of Forming Yarn into Needle Loops

There are three methods of forming the newly-fed yarn into the shape of a needle loop:

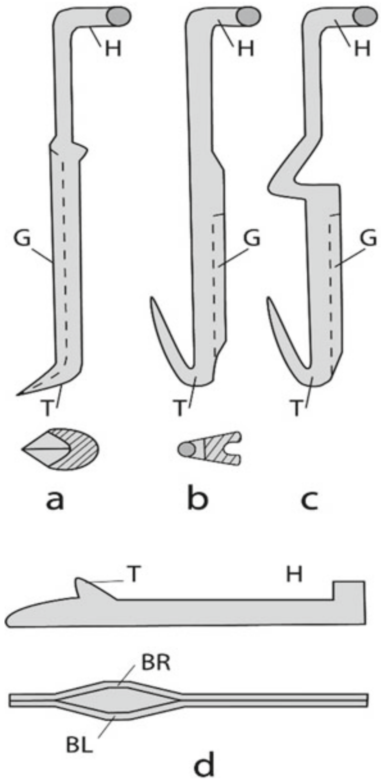


Fig. 11.9 Hooks. **a**, **b**, **c** stationary hooks; **d** movable hook

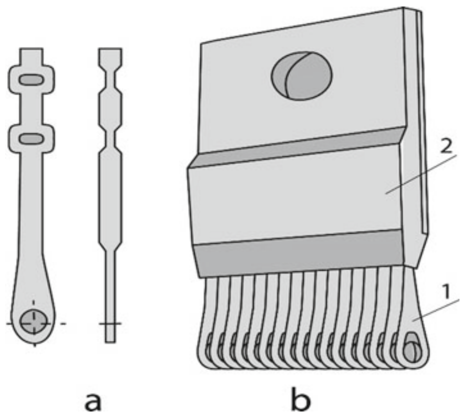


Fig. 11.10 Warp yarn guide. **a** Single yarn guide. **b** Fixed yarn guide to special bar

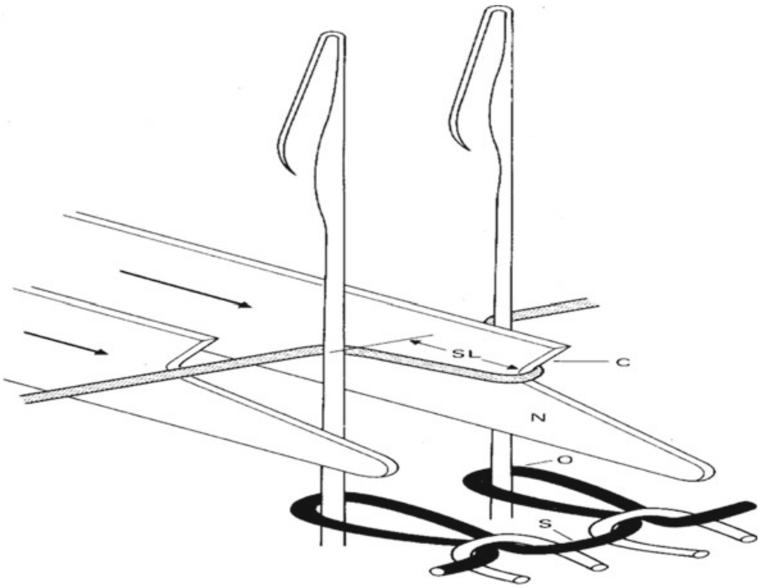


Fig. 11.11 The action of the loop-forming sinker. Reprinted from Ref. [8] Chap. 4, Basic mechanical principles of knitting technology, Page No. 32, copyright 2001, with permission from Elsevier

(1) (Figure 11.11)—By sinking the yarn into space between adjacent needles using loop forming sinkers or other elements which approach from the beard side. The action of a straight bar frame is illustrated. (Other obsolete circular bearded needle machines such as the sinker-wheel and loop-wheel frame employ the same technique). The distance SL, which the catch of the sinker moves past the beard side of the needle, is approximately half the stitch length.
(2) (Figure 11.12)—by causing latch needles to draw their own needle loops down through the old loops as they descend, one at a time, down the stitch cam. This method is employed on all latch needle weft knitting machines. The distance SL that the head of the latch needle descends below the knock-over surface (in this case, the belly of the knock-over sinker) is approximately half the stitch length.
(3) (Figure 11.11)—By causing a warp yarn guide to wrap the yarn loop around the needle.

The lapping movement of the guide is produced from the combination of two separate guide bar motions:

- A swinging motion which occurs between the needles from the front of the machine to the hook side and returns.
- A lateral shogging (or racking) motion parallel to the needle bar on the hook side and also on the front of the machine.

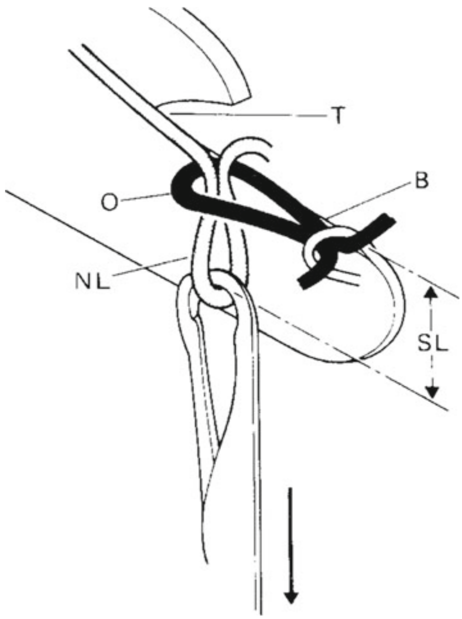


Fig. 11.12 Action of the knock-over sinker. Reprinted from Ref. [8] Chap. 4, Basic mechanical principles of knitting technology, Page No. 32, copyright 2001, with permission from Elsevier

The swinging motion is fixed, but the direction and extent of the shogging motion may or may not be varied from a pattern mechanism. This method is employed on all warp knitting machines and for wrap patterning on weft knitting machines (when a fixed wrapping movement is used). The length of the yarn per stitch unit is generally determined by the rate of warp yarn feed.

11.5 The Knitting (Interlooping) Processes on Knitting Machines

11.5.1 Concept of Knitting Machines' Classification

The classification of knitting machines, adopted in different countries, has differences. The principles underlying the classification may be determined by:

- Frequency of needles arrangement in needle bar;
- Method of knitting;
- The shape of the needle bars and their dimensions;
- Number of needle bars and their construction;
- Features of knitted production, where machines are used;
- Signs of manufactured products

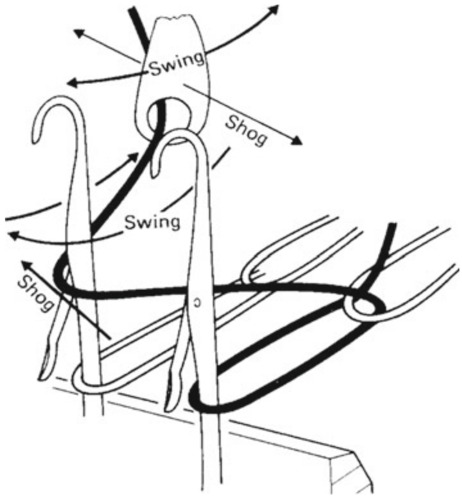


Fig. 11.13 Loop forming by warp guides. Reprinted from Ref. [8] Chap. 4, Basic mechanical principles of knitting technology, Page No. 32, copyright 2001, with permission from Elsevier

The most common classification in all countries is the first principle, frequency of needles arrangement, it means knitting machines are classified by machine gauge (Fig. 11.13).

The gauge of the knitting machine is the number of needles per unit of length.

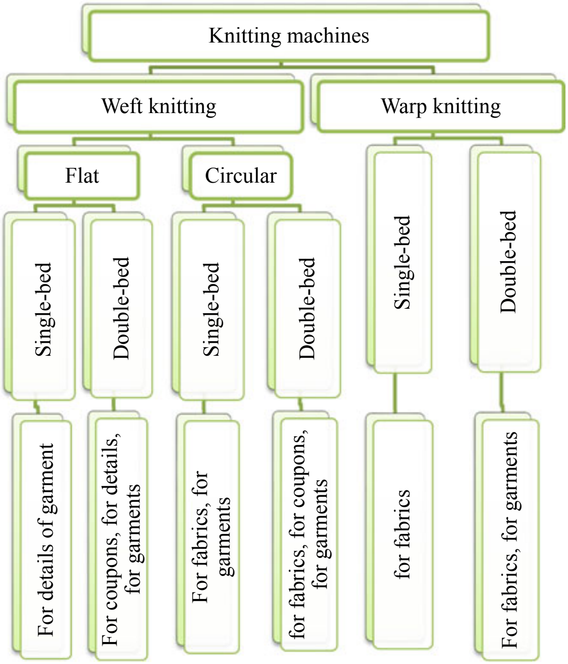
For machines of various kinds, inches -English, Saxon or French are taken as units of length.

The class of knitting machines can be divided into two subclasses based on the principle of knitting: weft knitting machines and warp knitting machines (Fig. 11.14).

11.5.2 *Features of Knitting (Interlooping) Processes on Single Bed Knitting Machines*

There is a large number of various knitting machines for the production of single knitted fabric and knitwear. Each knitting machine is primarily designed to perform the knitting process and turn the yarns into fabric or parts of the garment. The process of forming yarn into loops on the single bed knitting machines can be carried out by three methods (see Sect. 11.4.4 The methods of forming yarn into needle loops) dependent on: (1) mechanisms and devices of yarn feeders; (2) mechanisms and devices of knitting. Single bed knitting machines have bearded, latch, compound or slide needles. In addition, in these machines sinkers, pressers and yarn feeders are involved in the knitting process.

Fig. 11.14 Classification of knitting machine



11.5.3 Weft Knitting Machine. Knitting Process with Bearded Needles on the Circular Knitting Machine

The knitting process with bearded needles is conditionally divided into separate knitting actions to improve and facilitate its optimization (Fig. 11.15).

(1) **Clearing**. The content of this operation consists into move already formed (old) loops from the under needle hooks to lower position of the stem so that it would be possible to lay yarn in needle stem between the end of hook and old loop. On the circular machine with the bearded needle, the already formed (old) loops are moved by clearing disk (Fig. 11.15a).

(2) **Yarn feeding**. The content of yarn feeding action consists of sequentially threading the needles in the interval between the groove of the bearded needle and the old loop. On the circular knitting machine with bearded needle new yarn is laid by the movement of the sinker wheel frame relative to needles (Fig. 11.15b).

(3) **Sinking or kinking**. This operation refers to the sequentially forming yarn into needle loops by sinking the yarn into space between adjacent needles using loop forming sinkers (Fig. 11.15c).

(4) **Lifting the needle loop**. This is the operation of moving the kinked yarns (new needle loops) under the needle hooks (Fig. 11.15d).

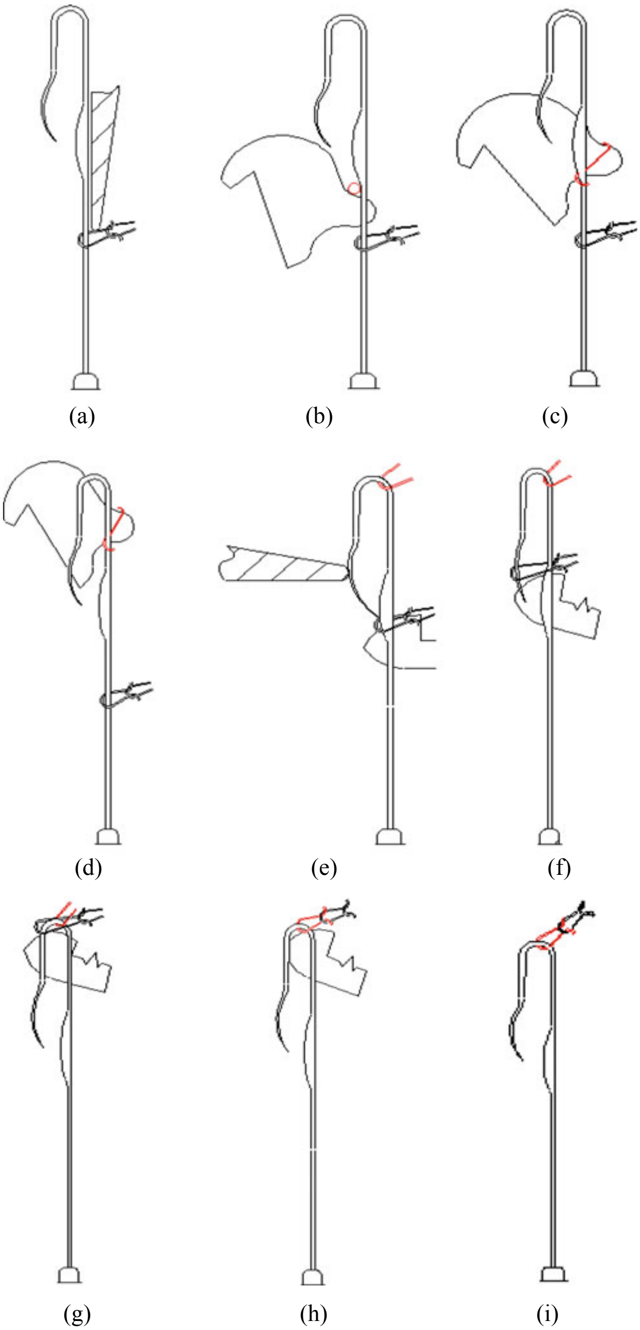


Fig. 11.15 Basic knitting actions of the bearded needle on the circular knitting machine: **a** clearing; **b** yarn feeding; **c** sinking or kinking (new needle loop forming); **d** lifting new needle loop; **e** pressing; **f** sliding old loop; **g** joining; **h** throwing down old loop; **i** drawing through and drawing off

(5) **Pressing**. This is closing the hook of needles by sinking the end of the hooks into the groove of needles. Pressing can be performed by pressing on the hump of the hook by a special presser (Fig. 11.15e).
(6) **Sliding old loop**. Its content is to land the old loops onto the outside of the closed hook of the needle. On circular knitting machines with bearded needles, old loops slide on the hook by moving up the knocking over sinkers (Fig. 11.15f).
(7) **Joining**. This is an operation to contact an old loop with a new loop. After joining the old and new loops, the dimensions of the last loops cannot be changed (Fig. 11.15g).
(8) **Throwing down the old loop**. It is moving the old loop from the needle to the new loop. When throwing down, the knocking sinker moves to the top starting to move away from the needles (Fig. 11.15h).
(9) **Drawing through**. Its content consists in the new loop is drawn through the head of the old loop. Simultaneously, the old loop casts-off the new loop. The loop formation is considered as finished if the new loop is drawn through the old one completely (Fig. 11.15i).
(10) **Drawing off**. The old loop hangs from the feet of the fully formed new loop and then a new loop is drawn off behind the back of the needles. So that, the old loops were unable to re-enter the needles when the loops were moved for clearing operation—initial operation of loop formation (Fig. 11.15i).

Thus, when describing the process of loop formation on bearded needles 10 operations are marked: clearing, yarn feeding, sinking or kinking, lifting the needle loop, pressing, sliding old loop, joining, throwing down old loop, drawing through and cast off, drawing off [10].

11.5.4 Weft Knitting Machine. Knitting Process with Latch Needles on the Circular Knitting Machine

The knitting process accomplished with a latch needle on the circular knitting machine is shown on Figs. 11.16 and 11.17.

The sequence of the knitting process with latch needle: It is clear from Fig. 11.17 that the needle N_1, having formed a loop, starts to rise (move forward). The latch of the needle N_1 may be opened or closed depending on firstly, how freely it sits on the rivet and is located in the needle slot, and secondly, by how much greater inertia force occurs in the latch of needle when needle changes its movement from downward (backward) to upward (forward). Needles N_2 - N_4 gradually rises (move forward), and their old loops slide relative to needles down (backward).

When the needle N_4 ascends the old loop must open the needle latch, or stretches due to adjacent needle loops, or finally breaks. After opening the latch (see needle N_6), when the needles are further ascending, the old loops of the needles, slide inside the latches (see needles N_6 and N_7), when needle reaches the top of the cam, the old

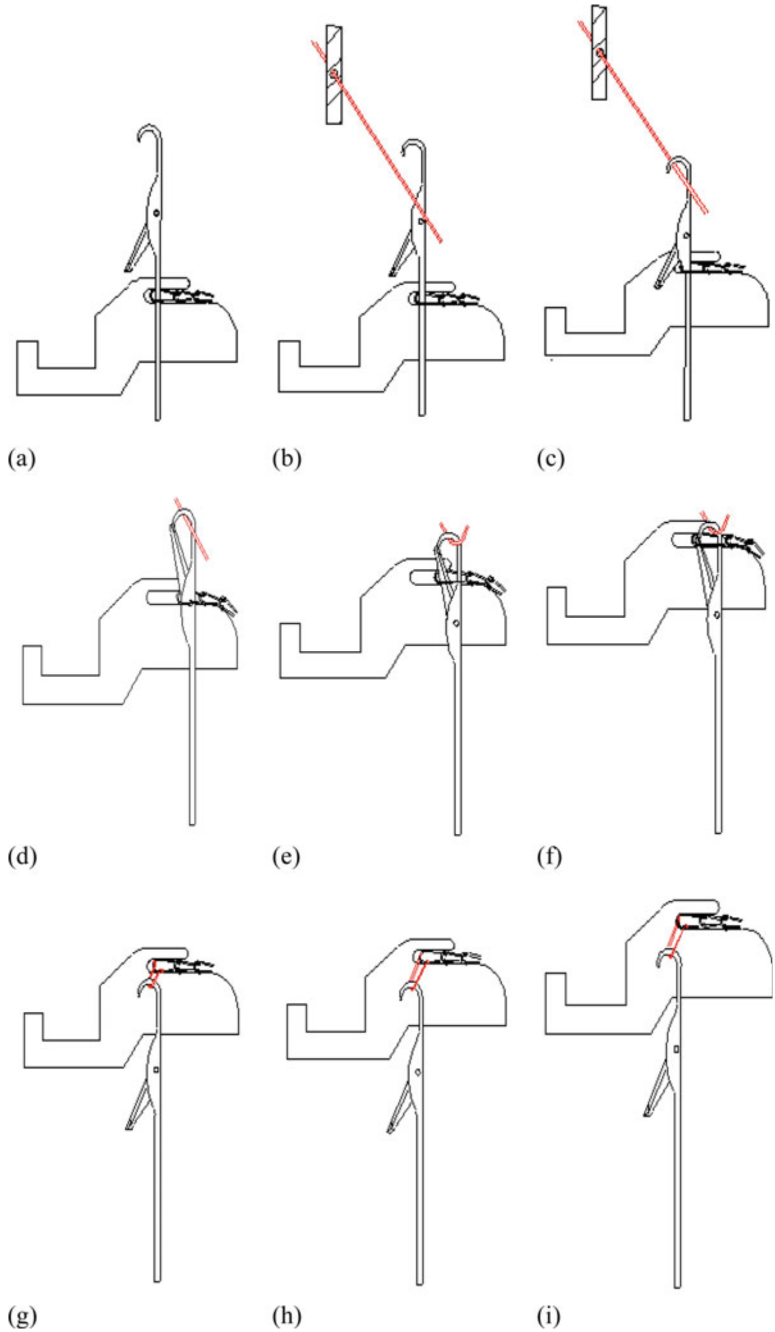


Fig. 11.16 Basic knitting actions of latch needle on the circular knitting machine: **a** rest position and clearing; **b** yarn feeding; **c** lifting yarn under the hook; **d** pressing; **e** sliding the old loop; **f** joining; **g** yarn forming into needle loop; **h** throwing down old loop (knocking over); **i** drawing through and drawing off

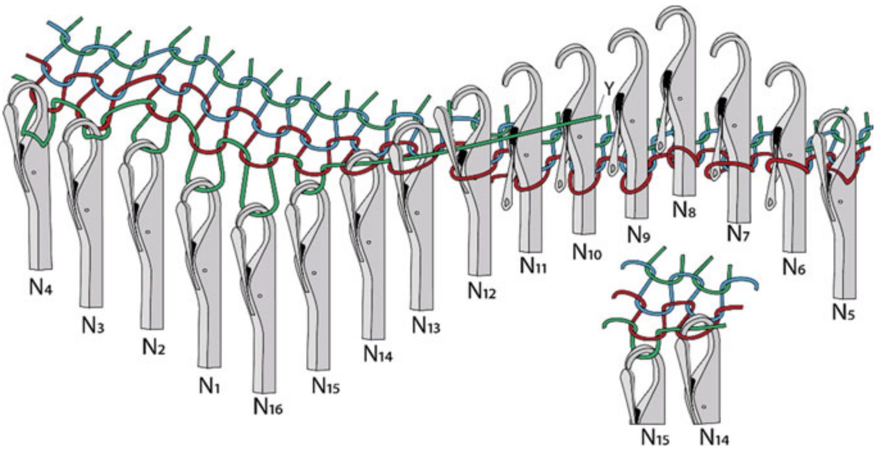


Fig. 11.17 Arrangement of needles during the knitting process on latch needles

loop is cleared from the latch spoon on to the stem (see needle N_8). In this way, the **clearing** operation is carried out.

The old loop must then be drawn off the back of the needle, to press it against needle stem. If the size of the old loop is small, then there is no need for it; at large size, if the loop is not pressed against the needle stem, it can get back onto the latch as it starts to descend (see needles N_9, N_{10}, N_{11}). The old loop must necessarily close the latch, if it gets into the latch, the latch will not be closed and the process will be broken. In this case, a defect called a “set of the loop” may occur.

If the old loop falls under the open latch, as shown on needles N_{10}, N_{11}, so latch can be closed by the old loop (see needle N_{12}), i.e. the **pressing** operation is performed: the entrance under the needle hook is closed.

Before closing the latch (before pressing), the yarn must be feed on the needle to form a new loop. The yarn should be laid on the needle below the hook, as illustrated on the needles N_{12} - N_{13}. This is a **yarn feeding** operation.

When the needle is further descended, the yarn falls under the needle hook, as it is shown on the needle N_{14}, i.e. the **ascending yarn under the hook** operation is performed. At the same time, the old loop starts sliding on the closed latch (see needles N_{13} and N_{14}). The laid yarn on the needle gets under the hook and cannot move further along the needle, the old loop draw near it, as shown on the needle N_{14}, i.e. there is a **joining** operation.

From the figure (see needle N_{14}) it can be seen that the old loop cannot be slide off from the needle because it is held by the yarn under the hook. This can only happen after kinking this yarn. Therefore, after joining, firstly, the **yarn forms into needle loop** and only then the old loop slides off the needle **(throwing down the old loop** operation**)**, as it is shown on the needle N_{15}.

After throwing down the old loop, the needle N_{16} descends to drawing the new loop through the old loop, as shown on Fig. 11.17. The continued descent of the needle draws the loop length. By drawing the new loop through the old one and moving the sinker forward, the old loop casts-off fully and hangs from the feet of the fully formed new loop. And there the loop formation process will be completed (drawing through and knocking over operation).

After that, the needle starts ascending to the rest position and to accomplish the clearing operation. So that, at the same time the old loop could not be strung again on the needle when the needle N_1 is gradually ascending, the old loops are **drawing off** to the back from the verge.

11.5.5 Knitting Process with Bearded Needles on the Warp Knitting Machine

On the warp knitting machines, the process of loop formation is carried out according to the warp knitting method. In this method, the loop formation sequence is the same as in the knitting method; the difference is that each needle gets its own warp yarn (Fig. 11.18). The knitting operations on the warp knitting machine with bearded needles at the time receiving loops on all needles are given. In such a process, yarns filled into the warp yarn guide, are feed the needles by lapping movement yarn guide between the needle heads by swinging and shogging motions.

During yarn feeding, the needles are in the clearing position (Fig. 11.18a). From the initial position, the warp yarn guide is shogged behind the needles firstly, swung between the needle heads, shogged on the beard side of needles for overlapping across the beard, and again swung between the needle heads, at the end returns to the initial position. As a result, each needle is wrapped with a warp yarn, wherein a portion of the warp yarn, extending from the warp yarn guide to the knitted lap is feed on the needle.

On the bearded needles, the yarn is laid on the needle beard (Fig. 11.18b), then the needles start to rising fully and newly formed overlaps slip off the beards onto the stems above the old overlaps (Fig. 11.18c).

Warp yarns, if they are laid by the warp yarn guide, cannot be laid on the needle stem at once, because warp yarn guide should be descended below between the needles. In this case, not only a portion of the warp yarn extending from the warp yarn guide to the knitted lap but also a portion of the yarn extending from the warp yarn guide to the beams could be feed on the needle simultaneously.

After the yarn feeding the following loop forming operations are performed: the lifting the overlap under the hook (Fig. 11.18d), pressing with presser (Fig. 11.18e), landing the old loop (Fig. 11.18f), joining (Fig. 11.18g), forming lap length, knock over, lap fully formation (underlap shog) (Fig. 11.18h–j), holding down (push away from ascending needles) (Fig. 11.18k).

A feature of the basic method of loop formation is more favorable conditions for performing the knock over operation compared to the knitting method: when the needles are descent, the branch of the warp yarn going to the warp yarn guide is

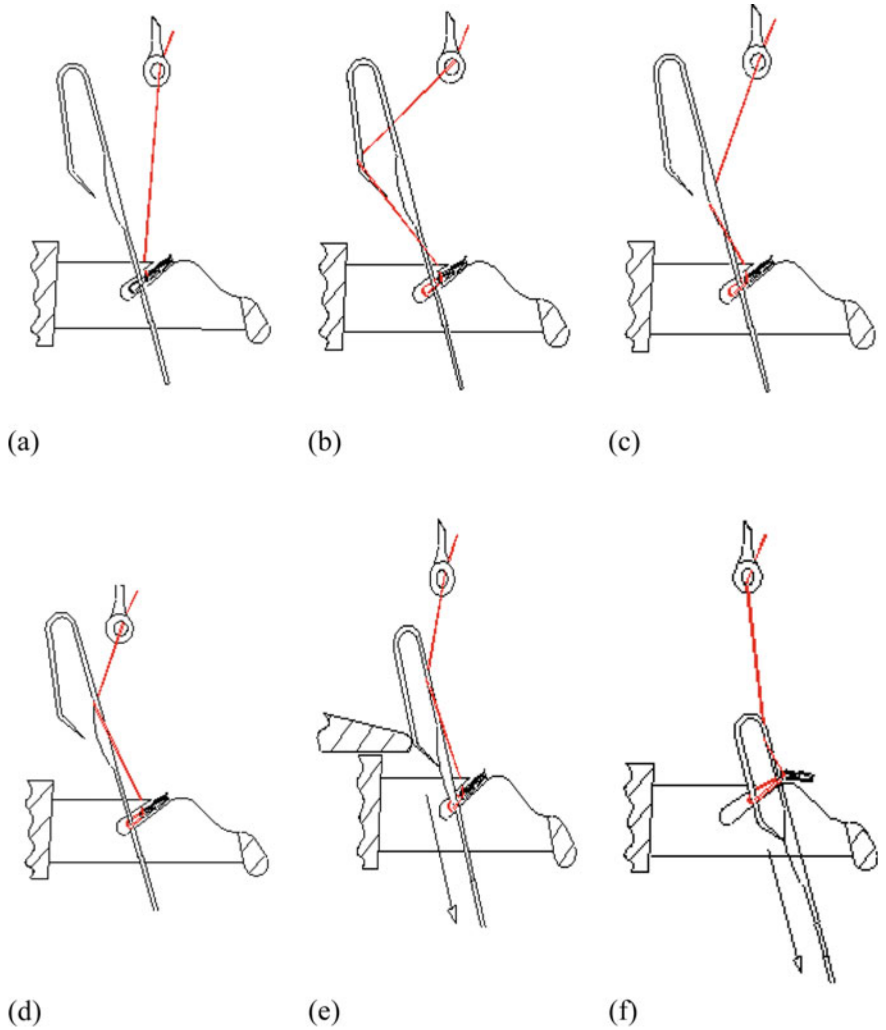


Fig. 11.18 The basic knitting actions on the warp knitting machine with bearded needles: **a** rest position; **b** yarn feeding (swing and shog); **c** rising the needle fully and ending of the yarn feeding action; **d** lifting the overlap under the hook; **e** pressing the beard; **f** landing the old loop; **g** joining; **h** forming lap length; **i** knock over; **j** lap fully formation (underlap shog); **k** holding down (push away from ascending needles)

already kinked in the needle head. Another feature is that the length of the lap to be formed is determined by the drawing through of the warp yarn and the knitted laps (Fig. 11.18i): if there is the greater draw force of the old loops, the larger size of the new lap can be formed; with an increase warp yarns tension, the conditions, drawing through from the warp yarns to the forming laps deteriorate and the laps could be formed smaller.

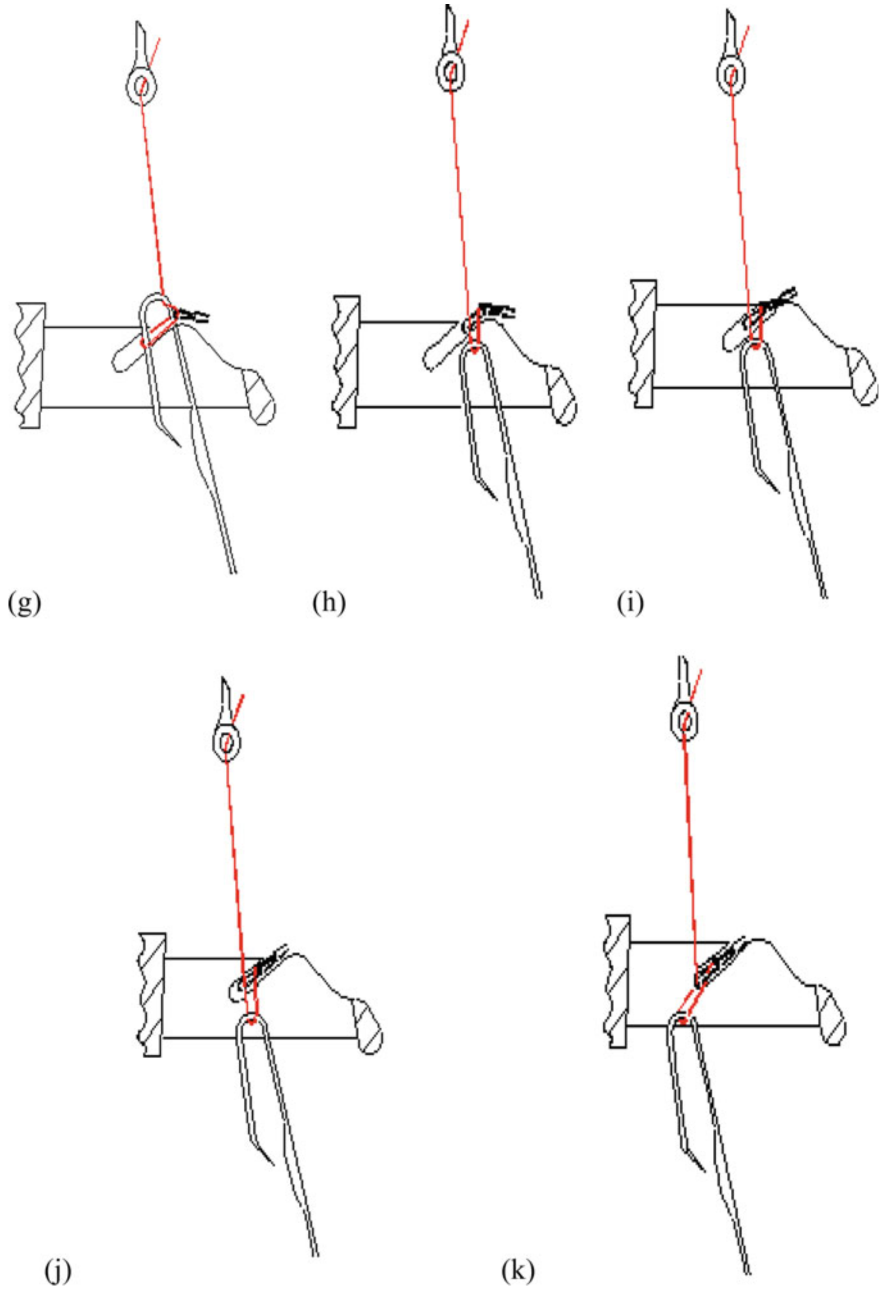


Fig. 11.18 (continued)

11.5.6 Knitting Process with Compound Needles on the Warp Knitting Machine

Figure 11.19 shows the process of knitting on warp knitting machines with compound needles. It includes the same operations as for bearded needles: rest position and clearing (Fig. 11.19a); yarn feeding (Fig. 11.19b); lifting the overlap under the hook (Fig. 11.19c); pressing (Fig. 11.19d), landing the old loop, joining, (Fig. 11.19e, f); forming lap length, knocking off (Fig. 11.19g). Lap fully formation (Fig. 11.19h), holding down (push away from ascending needles) (Fig. 11.19i). The difference consists of less general movements of compound needles, pressing them by the sliding closing element and possibility of warp yarn feeding into the needle hook.

11.5.7 Features of Knitting (Interloping) Processes on Double-Bed Knitting Machines

The necessary condition for the formation of double knit fabric or knitwear - having a two-needle bar and on each of them could be implemented in the processes of knitting. At the same time on different needle bars, the knit loops can be formed by both the same and different methods.

The double-bed machine working on weft knitting and warp knitting methods are known. The needles of each needle bar can form loops by simultaneously, alternately and distribution methods. At simultaneously passing the process of knitting, loops on needles of divers needles bar are formed at the same time. When the knitting process proceeds sequentially, the loops are first formed on the one and then on the other needle bar in the same or different ways, for example, in a purl knitting. When the knitting process passes by distribution method, loops are first formed on one needle bar and then on another, by borrowing for them a yarn from loops already formed on the first needle bar.

To the needle bar, on the needles of which the loops are formed from the yarn coming from the yarn feeder is called an active; to the needle bar, on needles of which loops are formed by borrowing yarn from loops of the active needle, is called passive.

11.5.8 Weft Knitting Machine. The Technology of Knitting with Latch Needles on Double-Bed Circular or Flat Knitting Machines

The basic actions of knitting performed by the sequential knitting method on double-bed flat or circular-knitting machines are given on Figs. 11.20 and 11.21.

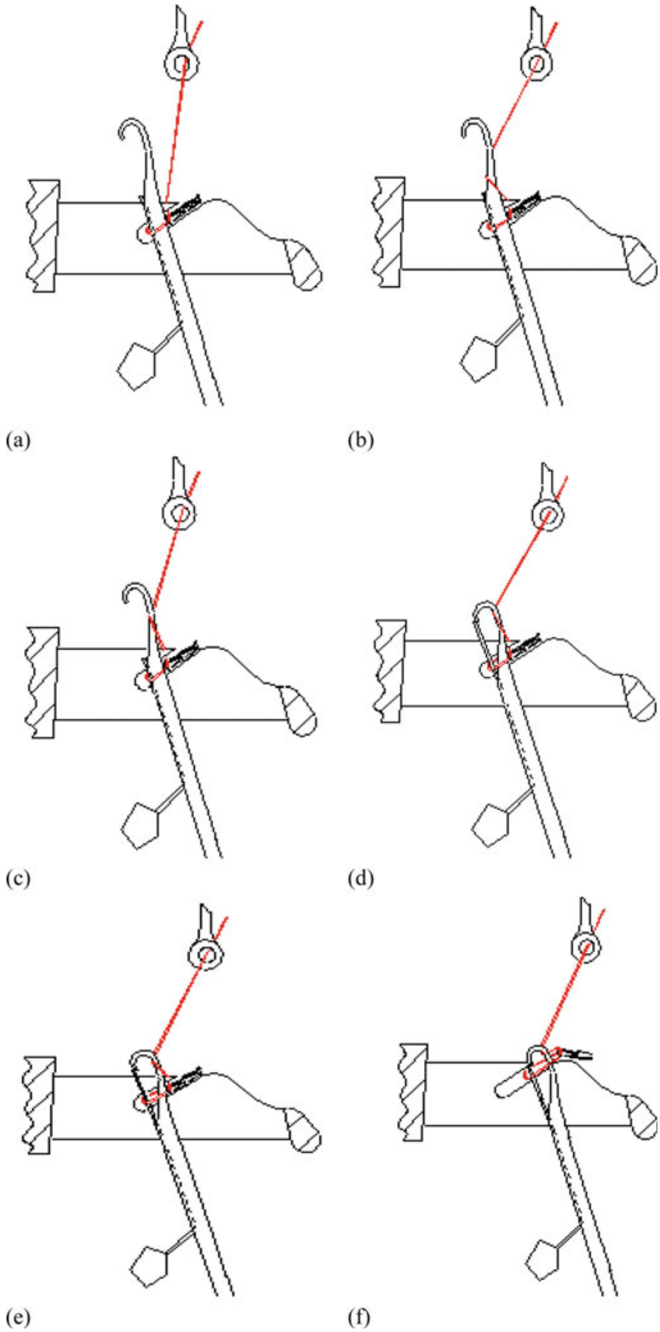


Fig. 11.19 The basic knitting actions on the warp knitting machine with compound needles: **a** rest position and clearing; **b** yarn feeding; **c** lifting the overlap under the hook; **d** pressing; **e** landing the old loop; **f** joining; **g** forming lap length and knocking over; **h** lap fully formation; **i** holding down (push away from ascending needles)

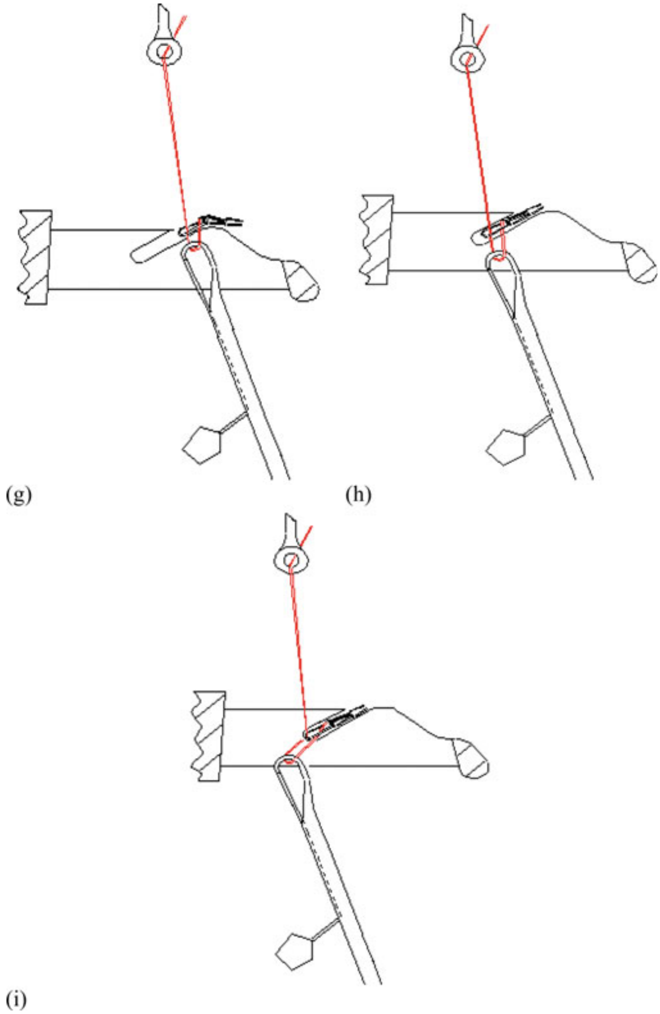


Fig. 11.19 (continued)

It can be seen in Fig. 11.21. that latch needles marked with odd numbers are located in the channels of needle bar A, latch needles marked with even numbers—in the channels of needle bar B. The verge T of needle bar are located relative to each other at distance *a* and set depending on the machine construction to the angle φ. On the circular knitting machines $\varphi = \pi/4$, on the flat knitting machines—$\varphi > \pi/4$. When performing operations of knitting a needle of each needle bar carries out the general movement of S. The letter Z indicates the sinking (kinking) depth. The draw force *q* of the fabric attached to the formed loops of knitting and prevent the loops from moving together with the needles. The number and sequence of knitting operations performed on each needle are the same and correspond to the knitting method with

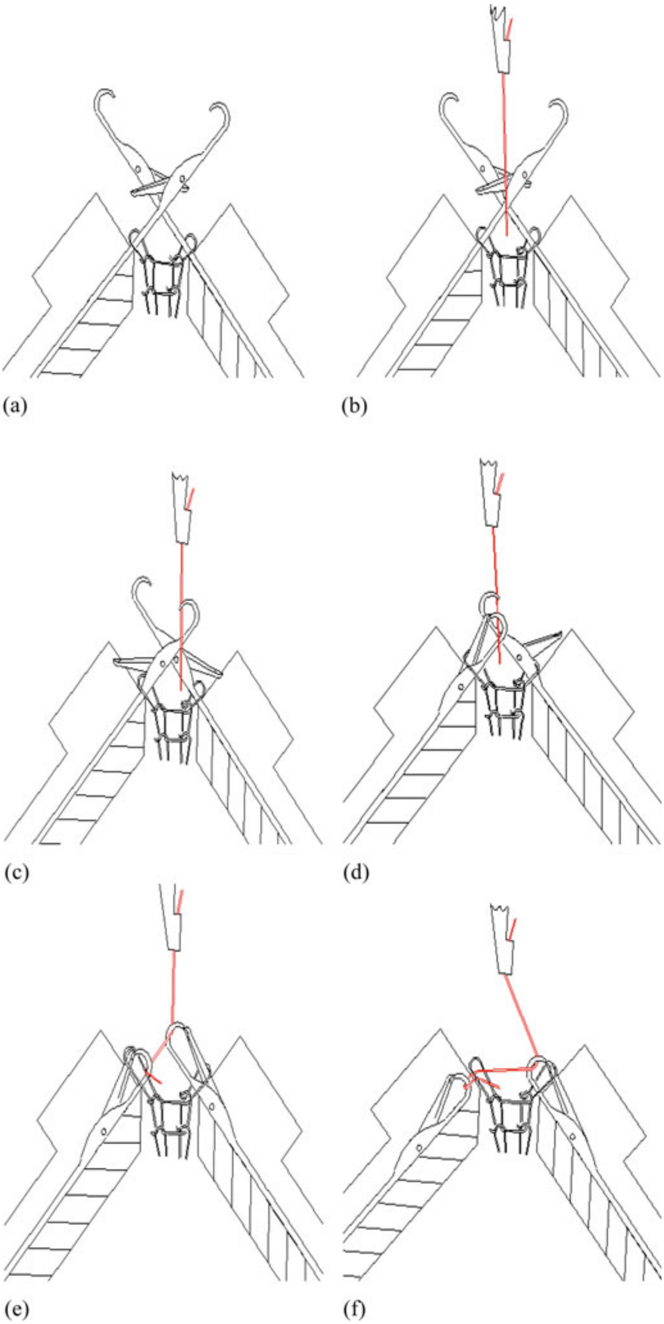


Fig. 11.20 The basic knitting actions on the double bed weft knitting machine by sequential knitting method. **a** Rest and clearing position. **b** Yarn feeding. **c** Lifting the yarn under the hook. **d** Pressing. **e** Sliding the old loop onto the latch. **f** Joining. **g** Yarn forming into needle loop. **h** Knock over. **i** draw through (fully loop formation) and draw off

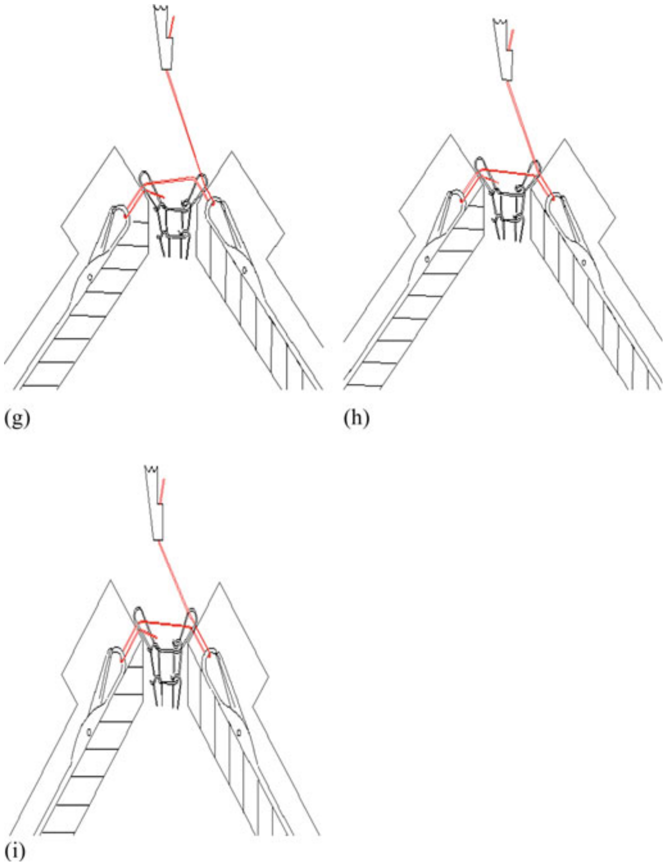


Fig. 11.20 (continued)

latch needles. The difference is that knitting actions performed on adjacent needles set in diver needles bars, with existing methods of moving needles by guard cam, are usually time-shifted by the amount of passage through the guard cam channel *0.5 t*, where *t*- is needle pitch of knitting machine. For example, needles on needle bar *A* in the direction of knitting shown on Fig. 11.21 perform and complete the knitting (interloping) actions earlier than on needle bar *B*. Thus, a knock over action is performed on the needle 9 and the sliding old loop onto the closed latch is performed on the needle 8. Needle 11 is completed the loop fully formation by drawn through the new loop completely and starts to ascending, clearing the newly formed loop, needle 10 performs the fully new loop formation action, etc.

A small-time shift on the drawing through (fully loop formation) action on the different needle bars is particularly important because it reduces the load on the kinked yarn and allows the yarn to move into the forming loop from the already formed loop on the opposite needle bar. This difference is illustrated in the combined

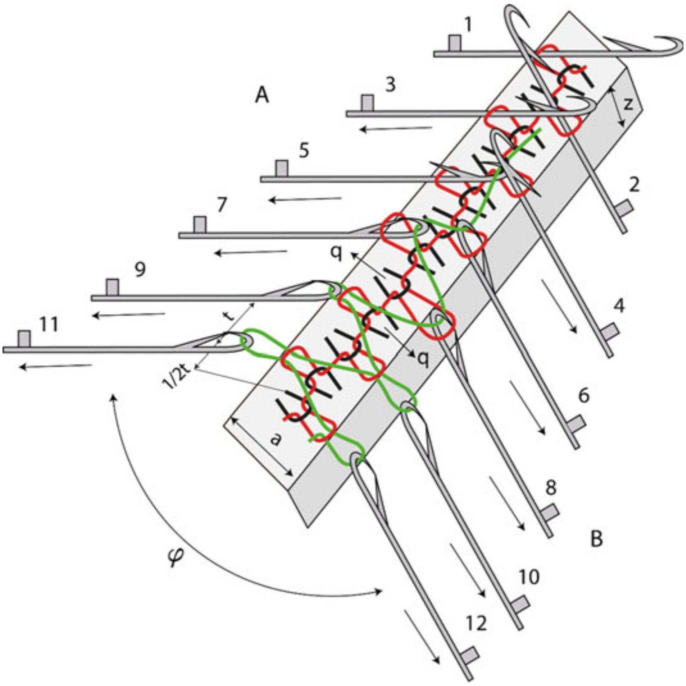


Fig. 11.21 Arrangement of needles on the needle bars during the knitting process without distribution

diagram of the vertical movements of the needle in the needle bars A and B during the knitting (see Fig. 11.22).

For example, when the needle of the needle bar A is descent to the value Z, the needles of another needle bar has not yet begun to fully loop formation action, the hooks of them are located from the verge at the distance S'$_n$ − Z: when the needles

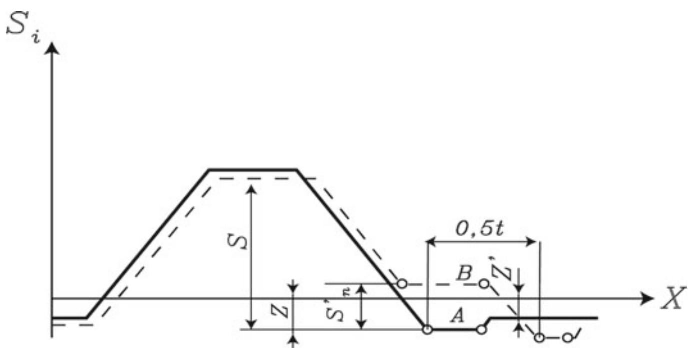


Fig. 11.22 Diagram of movement A and B needle bar needles

of needle bar B are descent to the depth of loop length forming (kinking) the needle of needle bar A ascending, released the yarn for drawing to the forming the loop and are at the distance Z ‘from the verge.

It is not difficult to see that on a loop formation by the sequential method of knitting on two needle bars, the total number of needles, simultaneously kink the yarn is twice that on one needle bar. On double-bed machines, the minimum number of needles which kinks the yarn is 4, on single-bed machines—2.

A distinctive feature of the knitting sequential method of loop formation is the independence of the action of the needles of both needles bar; when some needles of one needle bar are switched off the other needle bar performs all actions of the knitting process. So both needle bars are active. This feature is important for producing knitwear or fabric with pattern and combined effect of knit structure.

11.5.9 Weft Knitting Machine. The Technology of Knitting with Latch Needles on Double-Bed Knitting Machines with the Distribution

The knitting process of this method is shown on Fig. 11.23. One of the needle bars is active, the other-passive in the process of knitting with the distribution.

After fully forming of new loops on two needle bars the first, needles in the active needle bar start to rise for performing clearing action. The heads of needles of the active needle bars are ascent above the verge, then the needles of passive needle bars are moved forward, at that time the old loops holding down from moving along with the needles by needles backs of the active needle bar. The position of the needles in the rest position and clearing action on both needle bars are shown on Fig. 11.23a; the needles received maximum movement. Then the needles of both needle bars move simultaneously and come to the position shown on Fig. 11.23b. Here the yarn starts to be caught by the heads of the needles of the active needle bar. The needles of the active needle bar continue to descend, and the needles of the passive needle stand and form a new loop on the extended needles of the passive needle bar; these needles are extended so that the loop of the knitting stitch laid into the open needle head. When the loops are formed on the needles of the passive needle bar, the needles of the active needle bar are ascent and the yarn is released to draw it into the newly formed loop of the passive needle bar. From the above, it follows that the distribution method provides better conditions for drawing the yarn from already formed loops of the opposite needle bar, and also provides better evenness of the knitted loops. A disadvantage of the distribution method is the dependence of the knitting actions, performed by needles of different needle bars. For example, when some needles of the active needle bar are turned off, the operation of yarn feeding on the needles of the passive needle bar may be disrupted.

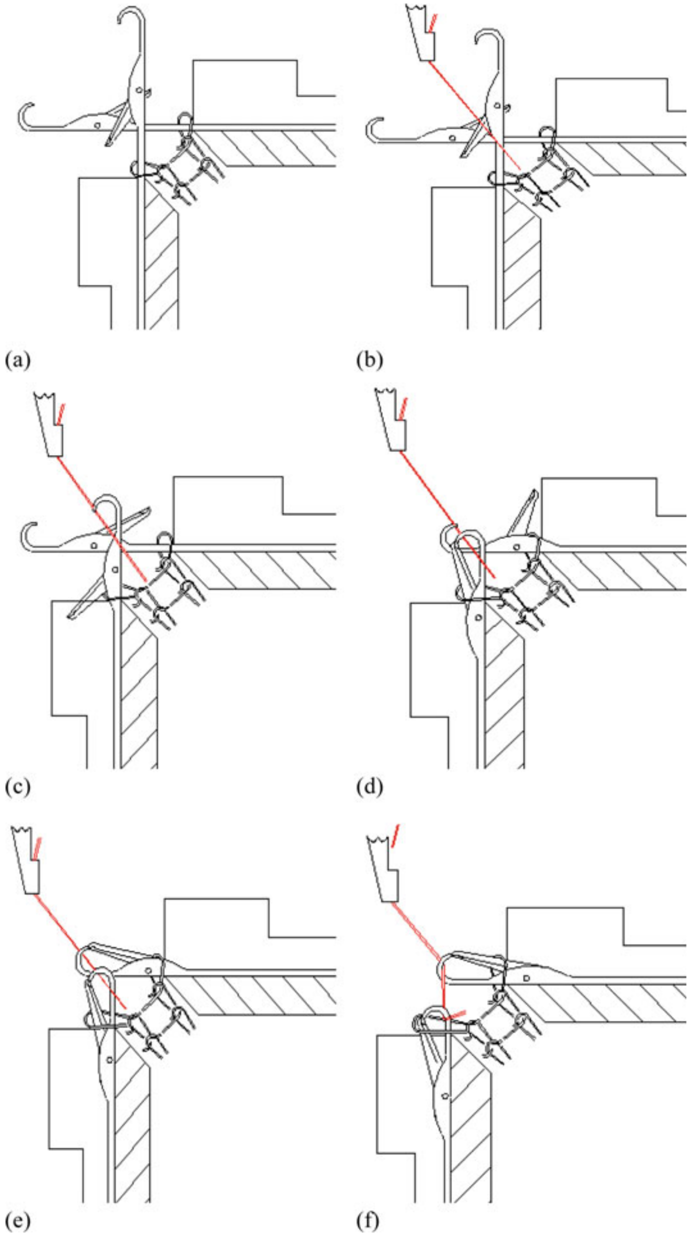


Fig. 11.23 The basic knitting actions on the double bed weft knitting machine by a distribution method: **a** rest and clearing position; **b** yarn feeding; **c** lifting the yarn under the hook; **d** pressing; **e** sliding the old loop onto the latch; **f** joining; **g** yarn forming into needle loop; **h** knock over; **i** draw through (fully loop formation); **j** hold down (draw off)

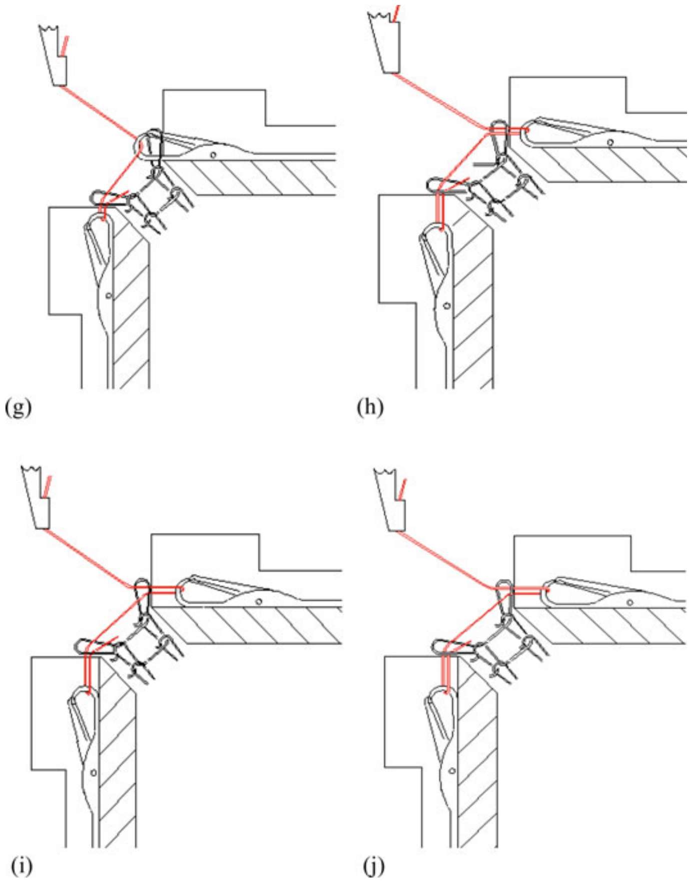
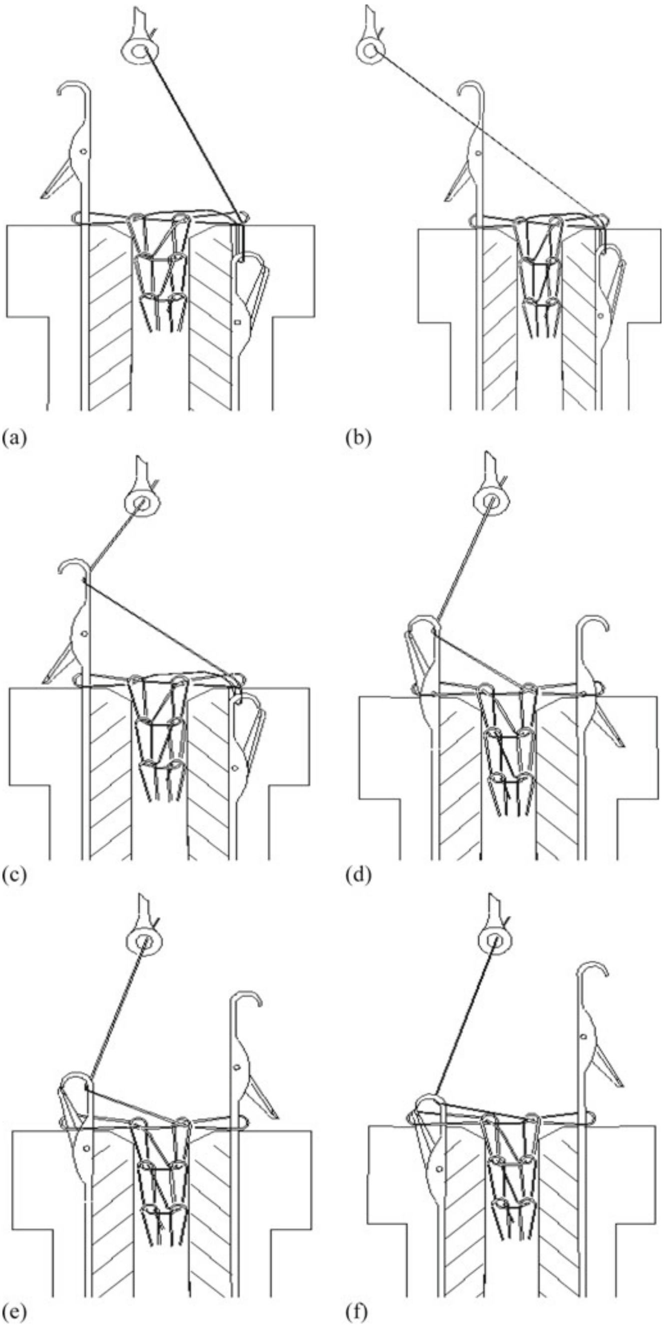


Fig. 11.23 (continued)

11.5.10 Warp Knitting Machine. The Technology of Knitting on the Double Bed Warp Knitting Machine by Warp Knitting Method

On double-bed warp knitting machines, regardless of the needles type used (latch, compound, bearded), knitting technology is implemented sequentially on each needle bar by the warp knitting method. The sequence and purpose of each knitting action on each needle are the same as on single-bed knitting machines. In order to form one course loop of double warp knitted fabric or knitwear, each needle must perform one cycle of the knitting process (see Fig. 11.24).

The process on the double Raschel knitting machine processes sequentially on one or the other of the needle bar, with the warp guide bar, makes six lapping during the formation of one course of loops on both needle bars, i.e. as in operation on a single warp knitting machine.



(a) (b) (c) (d) (e) (f)

Fig. 11.24 Process of loop formation performed on double-bed machines with a warp knitting method: **a** rest position and clearing; **b** yarn feeding; **c** lifting the overlap under the hook; **d** pressing; **e** sliding the old loop onto closed latch; **f** joining; **g** lap length formation (forming the yarn into lap); **h** knocking over; **i** lap fully formation (underlap shog) and holding down (draw off)

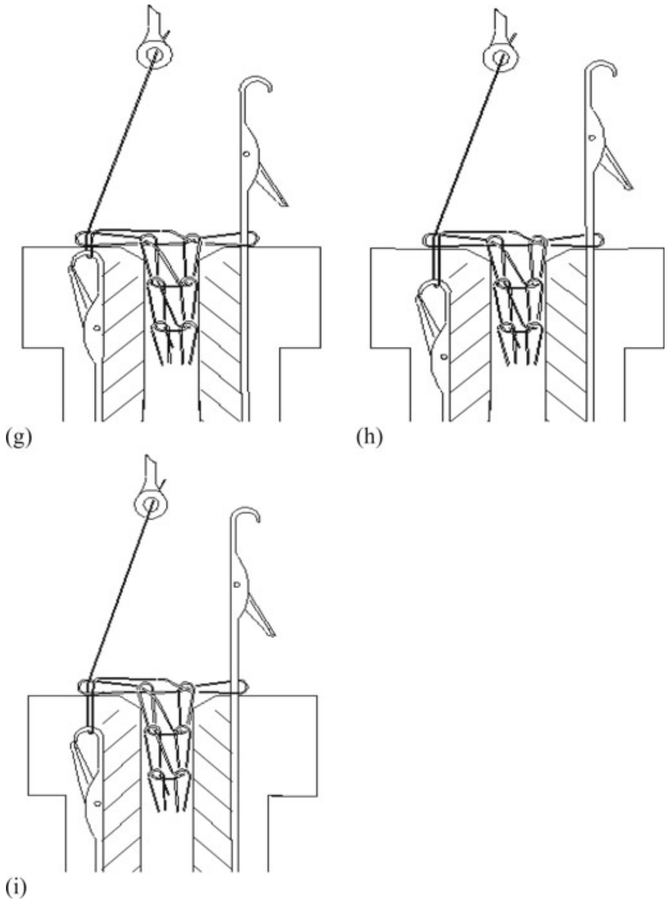


Fig. 11.24 (continued)

11.6 Structures and Properties of Knitted Fabrics

Knitted fabric is characterized by a great variety of knit structures. The knit structure of knitted fabrics is the most important quality characteristic and defines knitting properties: extensibility (elongation), unraveling, surface density, thickness, form stability, etc. By applying different knit structures, it is possible to obtain knitting with different properties, pattern or structural effects.

Knit structures of knitted fabrics can be classified (see Table 11.2). The basic, derivative, cardigan patterned and combined groups of knit structures are distinguished.

The **basic** group of knit structure (B) includes knit structures, which consist of identical elements of structure (loops). The fundamental knit structures have the simplest structure.

Table 11.2 Classification of knitted fabrics

Classification of knitted fabrics			
Group of basic knitted fabrics	Single	Weft	Plain stitch
		Warp	Pillar stitch Tricot lap Atlas lap
	Double	Weft	Rib stitch Purl stitch
		Warp	Double: pillar stitches, tricot lap, atlas lap
Group of derivative knitted fabrics	Single	Weft	Float stitch
		Warp	2 × 1 tricot lap (cord lap), 3 × 1 tricot lap (satin lap), 2 × 1 atlas lap (atlas cord), 3 × 1 atlas lap (atlas satin)
	Double	Weft	Double rib (interlock) stitch
		Warp	Interlock: pillar stitches, tricot lap, atlas lap
Group of patterned knitted fabrics	Single	Weft	Cardigan stitch Plated stitch Plush stitch Jacquard stitch Fleecy stitch A-jour stitch Inlay stitch
	Double	Warp	

The **derivative** group of knit structure (D) includes knit structures, formed from a combination of several identically basic knit structures, which mutually knitted so that, between the loop wales of one, the others loop wales or several similar loops are intermeshed.

The group of **patterned** (P) includes knit structures, formed on the basis of the basic or derivative knit structure, by appending additional elements into them (float loop, tuck loop, additional threads) or by changing the knitting processes, allowing to obtain knitwear or knit fabric with new properties.

Combined knit structures (C) combine the features of the different basic, derivative, or cardigan patterned knit structures.

Depending on the combination methods, knitted structures of various groups distinguish simple, derivative-combined, cardigan patterned and complex combined knitted structures [11].

Apart from the groups (classes), the knit structures can be characterized by rapport (repeat unit) of knitting. As is known, rapport of knitting is the smallest number of loop course (rapport in height Rh) or loop wales (rapport in width Rw) after which alternation order of yarns segments as a knit stitch, float stitch, or tuck stitch in the knit structure is repeated.

Weft (crosswise) and warp (lengthwise) knitting fabrics are distinguished.

In the first loop, the course is formed coherently, loop by loop or in the certain alternation of one or more yarn systems in the direction of the loop course. In the second wales of the loop is formed simultaneously by one or more yarn systems (warps), wherein one or two laps are formed from each of the warp yarn.

The most complete picture of the knitted structure gives its graphical notation. By the graphical notation, the method of yarn feeding, which forms a rapport of the knitted fabric, is conventionally indicated.

11.7 Features of the Structure and Properties of the Basic Weft Knitted Fabrics

11.7.1 Single Weft Knitted Fabrics. Plain and Its Properties

Plain stitch is (see Fig. 11.25) a single fabric, in which a course of the loop is formed by knitting the same yarn into loops sequentially. By knit structure, it is the simplest and most common fabric. Its technical face is dramatically different from the technical back. Its technical face is smooth, with the side limbs of the needle loops having the appearance of columns of V's in the wales. On the technical back, the heads of needle loops and the bases of sinker loops form columns of interlocking semi-circles, whose appearance is sometimes emphasized by knitting alternative courses in different colored yarns.

The plain has a small thickness equal to the two thicknesses of the yarns from which it is formed. The durability of the knitted fabric is determined by the values of the breaking load related to one loop. The durability of the plain depends on the kind of raw material and the horizontal and vertical density. The breaking load can be determined separately in width and length, as well as together. In the latter case, the strength will be common.

Plain can be unroved from the course knitted last by pulling the needle loops through from the technical back, or from the course knitted first by pulling the sinker loops through from the technical face side. Loops can be prevented from unroving by binding-off.

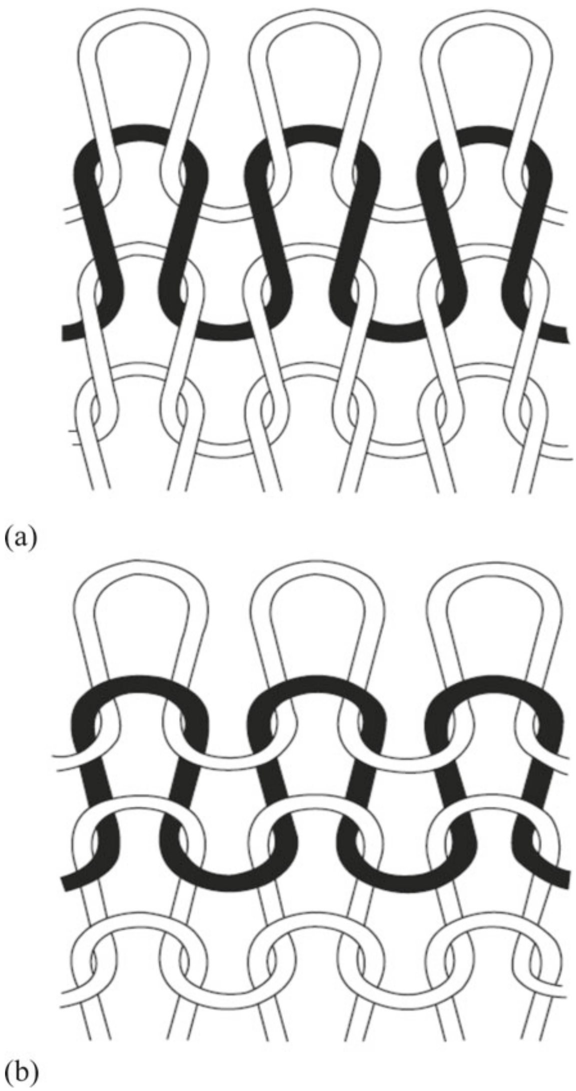
The unraveling property adversely affects the knitted fabric quality, since if a single loop yarn breaks, it is possible to unrove all previous loops of this loops wale.

Curling. In the free state, the edges of the plain are curled, due to elastic deformations, which are arisen during the forming of the yarn into loops. For the same reason, there is sometimes a skewness of loop wales.

Extensibility (Elongation). The plain is characterized by good extensibility, especially if the tensile force is applied in one direction, in length and width. The plain extends, when it is stretched in length and narrows in width; when stretched in width, it increases in width, shrinks in length.

If the plain is stretched simultaneously in both length and width, it will increase both in width and length, but to a lesser extent than when it stretched in one direction.

Fig. 11.25 Plain knit structure: **a** technical face; **b** technical back. Reprinted from Ref. [12] Chap. 10, Weft knitting, weft-knitted fabric and knitwear design, Page No. 96, copyright 2001, with permission from Elsevier



The plain is characterized by sufficiently high porosity (with more through pores), air and steam permeability, low capillarity and low heat protection.

The disadvantage of the plain is the easy unraveling along with both the loop courses and the loop wales. Yarns with an increased coefficient of friction or twisted in two layers are used to reduce the unraveling of the plain. The reduction of unraveling is also achieved by increasing the density and reducing the loop length.

11.7.2 Double Weft Knitted Fabrics. Rib and Its Properties

The rib is the most common double weft knitting fabric. It consists of a system of open loops forming two-loop layers across the thickness of the knitted fabric; the loops are intermeshed along the line of the loop courses by sinker loops such that, the face loop of one loop layer is intermeshed to the adjacent back loop of the other loop layer (see Fig. 11.26).

On each side of the loop layer in a rib structure, the face loop wales are most visible; the technical back loop courses are less visible as they are less illuminated and it seems that the rib consists only of the technical face loops. This circumstance gives a reason to call the knitted fabric like a double-faced rib in some countries, although in it, there are the technical back loops in the same amount as the technical face loops.

Thickness. Since in the rib structure the back loops pick up the face loops, it is obvious that the thickness of such a rib structure will be twice the thickness of the plain produced from the yarn of equal thickness and density.

Unraveling. The rib 1 × 1 is unroved only in the opposite direction of knitting. When yarn is broken in a loop, the loop wale of that loop will also unraveled only in the opposite knitting direction. In rib of other combinations, for example, 2 × 2 (at the break of yarn in loop wales of that loop can be unraveled also in the direction of knitting, as the adjacent loop wales in such rib structure intermeshed by tuck loops in one loopy layer represent the segments if plain structure. In the rib, as in the plain, it is possible to miss the loops when the yarn breaks in the loop and apply tensile loads to the rib structure.

Curling the edges. A rib with the same combination of face and back loops does not twist from the edges, length or width, as the desire of the loops to curl one side

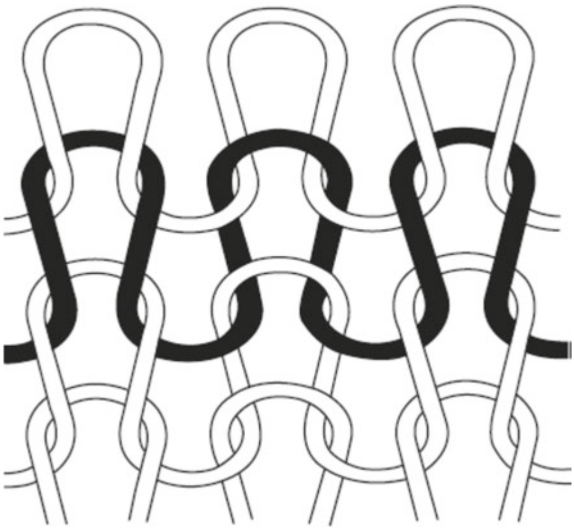


Fig. 11.26 Rib1 × 1 knit structure. Reprinted from Ref. [12] Chap. 10, Weft knitting, weft-knitted fabric and knitwear design, Page No. 97, copyright 2001, with permission from Elsevier

of the rib is balanced by the desire of the other side loops to curl in the opposite direction. A rib having a significantly larger number of face loop wales on one side than on the other side will tend to curl in crosswise to the side where the number of face loop wales is smaller and in lengthwise to the side where they are larger. This is because the forces causing the knitted fabric to curl will be larger on the side where there are more loop wales.

Extensibility. From the plain, the rib structure is characterized by increased extensibility, especially in width. Therefore, it is recommended to use the rib structure in those garments which should have greater extensibility in width and a relatively small length.

11.7.3 Double Weft Knitted Fabrics. Purl and Its Properties

The purl of the knitted fabric is called because both sides of it are similar to the backside of the plain, i.e. on both sides, it is visible mainly sinker loops. The purl is formed from open loops extending through each other such that the face and back loop courses are alternated (see Fig. 11.27).

The face and back loop courses in the purl knit structure, as well as the loop wales in the rib structure, can be combined in different sequences.

Unravelling. The purl can be unroved just like the plain knitted fabric.

Thickness. The thickness of the purl is twice the thickness of the plain and approximately equal to the thickness of the rib.

Curling the edges. The purl knitted fabric is not curled on either the face or backside, as the desire of loops of one course to turn the knitted fabric in a certain

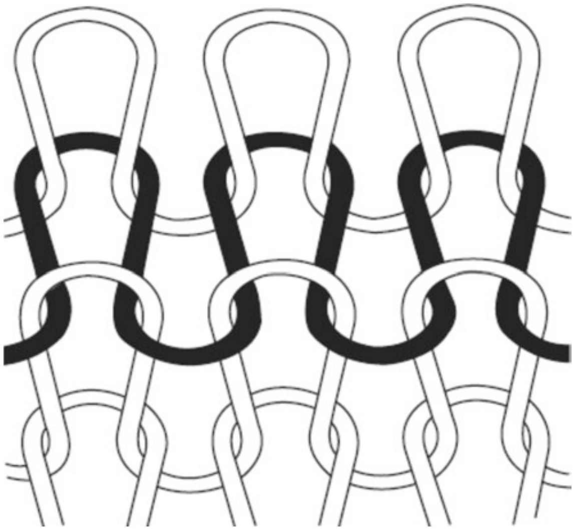
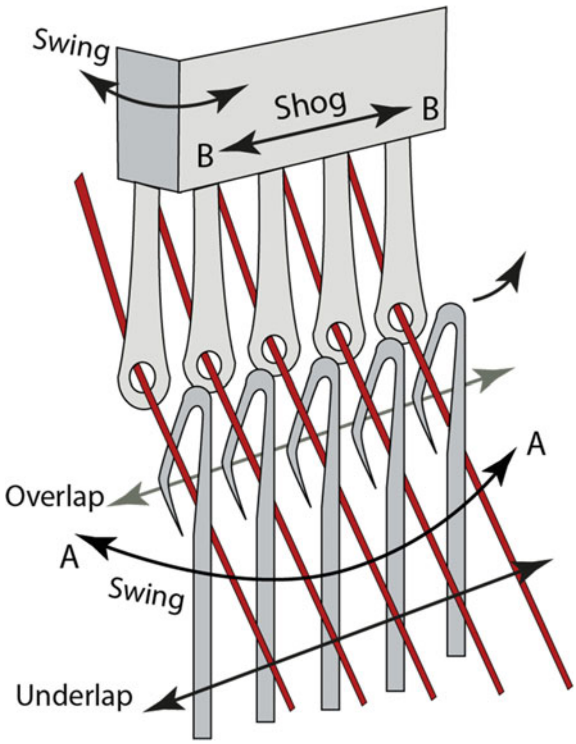


Fig. 11.27 Purl 1 × 1 knit structure. Reprinted from Ref. [12] Chap. 10, Weft knitting, weft-knitted fabric and knitwear design, Page No. 98, copyright 2001, with permission from Elsevier

Fig. 11.28 Guide bar lapping movement



direction is counteracted by the desire of loops of the other course to turn the knitting in the opposite direction. The desire to turn the loop courses of purl knitted fabric only affects its shortening.

Extensibility. The purl knitted fabric at maximum tension increases in length and width, as the plain.

Mainly headscarves are produced with purl knit structure, as they must stretch equally in width and length (Fig. 11.28).

11.8 Features of the Structure and Properties of the Basic Warp Knitted Fabrics

In a warp knitted structure, all ends supplied from the same warp sheet normally have identical lapping movements (see Sect. 11.4.4, Fig. 11.11) because each is lapped by a guide attached to the same guide bar (Fig. 11.27). Beams supply the warp sheets in parallel form to the guide bars, whose pattern control determines the timing and configuration of the lapping movements in the form of overlaps and underlaps. The needles intermesh the new overlaps through the old overlaps to form the intermeshed loop structure.

11.8.1 Single Warp Knitted Fabrics. The Single Pillar Stitch and Its Properties

Single pillar stitches. In the pillar or chain stitch, the same guide always overlaps the same needle. This lapping movement will produce chains (pillars) of loops in unconnected wales, which must be connected together by the underlaps the second guide bar (see Fig. 11.29). The closed-lap and open-lap pillar stitches are distinguished. The pillar stitches are usually used in combination with other interlacings, it is the most important element of knitted fabric sets of garments, curtains, lace, fringes, crochet fabrics, etc.

Unravelling. The single pillar stitches can be unroved only in the reverse knitting direction, from the end knitted last and by attaching the tensile forces. If the needle loop of pillar stitches is cut, the cut end of one of the two side limbs connected with tuck loops may fall out of the loop frame of the previous loop course; the other end of the thread (right) will be drawn through the loop frame. If the end of this thread pulled, the pillar stitch will not unrove even in the opposite direction of knitting. When the pillar stitches are stretched to break, not all, but part of its threads usually break in the loop at the same time, and depending on the point of the break, the pillar stitches may unrove.

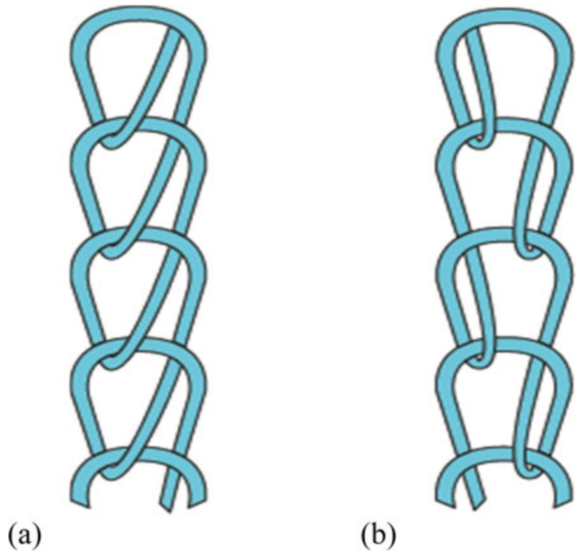


Fig. 11.29 Single pillar stitches: **a** closed lap pillar stitch, **b** open lap pillar stitch

Extensibility (elongation). Elongation of pillar stitches can occur due to thread offsets at the contact points, compressing and stretching of the yarns. Pillar stitches extensibility increases regardless of yarn length in its loop as yarn extensibility increases. When using inextensible and non-collapsible yarns, the single pillar stitches do not stretch.

Curling. Single pillar stitches in an equilibrium state are curled into a spiral on the front side under the action of elastic forces of yarns formed into loops.

The durability (breaking load). As the length of the yarn in the lap (loop) increases, the degree of thread segments orientation of the pillar stitches, involved in the break increases; therefore, the breaking load of the pillar stitches also increases.

11.8.2 Single Warp Knitted Fabrics. Tricot Lap and Its Properties

A single tricot lap is a single warp knitted fabric, which has the simplest lapping movements, and simplest of producing overlaps in alternate wales at alternate courses with only one thread crossing between adjacent wales (see Fig. 11.30). All single tricot laps have only one-sided tuck loops. It may consist of closed laps, opened laps, or closed and opened laps alternating in courses. Due to the inclination of the loops, the loop wales have a zigzag structure.

Thickness. The Trico is a single warp knitted fabric, and in the stretched state its thickness is equal to the thickness of the plain, i.e. 2F. In the Free State, due to the rotation of the loop frame into a plane perpendicular to the plane of the fabric, the thickness of the tricot lap increases and becomes approximately 3F. Thus, the warp-knitted tricot lap is 1.5 times thickness than a plain.

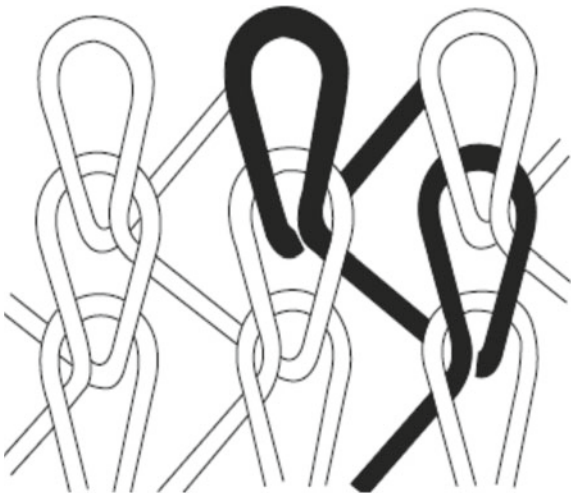


Fig. 11.30 Single tricot lap. Reprinted from Ref. [12] Chap. 10, Weft knitting, weft-knitted fabric and knitwear design, Page No. 94, copyright 2001, with permission from Elsevier

The unraveling of the loop wales when the thread breaks in the middle of the tricot lap are very important. In case of a break of thread in a loop, the loop wales are disconnected. Thus can be concluded:

1. The warp tricot lap is unraveled in the reverse knitting direction, provided that the loops of the last course are released from the ends of the warp yarns if the warp yarns have been cut together with the last course of loops.
2. The warp tricot can be freely disconnected along the loop wale line when the yarn is broken in the loop and when the knitted is stretched in wide; that is the biggest lack of tricot lap.

Curling. Due to the fact that the tricot laps are located by on a plane their loop frame, perpendicular to the plane of the fabric, the curling of the tricot lap from the edges is almost not observed at all.

The durability (breaking loads). The length strength of the tricot knitted fabric is approximately 1.5 times greater than the width strength. It follows that it is only necessary to cut out the tricot in the longitudinal direction. Tricot has great extensibility, used mainly as soil to produce fabrics of more complex knitting.

11.8.3 Single Warp Knitted Fabrics. Atlas Lap and Its Properties

Single atlas lap. This is a warp knitted structure in which each warp yarn sequentially forms laps in many loop wales with one-direction or two opposite direction tuck loops. At the same time, the warp thread is laid all the time by a certain number of needle pitch to the right and then moved by the same number of needles to the left (see Fig. 11.31).

Tuck loops on one-direction have only rotary loops, and on two directions—all others. It distinguishes between simple and complex atlas-lap structure. Simple atlas-lap are characterized by the simplest order of alternation of warped thread in both one and opposite directions. The thickness of the atlas lap is equal to two thicknesses of the threads constituting it.

Unravelling. Atlas-laps with the high knit unit and one direction tuck loops are unroved as plain. Atlas-lap with minimal rapport in height has the lowest unraveling. Such an atlas-lap is unknitted only in the direction opposite to knitting, provided that the limbs of its loops are released from the ends of the thread and tensile forces are put on the atlas-lap sample.

Curling. The atlas lap fabric is curled from the edges: in the direction of the loop wales—to the front side, by shortening along the length, in the direction of the loop courses—to the back, by shortening along the width.

Extensibility (Elongation). The tensile extensibility of an atlas-lap comprising loops with two-direction tuck loops is defined as the extensibility of a plain, stretched at an angle to the loop wales. As the inclination angle of the atlas-lap loop wales to

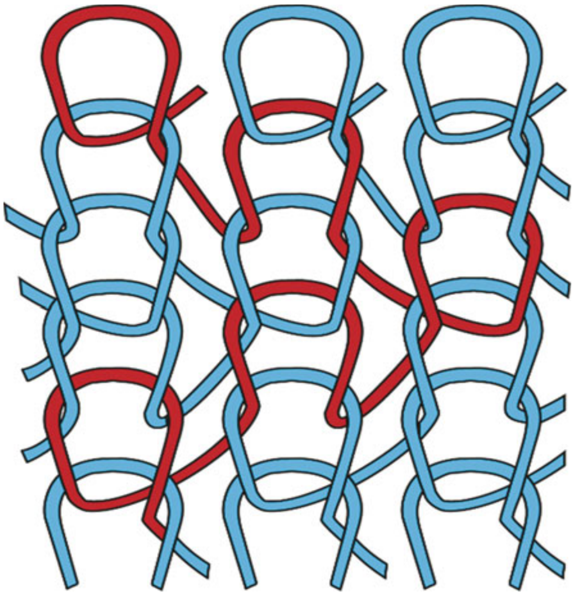


Fig. 11.31 Single atlas lap

the horizontal increases, the extensibility of the knitted fabric increases in width and decreases in length.

Durability. The atlas-lapped fabric has insufficient strength and low form stability. Atlas-laps is used in combination with fabrics of other knit structures for the production of outerwear and underwear knitted fabric.

11.8.4 Double Warp Knitted Fabrics. Double Pillar Stitches and Its Properties

It is the simplest double warp knitting structure, loops of which are formed by one yarn and consist of two-loop wales: front side and the reverse side (see Fig. 11.32). A double pillar stitch is obtained by laying the yarn onto the same needle of each needle bar. When knitting double pillar stitches, the yarn can be laid not only on the opposed needles of needle bar but also adjacent to them. In any case, separate, unrelated loop wales are formed. The length of the yarn in the tuck loop which connects the backside loop depends on the distance between the front and reverse side loops and the shift of the needles forming the pillar stitches.

The double pillar stitches ere not curled, it is unroved only in the direction opposite to knitting. When the yarn is broken in one loop wales and the pillar stitches are stretched, the wales may unrove, making the double pillar stitches to single. The double pillar stitches, like the single pillar stitches, is a knit structure with little extensibility.

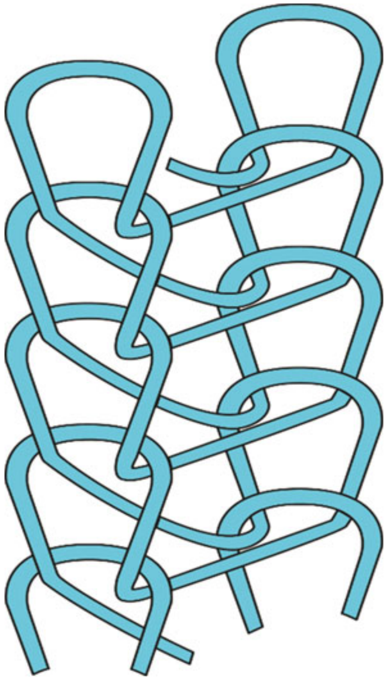


Fig. 11.32 Double pillar stitch

The extensibility of the double pillar stitches also increases with the increase of the tensile elongation of the yarn and the gradient of the thickness of the yarn.

11.8.5 Double Warp Knitted Fabrics. Double Tricot Lap and Its Properties

It is a warp knitted fabric, each yarn in which sequentially forms loops first in one loop courses on the front side and on the back in the same loop wales, then in the next course in the adjacent loop wales on the front side and on the back, then in the initial loop wales. Both sides of the double tricot have the same structure, all loops - one-sided tuck loops. The laps of the knit are inclined to the side opposite to the tuck loops, and the loop wales are arranged zigzag.

The double tricot lap in its structure is similar to the single one but consists of paired loop wales arranged behind each other and connected by tuck loops (Fig. 11.33).

Unravelling. The double tricot lap, like the single tricot, can be unroved only in the direction opposite to knitting. The unraveling degree of the double tricot lap, under the same conditions, is less than a single one, since for its unrove it is necessary to sequentially unravel loops of one and the other side of the knitted fabric.

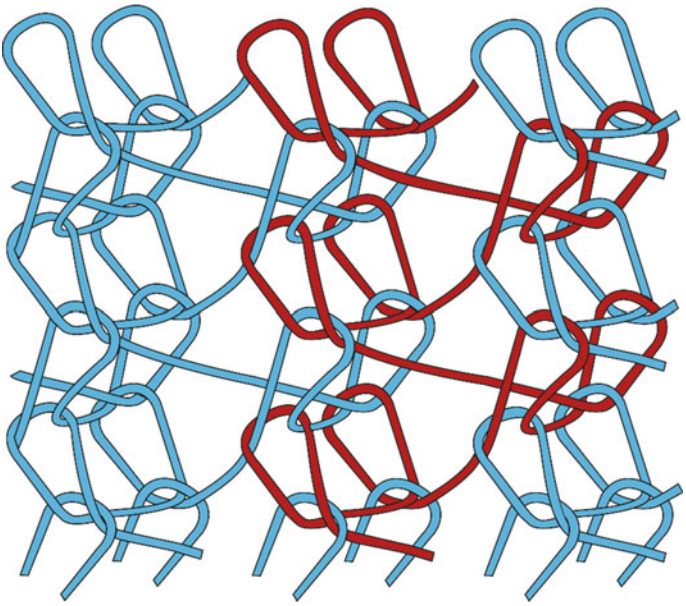


Fig. 11.33 Double tricot lap

In a double Trico, laps can only undo on one side of it; in this case loops of opposite loopy wales strongly increase due to the unknitted loop wale.

When several loop wales are unraveled on one side successively, the double tricot becomes into a single one.

Curling. The tricot warp knitting fabric is not curled in the free state, because the desire of the loop frames of one side of the knitted fabric turn under the action of the elastic forces of the thread to one side, is balanced by the same forces developed by the loop frames on the opposite side of the knitted fabric.

Durability. When the lap of the double tricot is drawn until it breaks in width, as in single tricot lap, only one thread resists to breaking, and when stretched along the length - five threads resist breaking: four limbs and tuck loops connecting adjacent loop wales. Subsequently, the length and width tensile strength of the double tricot lap is unequal than that of the single tricot lap.

11.8.6 Double Warp Knitted Fabrics. Double Atlas Lap and Its Properties

It is a basic warp knitted structure in which loops are sequentially formed in many loop wales successively in one direction or first in one direction and then in the other (see Fig. 11.34).

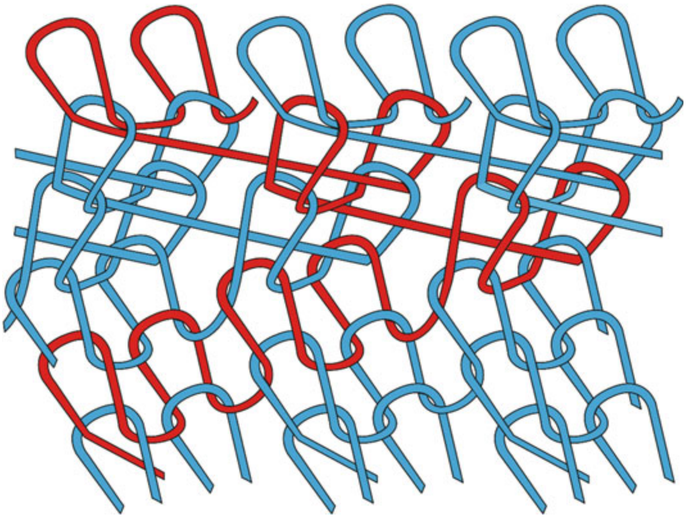


Fig. 11.34 Double atlas lap

In high-rapport multi-wales atlases, large sections of knit fabric are formed with loops having two-sided stretches disconnected between each other by rotary loop wales.

Unraveling. The Atlas knit fabric with high repeat unit on areas with double-sided tuck loops are unraveled, as well as a rib structure, in the direction opposite to knitting. The degree of the unraveling of the double atlas under the same conditions decreases with decreasing its knitting rapport in height. The double atlas does not curl from the edges.

11.9 Features of the Structure and Properties Group of Derivative (Variation of the Basic Group) Weft Knitted Fabrics

11.9.1 Single Derivative Weft Knitted Fabrics. Float and Its Properties

A float stitch is composed of the held loop, one or more float loops and knitted loops. It is produced when needle holding its old loop fails to receive the new yarn that passes, as a float loop, to the back of the needle and to reverse side of the resultant stitch, joining together the two nearest needle loops knitted from it (see Fig. 11.35).

Unraveling. The float stitch, unlike usual plain, unraveled only in the direction of the opposite knitting. In case of yarn break in the float stitch, the wale loops may be

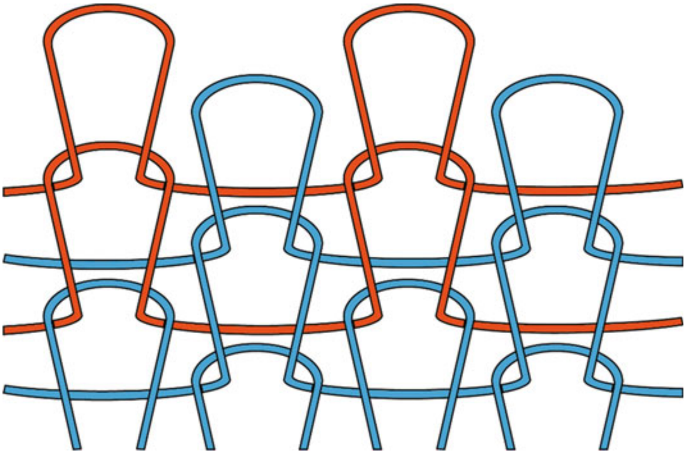


Fig. 11.35 The float stitch

unroved as it is stretched. The float stitch is unroved under the same conditions more difficultly than the plain.

Curling. The float stitches or welt stitch cut from the fabric is curled from the edges. The direction of curling along the loop course and loop wales is the same as that of the plain.

Extensibility (Elongation). The extensibility of the float stitch in length due to the denser compressing of the loop wales is shorter than the plain. Extensibility in width is also a lesser, consequence of the fact that the number of drawn loops, in it is less than two-three times, although the height of the loop course is greater than that of the plain.

Durability. The durability along the length of the float stitch, as well as the durability along the width, is greater than the durability of the plain. At the same time, its strength in width is greater almost two times, as each loop has still a tuck loop behind itself, which also participates in resistance to break.

11.9.2 Double Derivative Weft Knitted Fabrics. Double Rib (Interlock) and Its Properties

Double rib or interlock, is a derivative double weft knitting fabric, is an inseparable combination of two ribs, designed such that the loop wales of the other rib are placed in the gap between the loop wales of one rib (Fig. 11.36).

The loops of interlock are located in two-loop layers, with only the face loop wales visible on each side; following, interlock knitted structure is two-faced.

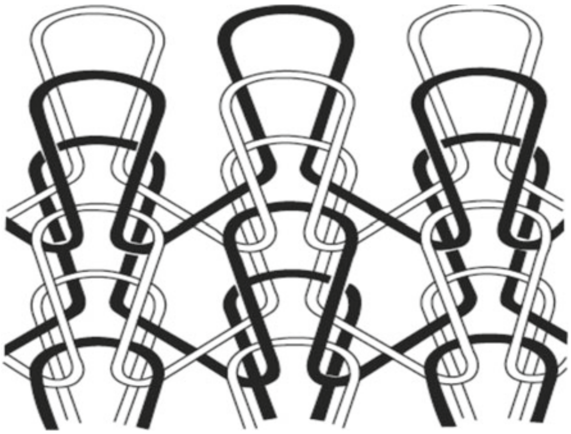


Fig. 11.36 Double rib (interlock) structure

In the equilibrium state on each side of the knitwear, adjacent loop wales, just as in the rib, contact each other. In addition, they, as in the float stitch, are offset from one another by approximately half the height of the loop course.

The interlock knit structure, like a rib, is unroved only in the opposite direction of knitting. When the yarn breaks in the loop, the unraveling of the loop wales when the interlock is stretched is less intense than that of the rib or float stitch. Interlock structure produced from cotton, wool yarn or high-volume yarns and yarns of various kinds, loop wales do not unravel even in case of significant deformation on knitted fabric. This is due to the fact that when the interlock is stretched, additional points of contact arise in it not only between the tuck loops but also between the yarns of the face and back loop wales; Furthermore, the loads on the unraveled loop wales as it is unroved are perceived by those formed from another, unbroken system of yarns.

Curling. The interlock knit structure for the same reasons as the usual rib, from the edges, does not curl.

Extensibility (Elongation). The 1×1 double rib, which represents a combination of ribs, should have less relative width extensibility than the rib produced with such a loop module. But it must be kept in mind that usually interlock structure has a loop modulus almost 1.5 times higher than the rib, so they interlock stretches almost as much as the rib. When the interlock is stretched into, its width is reduced by the length, and its thickness is reduced. The most practical value is the extensibility of the knitwear in width. As loop length increases, knitwear extensibility increases.

Durability. The interlock, like the rib, is unequal in tensile length and width. The breaking load of the interlock across the width is twice that of the rib since the breaking is resisted in each loop course not by one, as in the rib, but by two yarns. The breaking load of double rib 1×1 at length draw is approximately (depending on the density ratio) twice that at width draw.

11.10 Features of the Structure and Properties Group of Derivative (Variation of the Basic Group) Warp Knitted Fabrics

11.10.1 Single Derivative Knit Structures of Tricot (Cord and Satin) and Atlas Lap. Their Properties

Single tricot lap derivatives are combinations of two, three, or more tricot interconnected so that one, two, or more of the other tricot's laps are placed in the gaps between adjacent laps of others.

Trico derivatives produced by a combination of two tricots are referred to as 2 × 1 tricot lap or cord lap (Fig. 11.37a), and a combination of three tricots are t-tricot, or satin lap (Fig. 11.37b).

Knitted fabric **cord lap** is formed by one system of threads, at that loops of each thread are arranged alternately in two-loop wales through one. Loops in the cord lap have only one-sided tuck loops, so loop wales (visible on the front side) have a zigzag structure; on the backside of the knitwear, the frame loops are crossed by tack loops.

The satin differs from the cord lap in length of tuck loops and is also knitted from one thread system, with loops from each thread being formed alternately in adjacent loop wales through two loop wales.

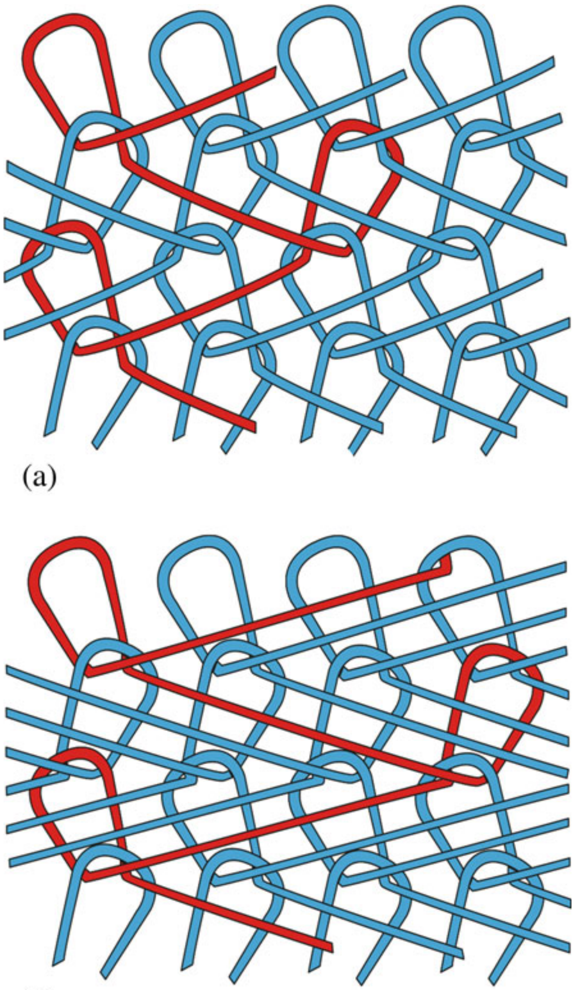
Single derivatives of the atlas have a structure similar to that of tricot: one or more wales of the other or other similar atlases are inserted between loop wales of one atlas. In the cord-type derivative atlas (Fig. 11.38), the threads form loops through one loop wales first in one direction over several courses and then in the same order in the other direction.

Derivatives atlases heavier than Tricot's, due to the increase in the length of their tuck loops, have less extensibility in width.

The single Tricot and atlas derivatives are difficult to unrove and only in the reverse knitting direction; the degree of their unraveling for this kind of thread decreases with the increase of several basic knit structures forming the derivatives. Thus, to unrove the cord laps, it is necessary to distribute at least three-loop wales, satin laps - four-loop wales, etc. Single atlas derivatives are even more difficult to unrove than tricot's derivatives because their rapport across the width as the number of basic knit structures forming the derivative increases significantly.

Derivatives of single tricots and atlases can be attributed to hard-to-unrove warp knitting fabrics.

Curling. The knitwear of derivatives of single tricots and atlases is curled from the edges, as well as all single knitted fabrics: in the direction of loop wales—to the front side, in the direction of loop course—to the back.



(a)

(b)

Fig. 11.37 Single derivative knit structures of tricot lap: **a** 2 × 1 tricot lap. Cord lap; **b** 3 × 1 tricot lap. Satin lap

11.11 Conclusion

This chapter provides fundamentals of the warp knitting and weft knitting process, related to the structure of the fabrics. The basic and derivative group of weft and warp knitting structures and their properties are overviewed. It does not cover in detail the stitch building and properties of pattern and combined knit structures, as these are not the object of current chapter. Information about these topics can be found in the book of Professors L.A. Kudrjavin, I.I. Shalov. [7], A.V. Charkovsky [11], OI. Marisova [13] in Russian, in English in the book of Yordan Kyosev [14] and etc., in Uzbek in the book of Professors M.M. Mukimov [10], N.R. Khankhadzhaeva [15]

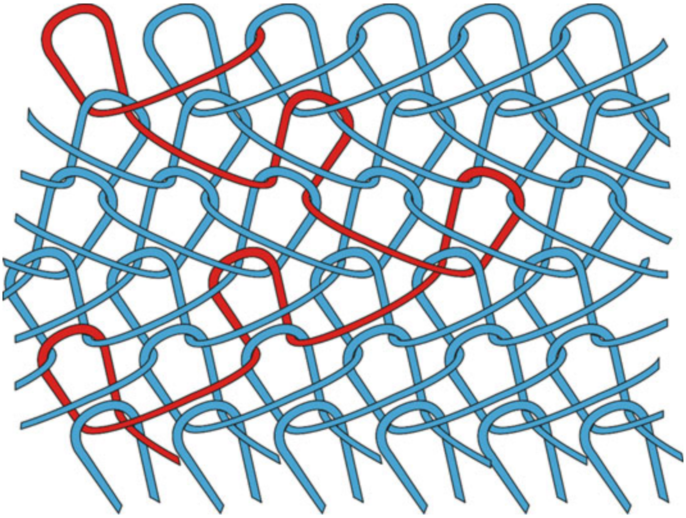


Fig. 11.38 Single derivative knit structure of the atlas lap

and about progressions in knitting technology the book [16] edited by K.F. Au is recommended.

Also, in this chapter the role of cotton fiber in knitting industry and its advantages are discussed. Cotton knitted fabrics are widely usable. They can be produced in a variety of structures, qualities and dimensions: in panels, fully-fashioned or seamless. Cotton knitwear has a loose loop structure, to the touch is rather soft and pleasant, and sufficiently well absorbs moisture, as well as heat-resistant. At the same time, those skilled in the art recommend the choice of combination options, because the use of additional synthetic fibers allows the product to have better operational characteristics. More knowledge in this field can be found in the research works such as [17–20] and etc.

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Chapter 12
Cotton in Nonwoven Products

Muhammad Awais Imran, Muhammad Qamar Khan, Abdul Salam, and Arsalan Ahmad

Abstract Nonwoven is one of the growing sectors of textile materials, and due to recent COVID-19, it has become the fastest-growing sector in the global textile industry. Consumers are shifting towards disposable products by which they can use the single-time product to remain hygienic, healthy, and safe from bacteria and viruses. However, disposable products increase landfill site, and this may harm our environment, so in such situations, cotton comes in the mind that is natural, sustainable, and biodegradable. In this chapter, our focus was to present the potential uses of cotton in different nonwoven products that are being used in our daily life, including commodity and technical products. Personal care products are one of the most growing areas of nonwoven applications where cotton is dominated as compared to other textile fibers, and next to this application area is medical nonwovens, which also supports cotton fiber because of biocompatible, breathable and comfortable properties which suit to the human body. This area has recently attracted exponentially by consumers due to novel pandemic coronavirus.

Keywords Cotton nonwoven · Wipes · Diapers · Disposable · Hypoallergenic

12.1 Introduction

Cotton is a key contributor in the woven and knitted based apparel and home textile industry. It also has the potential to be used in the nonwoven industry as its natural structure and attributes attract the nonwoven industry. Cotton fiber is a cellulosic, plant-based natural and leading fiber among all available natural fibers. Cotton has many unique properties like softness, excellent absorbency, breathability, static-freedom, ease of blending, natural feel, and reasonable strength [1]. The critical characteristic of cotton is comfort when it comes to human body interaction. Despite these

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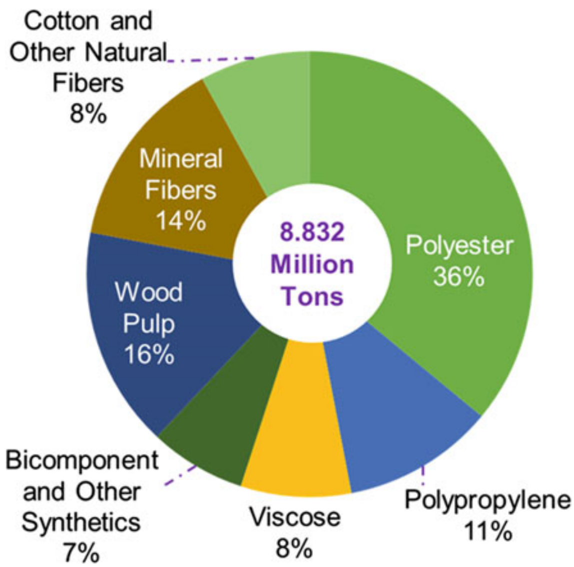

Fig. 12.1 Global consumption of staple fiber in nonwoven products in 2018 [3]

facts, as per European Disposables and Nonwovens Association 2019, see Fig. 12.1 cotton in nonwovens has comparatively less contribution than other synthetic fibers, e.g., polyester, polypropylene, polyethylene, nylon, and rayon, due to some issues like cost, trash content (intensive cleaning process required), color variations, fiber length variations, dusting and linting and nep formations [2]. However, owing to biodegradable, it has attracted much attention due to the pertaining global issues of sustainability, better processes, and circularity, the usage of cotton is increasing globally in nonwoven products. The application of cotton in the nonwoven product is mainly in the segments of personal care, wipes, and medical or healthcare.

In a nutshell, there are three reasons for greige cotton is expected to grow in nonwoven products;

1. Pre-cleaned cotton is nowadays commercially available for the clean-free process for nonwoven manufacturing as pre-cleaned cotton does not need further cleaning process.
2. The pressure from the buyers to stick with natural fibers and strict environmental concerns of global warming is bringing closer to cotton to the nonwoven manufacturers.
3. Hydro entanglement system is suitable for pre-cleaned greige cotton that potentially eliminates the wet pretreatment of cotton fibers, and this allows increasing the yield in terms of economy and giving environmental advantages.

The disposable market is the segment of nonwoven where cotton has limitations due to its cost and uncertain seasonal availability. However, spun lace manufactures prefer cotton due to low wet modulus property by which it interacts with

Table 12.1 Cotton properties for nonwoven products [5]

Property	Values
Micronaire	>4.9
Length (inches)	>0.95
Uniformity (%)	>81%
Strength (g/tex)	>23
Non-lint content (%)	Max. 0.8
Fiber-to-fiber cohesion (g force)	Max 1700
Fiber openness (cc/gram)	Min 100

Table 12.2 Cotton properties and their effect on the product [5]

Property	Effect
Micronaire	Fabric appearance
Length	Weight of nonwovens
Uniformity	Fabric appearance
Strength	Weight of nonwovens and durability

water jet easily, and its cohesive forces in wet conditions support better fiber entanglement during the nonwoven manufacturing processes [4]. In Table 12.1, Cotton Incorporated has suggested the following cotton properties required for nonwovens.

In Table 12.2**,** there are some cotton critical properties which affect nonwoven products, e.g.

There are two types of cotton fibers available; bleach and unbleached. Unbleached cotton is cheap, and during the spun-lace process, it is made absorbent and whitened quickly, and can be dyed or finished in later stages.

The selection of fiber to make nonwovens depends on followings requirements;

1. Cost-effectiveness
2. Ease in processability
3. End-use characteristics of the web.

12.2 Cotton in Nonwoven Personal Care Products

The personal care product segment is one of the strongest and growing application areas of cotton nonwovens products. Some of the significant applications are presented in Fig. 12.2. The selection of fiber and design for personal care products depends on the intended end-use of the nonwoven products. Below are characteristics that are considered before making a particular personal care product [6]. There are seven main requirements of personal care products in terms of property.

1. A first and foremost essential requirement of personal care nonwoven is water, and saline absorption like it helps in diapers.

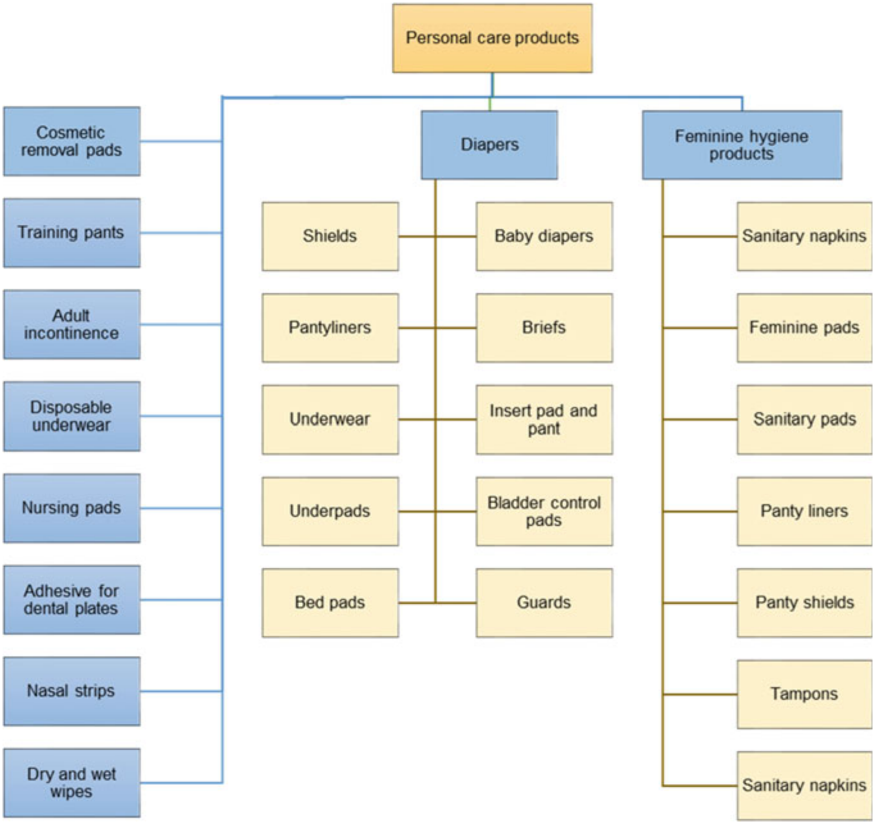

Fig. 12.2 Some examples of cotton in nonwoven personal care products

2. The product must not pass particulate, fluids, bacteria, and viruses, which cause discomfort to the human body and may cause different types of illnesses.
3. Reasonable strength, as it varies product to product and end-user requirements, and this property also supports the barrier performance of the personal care products.
4. Medical products are customarily subjected to the sterilization process, and this process runs at around 121–132 °C, or sometimes modern flash sterilization is used up to 138 °C. Therefore, the product should withstand such conditions.
5. Comfort is mandatory for such products because it is about skin contact. Comfort is linked with the absorption property and structural design of the product. Cotton and cellulosic fibers possess excellent absorption property. The product should be designed in a manner that it should be porous to have good breathability, but at the same, it must not pass any fluid or bacteria from it. Sometimes, surgical items are needed to sterilize; in that case, the porosity will help to sterilant to penetrate in the wrapped object. It should be noted that the breathability of the products affects a change in temperature.

6. Disposable means the product is discarded after single-time use. As per a recent study, disposable items have fewer environmental issues than reusable items. Most of the medical products (isolation gown, Howie coats, surgical masks, and surgical gloves) are made to use single-time due to the risk of bacterial or viral infection transfer to humans; however, other products can be reusable for some time. The main advantages of disposable items are cost-effectiveness, and better performance as a fresh item is available on each use.
7. Lint-free, it means that disposable products should be free from any fiber linters (loose fibers) as these linters harm the human body and may cause an issue in lint breaking of wipes.

12.2.1 Pain Relief

These are also a kind of pads impregnated with alcohol and benzocaine, which are used for minor scrapes, burns, and insect bites. Some pads contain natural herbal ingredients (Menthol), which can reduce the sensitivity of pain and improve healing from the source of the pain. These types of chemical agents have a curative effect on the human body. The Cold and heating pads are also available in the markets that contain-particular bioactive substances, which improve blood circulation and metabolism functions.

12.2.2 Nursing Pads

These pads are breast pads, and they serve gently to those women who feed their babies and protect them from stains and any nervousness when they feel milk coming out their breast during a day. These pads are kept on the breast; they absorb and retain milk that comes out from the breast and provides a sense of comfortableness to women. They stop milk drops onto fabric hence avoid milk stains. Women don't feel embarrassment upon leaking of milk. Two types of nursing pads are being used; therapeutic pads which keep warm or cold the breast during feeding and provide physiological comfort. Another one is, a brassier pad that absorbs breast milk leakage after feeding the baby and milk stain does not penetrate on apparel or wearing suits. These pads are available in both disposable and reusable forms [7, 8].

12.2.3 Adhesive Dental Sponge

Denture adhesive is made of cotton nonwoven sponge that makes sure grasping the denture in place. Cotton is the best selection as an absorbent which gives comfortableness, lint-free surface, natural texture, and soft feel to the patient. It is placed between the denture and the tissues. Denture sticks to the tissues and saliva in the mouth work as a cohesive bridge between the tissue and denture, and it provides retention, and as a result, physiological forces created in the tissues play an active role in adherence between them. The coherence of denture is higher than the coherence of saliva due to the textural structure of the cotton [9].

12.2.4 Nasal Strip

Nasal strips are a great help to all those who have difficulty breathing, so these are used to increase breathing quality and to prevent snore and improve sleep quality. When a wearer wears it on the nose, it will pull up the rounded sides of the nosy by adhesive powder, enhancing the airflow inside the nasal cavity for you to breathable smoothly.

12.2.5 Diapers

A diaper or nappy or training pants is an absorbent garment worn by individuals who are.

1. Incontinent (i.e., who lacks control over bladder or bowel movements)
2. Unable to reach the toilet when needed.

The disposable diapers are made up of an absorbent pad sandwiched between two sheets of nonwoven fabrics. The pad between two nonwoven fabrics absorbs and retains body fluids, and the fabrics around it maintain the comfortable shape and help to stop leakage. These diapers are made by a multi-step process in which the absorbent pad is first vacuum-formed, then attached to a permeable top sheet and impermeable bottom sheet. The components are sealed together by the application of heat or ultrasonic vibrations. Elastic fibers are connected to the sheets to gather the edges of the diaper into the proper shape, so it fits snugly around a baby's legs and crotch. When properly fitted, the disposable diaper will retain body fluids which pass through the permeable top sheet and are absorbed into the pad. Now a day, thinner disposable diapers are being produced to have less waste for landfills, which is sustainable demand from the customers.

The need for flushable nonwoven diapers liners is increased recently. As discussed earlier, the flush ability is vital for such disposable products. The use of non-degradable plastic in diapers is being used in the market due to cost constraints and inconvenience; however, recently, due to suitable demands, the diapers manufacturers developing cotton-based diapers with highly absorbent cellulosic fibers.

The major structural components are:

1. Top sheet
2. Acquisition or distribution layer

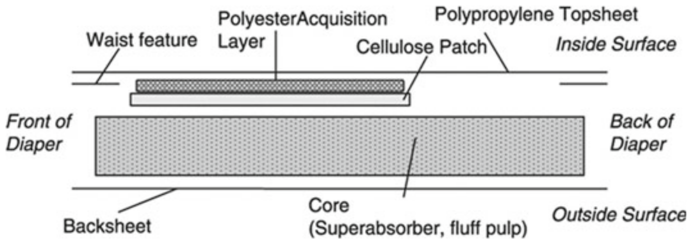

Fig. 12.3 Schematic illustration of the modern disposable diaper [10] © Wiley (Fig. 3 on page no. 430) published with permission

3. Absorbent core
4. Back sheet
5. Secondary component materials are:
6. Barrier leg cuffs
7. Elastomeric stuff
8. Hot-melt glues.

Firstly, the top sheet of the diaper should be soft and pliable to the baby's skin because it is in direct contact, whether the skin is wet or dry. At the same time, it should be hypoallergenic (e.g., made of cotton) so the baby's skin will not have any type of allergy or irritation. Secondly, the underneath absorptive layer gives high absorption rates, so this will give a "dry feel" effect on the baby's skin. High absorption rates will keep the body dry all the time (especially in the night when parents are sleeping). The arrangement of the layers in the modern disposable diaper is presented in Fig. 12.3.

Under the Pampers umbrella, protector and gamble have released a new natural baby diaper that possesses both softness and high absorption properties onto the delicate baby's skin. It is made of 100% premium cotton. Recently, they have also joined the Cotton LEADSTM program, which depicts that they are serving society with natural and sustainable products.

In general, diapers can provide an absorbent structure to obtain, absorb, and retain urine and waste from body waste. These diapers are manufactured in such a way that they perform absorption and retention property while having gentle touch with skin means no irritation, no contamination of the clothing, and be capable of disposal after use [6]. The diaper product is one of the major categories of the nonwoven industry. Even though they are second to feminine care sanitary napkins in leading market penetration into emerging markets, their volume overwhelms nonwoven demand. Adult incontinence follows much behind in the penetration rate curve, but because of the product size, they are beginning to equate feminine care in value as well as the volume of nonwovens consume.

Adult diapers provide a sense of security and psychological comfort. Those who work for a longer time without short breaks such as astronauts, nonstop drivers, and tourists and those patients who cannot control their continence are used this adult incontinence. These are like undergarments and can be used on several issues like Spa, massage, long drive, and in an emergency.

Adult diapers include the following products;

12.2.6 Cotton in Nonwoven Feminine Hygiene Products

As the name suggests, feminine (female) hygiene are those products that are used during menstruation and vaginal discharge. The key benefits of feminine hygiene products are illustrated in Fig. 12.4.

Feminine hygiene includes the following products;

These are used to absorb and retain menstrual fluid and separate the fluids from the body. Napkins should have comfortable, breathable, and durable properties.

The tampons absorb the flow of blood or fluids from the vagina during menstruation by inserting in it. They also absorb and retain fluids. Tampons should have comfort, breathable, and durable properties, and for this purpose, they are mainly based on cotton and its blends with cellulosic regenerated fibers. The nonwoven layer is used to cover the absorbent, which serves as protectors of fibers flushing and easy handling of the tampons. The cotton cord is used to remove the tampon.

Fig. 12.4 Benefits for feminine hygiene products

12.3 Cotton in Nonwoven Medicals and Surgery

Nonwoven fabrics have received much attention in the field of medicine, and health-care sectors like products include surgical gowns, bedding, dressings, surgical drapes, implantable like sutures, orthopedic, and tissue structures. Due to their versatile engineered structure, cost, effectiveness, and disposability, the demands of nonwovens are increasing, and people are adopting it quickly. The reasons cotton fiber makes excellent medical nonwovens are illustrated in Fig. 12.5.

Some characteristics of nonwovens due to which they are suitable in medical use are listed here.

- Superior barrier-providing capacity
- Good cross-contamination control
- Superior barrier-providing capacity
- Porosity
- Fabric weight
- Thickness
- Sterilization ability
- Limitless manufacturing customization
- Cost-effectiveness.

In terms of cost, effectiveness, disposability, and convenience, the use of nonwoven products in comparison to woven products is increasing in the health-care sector because it gives better performance. Cross-contamination is a common issue in the healthcare sector when it comes to reusing woven non-disposable gowns, masks, and other similar products as it is one of the causes of bacteria and viruses

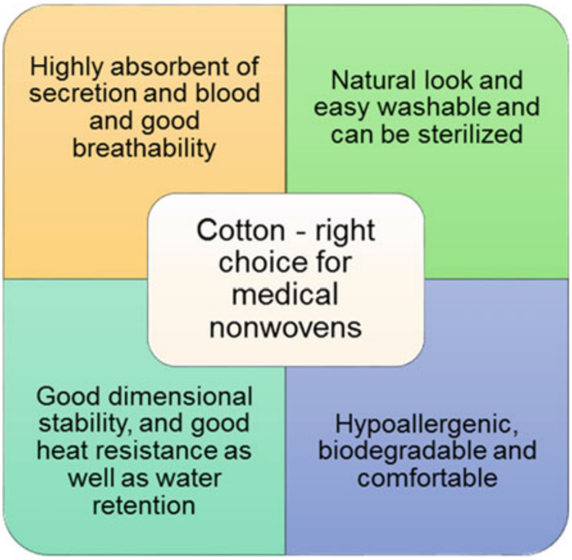

Fig. 12.5 Cotton—the right choice for medical nonwovens

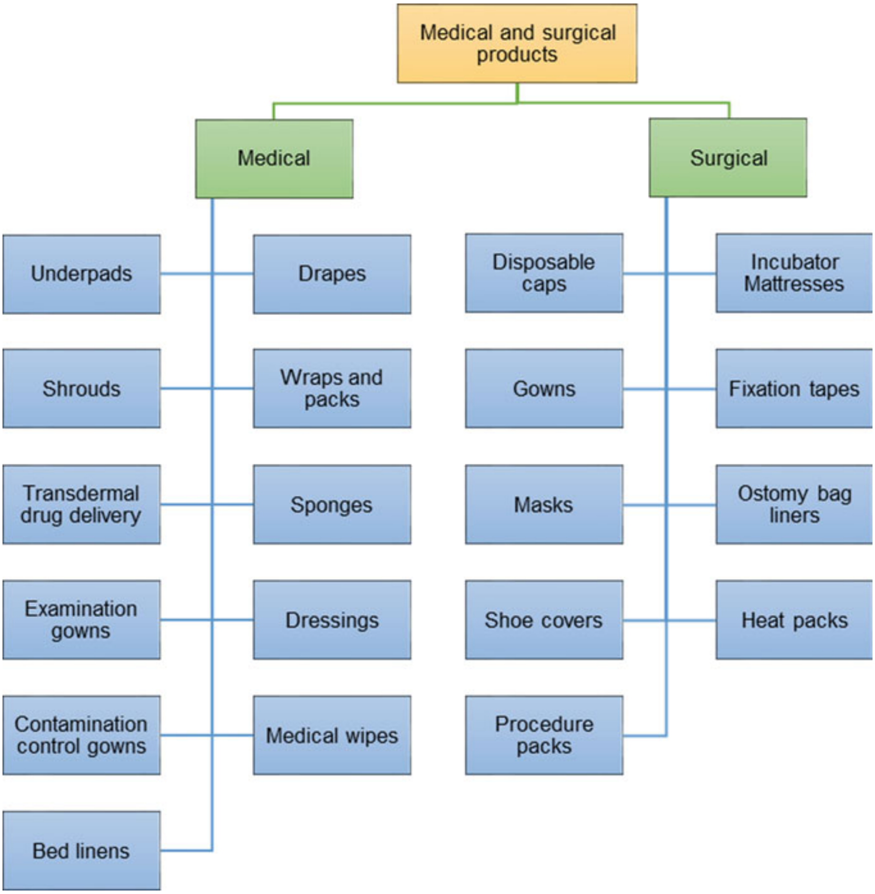

Fig. 12.6 Some examples of cotton in nonwoven medical and surgical products

transmission to human. In the recent past, when nonwoven markets have grown, the use of disposable nonwoven products in such areas has facilitated this sector and reduced the cross-contamination issues. Some typical nonwoven medical and surgical products of cotton nonwovens are presented in Fig. 12.6.

12.3.1 Transdermal Drug Delivery

It is patch type medicated adhesive, which promotes healing of an injured area, and it is kept on the skin to deliver a specified dose of medication through skin into the bloodstreams. It is a secure and reliable mechanism for drug deliveries.

12.3.2 Underpads

These pads are used as adult incontinence, which provides high absorbency and ideal for such conditions. These are available in extra-large sizes.

12.3.3 Surgical Disposable Caps, Gowns, Masks, and Shoe Covers

Surgical caps are made from nonwoven materials based on cellulose that protects doctors or surgeons from viruses or bacteria from the patients or hospital equipment. Surgical gowns are used to cover patients or doctors to protect the surrounding areas of patients or hospitals. The gowns should show inhibition or resistance or sometimes killing actions against bacteria or viruses and also absorbent to body perspiration and secretion from the wound. Shoe covers are used to protect nurses or patients or doctors from all bacteria or viruses from the floor, as recent studies have shown that many viruses survive in shoes and cause of virus transmission to the body.

12.3.4 Surgical Drapes, Wraps and Packs

Surgical drapes provide a complete physical barrier against germs contamination to all staff involved in the patient's operation or treatment. Drapes are kept in the operation theatre or treatment rooms around the incision site to cover the patent. Wraps are used to collect fluids of patients.

12.3.5 Surgical Dressing

Surgical dressings are used to cover, protect, adsorb, and support for the injured or diseased part. Nonwoven dressing performs better due to their effective barrier against bacteria and viruses, and they reduce airborne contaminants. They are used in following different types;

Wound dressing: It is placed on wounds to compress to promote healing and protect the wound from further bacteria and viruses.

Absorbents: it is used in surgery; usually napped surface is applied on cotton nonwoven fabric. Previously, loose woven were used, but nowadays, disposable absorbents are popular.

Bandages: Nonwoven cohesive bandage is used to restrict the movement of body parts to have reduced swelling. It should have the following properties;

- Cost-effective
- Self-adherence
- Good elastic strength
- Coated with suitable adhesives
- No-slip off.

Compressions, orthopedic, and supporting are types of bandages.

Protective: It is used to protect the eyes in the outpatient department and industrial department.

Adhesive tape: it is coated with adhesive materials and used with pads to stabilize them on the injury.

12.4 Cotton in Nonwoven Apparel

Nonwoven fabrics are versatile in the design range than woven fabrics as these nonwoven fabrics are easily cuttable and sewable. Although nonwoven as clothing is still non-durable because of strength and workability issues [11]. However, properties such as flexibility, wearability, comfort, and aesthetic make it a suitable material for the garment. Till now, the cotton nonwovens are not in a significant portion of apparel applications. However, the extensively use of nonwoven in apparel is as supporting fabric in interlining in garments, insulators in clothing and gloves, padding in bra and shoulders, shoe, and handbag components.

Interestingly, nonwoven fabrics have many advantages over woven fabrics, especially design factors and cost-saving. The short-wear apparel with cotton fiber possesses excellent wetting, flexibility, and extensibility. Some key advantages of using nonwovens in apparel manufacturing are presented in Fig. 12.7.

12.4.1 Cotton Interlining and Interfacing

Nonwoven interlinings are based on nonwoven materials that are used in the layers of apparel to have the desired shape, stress support, bulkiness, and aesthetic. This is done by sewn and bonded methods. Nonwoven interfacings are comprised of agglutinated and compressed fibers at one side, whereas the other side is comprised of fusible glue. There are some essential elements used in interlinings like fibers, binders, finishers, and hot melt adhesives.

Fig. 12.7 Advantages of nonwovens in apparel

12.4.2 Military Apparel

The military needs those apparels that are specialized fabrics and based on some functionality like fire retardant, water and oil repellent, and antimicrobial properties. Cotton nonwoven apparels give lightweight and easy to handling characteristics which suit in their daily movement and working. These types of functional nonwoven apparels based on functional agents are being used in military operations.

12.4.3 Contamination Control Gown/Examination Gowns

These gowns are used as medical uniforms to act as a barrier from bacteria and viruses to eliminate infection risks for doctors and patients. There are some main features of gowns listed below.

- Barrier function (against the bacteria and viruses)
- Prevent germ transmission
- Protection of users (patient and doctors)
- Skin compatibility
- Good drapeability
- Antistatic and low flammability
- Odorless.

Some popular apparel products made up of cotton nonwoven textiles are illustrated in Fig. 12.8.

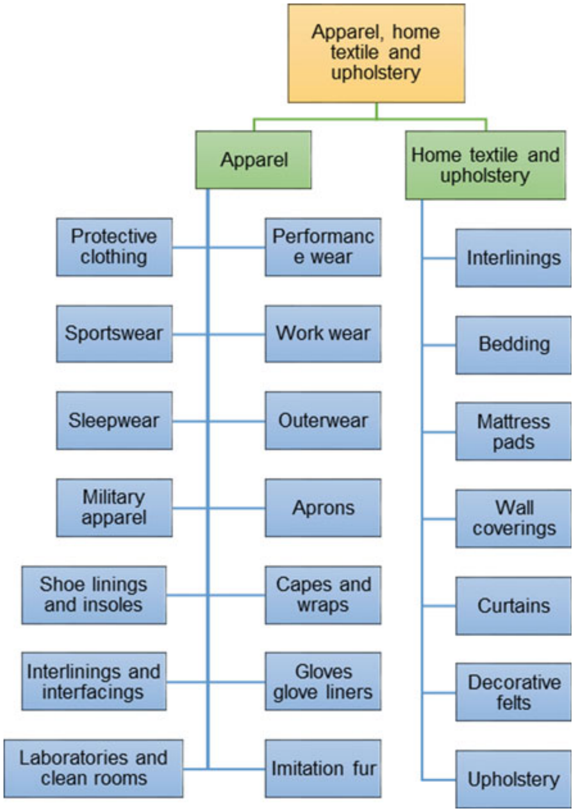

Fig. 12.8 Some examples of cotton in nonwoven apparel, home textiles, and upholstery

12.5 Cotton in Nonwoven Home Textile and Upholstery

Bedding provides a comfort level to the human body when the person at rest. The human body releases some amount of heat and perspiration during sleeping; therefore, thermal insulation capacity and moisture management properties are necessary. Cotton and other cellulosic fibers nonwoven serve these objectives in a better way as they are based on a complex nonwoven structure that provides better insulation property and moisture management. Some popular home-textiles and upholstery products made up of cotton nonwoven textiles are illustrated in Fig. 12.8. Besides, Table 12.3, depicts the main application of different types of household and upholstery nonwovens.

Table 12.3 Application of nonwovens in the home textile and upholstery [12]

Nonwovens Indoors application	Needle punched	Spunlaced/Hydro-entangle	Spunbonded	Chemically bonded	Thermally bonded	Wet-laid	Tufted
Backing for wallcoverings		✓	✓				
Bedding coverings		✓	✓				
Bedsheets		✓					
Blankets	✓						
Carpet underlay/backing	✓		✓		✓		
Curtain backing			✓				
Filters	✓		✓				
Floor covering	✓						✓
Furniture backing			✓		✓		
Tablecloths		✓	✓			✓	
Upholstery	✓	✓	✓		✓		
Wadding and padding	✓			✓	✓		

12.5.1 Bedding

As compared to conventional woven and knitted home textiles, nonwoven fabrics economically offer a wide range of functions. The complex engineered structure and performance of nonwoven fabrics give better dimensional stability, non-fraying, and better skin contact while sleeping. All functional properties (antimicrobial, self-cleaning, odor management, moisture management, abrasion resistance, and fragrance), which can be imparted on woven and knitted home textiles are also can be imparted on nonwoven fabrics. All variants of home textile products (sheets, pillows, mattresses, mattress pads, and covers, quilt covers, comforter, thermals, table covers and top of the beds) and their components including, mattress flanges, quilt backings, mattress insulation, spring covers, pillows, dust covers, and mattress pads are possible with nonwovens.

12.5.2 Mattresses

For mattresses production, nonwovens work as supporting and insulation materials, for example, as external or internal covering and replacement of conventional foams, and they are more efficient in such cases. The flame retardant based nonwovens are good alternate of polyurethane-based foam, as they reduced the danger of fire and health. Most of the suppliers are using nonwoven fabrics as filler in their quilt cover and comforters products.

12.5.3 Curtains

Shower curtains, net curtains, and roller blinds are made up of spunlaced nonwoven fabrics, and they are a better alternative to conventional curtains types. Nonwoven interlinings are being used inside the curtains. Usually, the interlining material is coated on one side or both sides with suitable hot-melt adhesives and thermally bonded to support the fabric.

12.5.4 Wallcovering

Nonwovens are better alternate of conventional wall coverings, although the uses of nonwoven fabrics are very limited in this sector. Several designs are available in the market, which good aesthetic looks. These nonwovens are also used in the backing of conventional fabrics for wall coverings. The use of wall nonwovens in wall covers is to fill space between the wall and the tensioned textiles while having the thermal and acoustic insulation, so it depends on end uses requirements that how much thickness is required between the wall and the textile substrate. Nonwoven fabric technologies that are common in this sector are wet-laid and, to some extent, needle-punched. It is observed that the handling of nonwoven is much easier than other wallpapers as it does not have any seam separation and easily removable. The wall covering made of nonwoven must have good dimensional stability, strength, and good acoustic properties.

12.5.5 Carpets

Floor coverings increase the aesthetic of an indoor environment while serving thermal insulation of the environment. Needle–punch technology is used to produce carpets for home and industrial sectors. Nonwovens carpets effectively reduce noise levels as compared to other conventional rugs. For carpet backing, nonwovens sheets are also used. Antimicrobial treatments on carpets can decrease and kill the dust mites and bacteria, which cause allergy and other diseases such as asthma. Wrinkle-free and water and oil repellent treatment have also attracted many consumers to have a neat and clean indoor environment; therefore, nowadays, in the majority, needle-punched carpets contain crease-free and self-leaning properties.

12.6 Cotton in Nonwoven Wipes

The nonwoven technology for nonwoven wipes is spun-lace, air-laid, wet-laid, needle-punch, and composite. The percentage of share is depicted below Fig. 12.9. Also, some typical products of nonwoven wipes are presented in Fig. 12.10.

As the name suggests, wipes mean to clean the surface with suitable material with minimal efforts that are convenient as it should be a quicker and easier method.

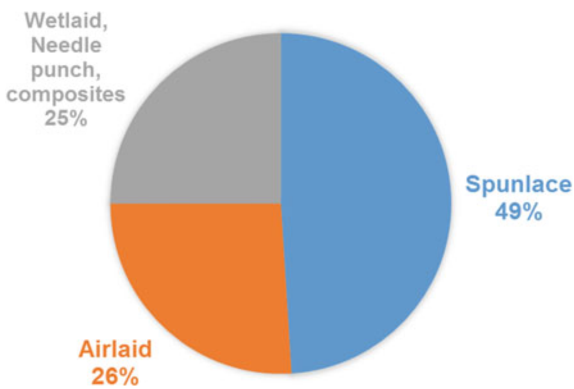

Fig. 12.9 Distribution of nonwoven wiping technologies [13]

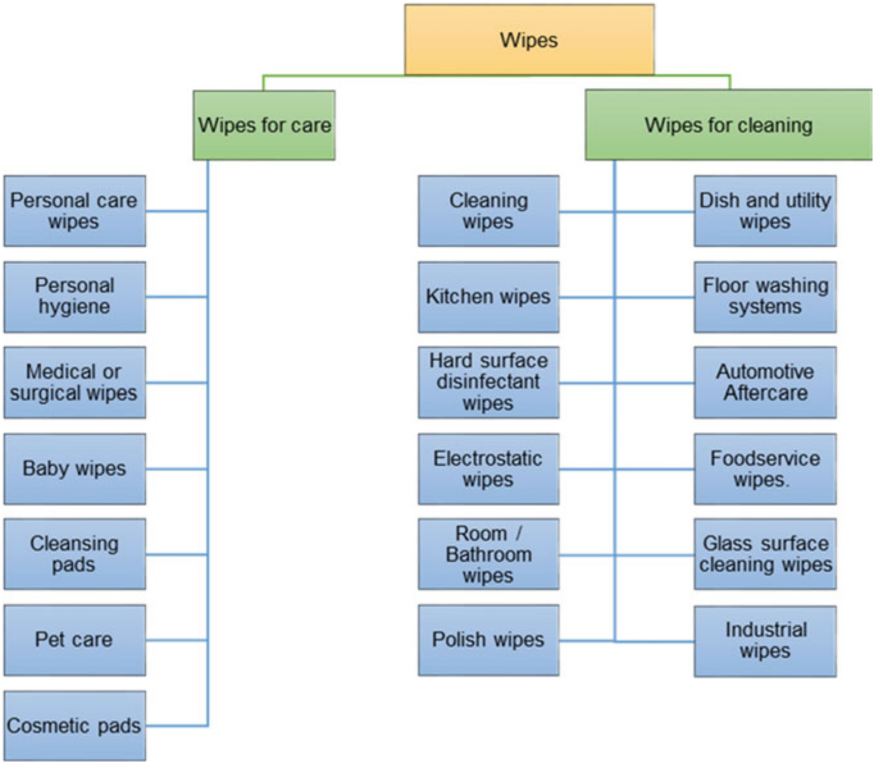

Fig. 12.10 Some well-known products of nonwoven wipes

Therefore, wipes are the products which are subjected to light rubbing or friction to remove dirt or liquid from the surface. In comparison to cloth or paper, the main advantage of the wipe is to provide convenient, quicker, and easy cleaning of surfaces. As far as concerned with wipes, the ideal fiber for it is cotton. The wipes include; baby wipes, feminine hygiene, and adult incontinence products. Cotton, in fact, a much suitable selection for wipes due to excellent absorbent properties. However, the cost factor and uncertain availability factors have led to think many industries to do a blending of cotton in their wipes with other synthetic fibers to give absorbent and cheap products.

Cotton and its blends nonwoven wipes give high cleaning room efficiency due to highly absorbency properties.

- Large spill pickup
- High-temperature surface cleaning
- Wide range working areas
- Critical tool and equipment wipe down
- Aerospace
- LCD and display cleaning

- Facial cleansing/makeup remover wipes [7].

The market share of wipes is depicted in the following graph. Demand for all types of wipes is forecast to expand 3.1% per year to $3.7 billion in 2023. In general, there two classes of wipes; wet and dry. Both have their advantages and disadvantages; it depends upon the end-user requirements. Mostly in personal care, wet wipes are used whereas in the household, automotive, and industry dry wipes are used. Wet wipes generally consist of water or alcohol or chemical agents like benzethonium chloride, quaternium-52, phenoxyethanol and methyl, ethyl, propyl parabens, and alcohol [10]. At the same time, dry wipes do not contain any water or chemical agents. Recently, flushable wipes have received much attention because they possess sufficient wet strength and good disintegration properties to dispose of them after use [14].

Wipes are made from nonwoven bonded fabrics. There are various usages of wipes like cleaning body, wounds, skin before dressing application, treat rashes, or burn [15]. There are several uses for cotton wipes; some important applications are presented here.

12.6.1 Personal Care Wipes

The disposable personal wet wipes products have been increased in the market recently. The reasons for its wide acceptance in both consumer and healthcare are due to convenience and ease of use.

12.6.2 Personal Hygiene

These wipes are pre-moistened packs. These types of pads contain antimicrobial agents, lotion, self-moisturizing agents, natural Vitamin E, and Aloevera ingredients, excluding Alcohol-free natural, and fresh. They can effectively clean, gentle protect tender skin, leaving skin smooth and tender to help keep skin healthy.

12.6.3 Medical or Surgical Wipes

These are made from cotton nonwoven bonded fabrics, which may be soaked with an antiseptic finish to use in the hospital and health care sectors. Demand for wipes used in healthcare settings is expected to increase by 3.8% per year to $594 million in 2023, according to a new report.

12.6.4 Baby Wipes

These are wet wipes that are used for the sensitive skin of babies. Cotton is hypoallergenic, which does not cause any irritation. Baby wipes are available in 100% cotton or blended with cellulosic fibers like bamboo or lyocell fibers. Typically these wipes are based on harsh-less chemicals like alcohol-based cleaners, nowadays solvent or alcohol-free wet wipes are available which contain aloe Vera or vitamins along with scented or non-scented agents and provide stable pH condition for all types of skins. Usually, their weights are in the range of 35 gsm to 60 gsm. These wipes are also embellished with different pattern styles like a diamond, pearl, and mesh.

12.6.5 Cleansing Pads

These are sponge type pads that are impregnated by water and other solvents. Mostly they are made of 100% cotton or blended with other natural bamboo or lyocell fibers, which effectively remove dirt and oil, leaving skin smooth, soft, and clear and especially clear exfoliation. These wipes are also embellished with different pattern styles like a waffle, pearl, and mesh.

12.6.6 Cosmetic Pads

This is the fastest-growing segment in personal care. According to Canadian Consumer Market Data Analytics 2015, this segment has proliferated, and the compound annual growth rate (CAGR) from 2000 through 2019 is estimated to be 5.2%. Facial care is, by far, the largest segment within skin care [15]. These wipes are used in makeup removal, skin cleansing, exfoliating, and nail polish removing and self-tan purposes. Moreover, anti-aging pads are growing across all facial care categories.

12.6.7 Pet Care

These wipes are used for animals' body cleanings. They do not contain any harsh chemicals which are sensitive to animals' body.

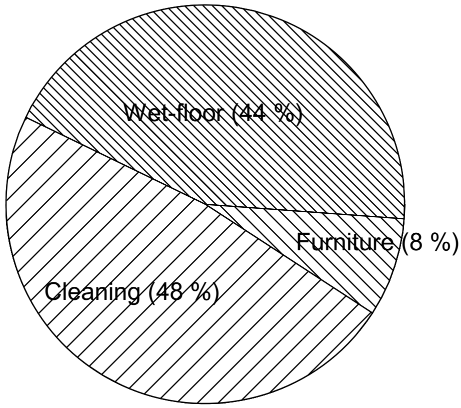

Fig. 12.11 Market shares of wipes in the household cleaning sector [16]

12.6.8 Household and Home Cleaning Wipes

Household wipes include a broad range of wipes [16]. Interestingly, there are multi-purpose applications in the household, like cleaning, filtering, embellishing, and disinfection activities in the areas of bedrooms, kitchen, and living rooms. The use of household nonwoven increases the hygienic, secure, and attractive of the living standards. The market share of wipes in the household cleaning sector is higher than other industries of nonwoven wipes, refer Fig. 12.11 [16].

In general, these wipes are impregnated with sodium hypochlorite (NaOCl), which is a potent bleaching agent and used as a cleaning and disinfection agent in houses, hospitals, industries, electronic industry, and medical devices industry. Sometimes, greasy and heavy dirt and dark stains in the glass industry are removed by using pre-saturated Isopropyl alcohol, which is practical and easily usable. It has been a universal solvent for cleaning floors and equipment. It is also used as a sanitizer in medical and hospitals. Hydrogen peroxide is a highly effective cleanroom disinfectant and sanitizer that has been used for decades within cleanrooms and controlled environments.

12.6.9 Industrial Wipes

The industrial requirements of wipes are different from personal wipes because of time and effective and strict performance at a minimal cost. Therefore, the selection of a good wipe is critical. In past cloth-based rags and laundered have been used in industry for all types of cleaning (dirt, oil, or dust) from equipment and floors. Nowadays, disposable wipes are getting more attention. Drawbacks of conventional rags over disposable industrial wipes are presented in Table 12.4.

Similarly, hospitals need a different size, cost, quality, and performance of wipes if compare to oil and gas or plastic or textile industry.

Table 12.4 Disadvantages of rags over disposable wipes [13]

Rags	Industrial wipes
Less absorbent	Highly absorbent
High cost	Low cost
High dirt contamination	Low contamination
Invariable and inconsistent quality	High quality
Poor performance after repeated laundry	Disposable

12.7 Cotton in Nonwoven Industrial and Technical Textiles

Industrial and technical textiles are primarily demanded specific functions (high mechanical strength and chemical resistance) of textile materials that do not favor natural cotton fibers to be used for such products; however, cotton fiber can be blended with synthetic and technical fibers. Synthetic fibers are in the major portion are being used in industrial and technical textiles products, like polyester and polyolefin fibers have almost 50% share as raw materials for technical textiles. However, some areas like automobiles, Geotech, and composites, where cotton has potential use, for example, USDA-SRRC and the University of Bremen, Germany, are working on cotton composites for automotive applications. Some examples of cotton nonwoven industrial textiles are presented in Fig. 12.12.

12.7.1 Filtration Textiles

The act of cleaning and separation of one material to another is called filtration. The pure materials get once filtration is done. There are various forms of filtration available; however, nonwoven filtration is ideal for said purpose due to random fibrous structure and thickness as they give high filtration efficacy.

Advantages of nonwoven filters are;

- Effective filtration
- Permeable
- Low blinding propensity
- No yarn slippage
- Unlimited for thickness
- High productivity.
- Continuous process.

Cotton and other natural fibers are suitable for making multi-layer nonwoven fabric filters.

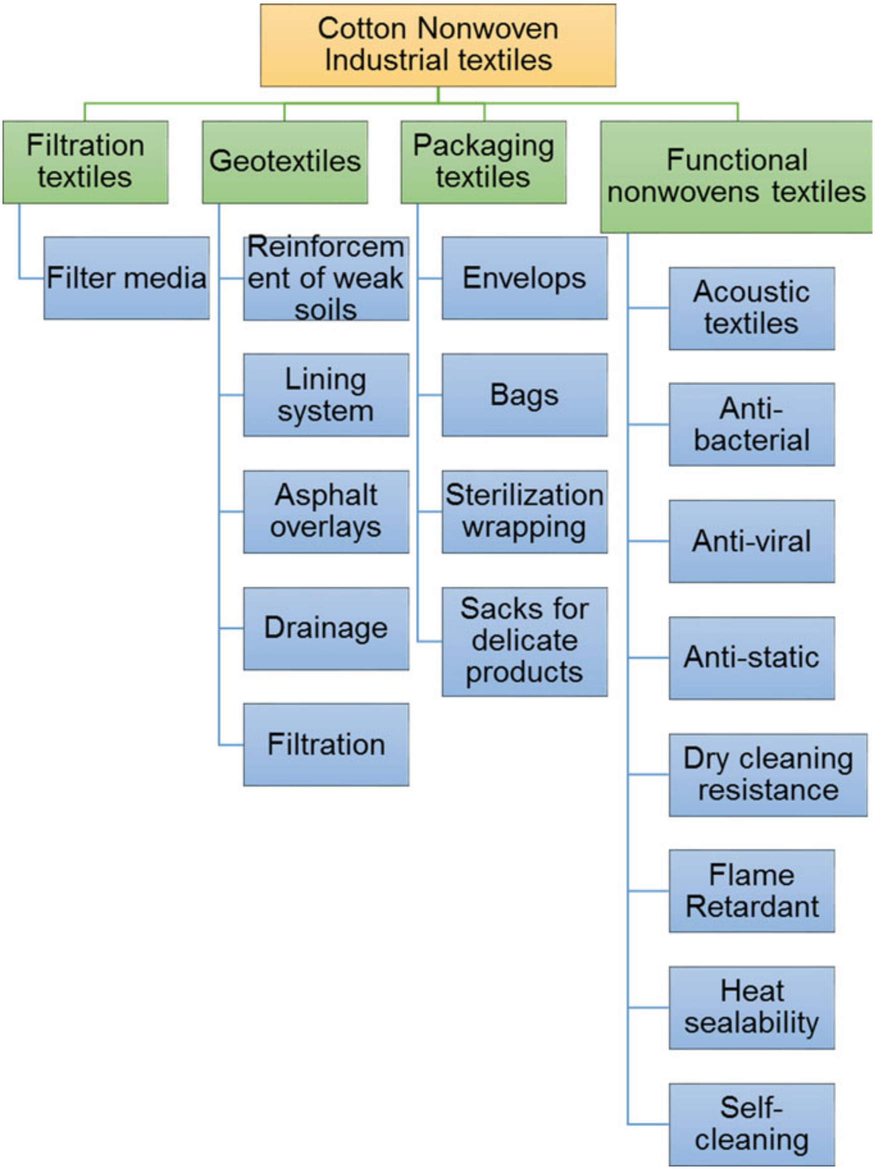

Fig. 12.12 Some examples of cotton nonwoven industrial textiles

Fig. 12.13 The illustration of land protection by herbicides versus geotextiles [17] (Fig. 1 on page 211) Copyright © 2010 John Wiley and Sons, Ltd

12.7.2 Geotextiles

Geotextiles are used to provide filtration (between soil and drainage gravel, separation (Prevention of mixing of two materials), reinforcement (to reduce soil movement), and drainage (to perform drain) applications, refer Fig. 12.13. Cotton geotextiles on agricultural land are used to reduce soil losses and increase infiltration [17].

12.7.3 Packaging Textiles

Nonwovens are becoming popular in packaging due to lightweight, ease in storage, durable properties. The advantages of using nonwovens in packaging.

- Recyclable
- Easy to convert into pads and shapes
- High tear resistance
- Light-weight.

12.7.4 Functional Nonwoven Textiles

Memon et al. [18] have reviewed the acoustical textiles, and they claimed the cotton nonwovens have good acoustical properties. Similarly, by imparting the following functions, cotton nonwoven can be used in functional nonwoven textiles. Recently, Fiedler et al. [19] have presented the application of Aloe vera microcapsules in cotton nonwovens to obtain biofunctional textiles. Yang et al. [20] have presented the superhydrophobic cotton nonwoven fabrics through atmospheric plasma treatment for applications in self-cleaning and oil–water separation. These are just examples, though a full coverage of functional nonwoven textiles is beyond the scope of this study.

12.8 Future Trend of Nonwoven Cotton

The demand for nonwoven cotton increases day by day. For the hygiene products, in the future, there will be another area of necessary work is to increased standards of thermo-physical and tactile support in portable hygienic materials. As regards product improvements, we are expected to see improved levels of absorbency efficiency and the use of lighter fabrics, resulting in higher levels of comfort and flexibility as well. Potential development is the use of bioactive fibers with cotton fiber into nonwoven products. These are used in blends of synthetic fibers to avoid disease cross-infection and to eliminate unwanted odor production. In the future, there will be even more advancement in Adult hygiene products in terms of fiber production and nanotechnology with performance coatings such as the introduction of skin health additives and improvement in infection and bedsore prevention, leading to the potential of growing demand. You can expect AIPs that look more and more like regular adult undergarments.

The most significant potential field for nonwovens in clothing will be expected to stay in medical protection garments for the near future. Modifications should be on nanofibers and micro-fibers levels to enhanced properties in lighter weights fabrics. As medical nonwoven fabrics are mostly disposable, therefore the cost will remain the main factor, with intense rivalry among suppliers of nonwovens. Consumers will search for the right balance of comfort and overall benefit. This will be possible when the producer will use the cotton fibers or blend them with some other fibers that will directly affect the cost of the product as well. Comfort often involves an adequate exchange of heat from the wearer's body into a protective layer. Working to improve this heat transfer will be the aim for industry, particularly for apparel. Another possibility is to establish nonwoven biodegradable fabric that will offer exciting opportunities for clothing, with an emphasis on sustainability. Because most of the garments are meant for the customer, a range of applications will be appealing to biodegradable fabrics, which can be developed at a low cost. Garments made from these fabrics will also be more convenient, making nonwovens more suitable in clothing.

Increasing awareness among people about using filters in different applications has elevated the filter's benchmark quality. These days, filters need to be reusable and reliable as well as biodegradable or recyclable, and chemical vapors can be purified. Filter media demand is expected to grow in the coming years. Consumption of air filters in commercial dust filtration fields (baghouse filters and tube filters), face masks, and in-cabin automotive air filters will improve dramatically. The growing demand for filter applications is rising due to an increased understanding of global environmental conditions. Finer fibers will be developed, and methods for processing filter media will be merged to satisfy new specifications and new application areas. Small particles with a scale of less than one micrometer can be filtered out, depending on the various process combinations. Filters are made from very fine fibers to achieve this. These fine fibers can be fabricated using different processes. The obstacles to be faced in the field of electrospinning include the development of mass processing equipment for the development of fibers, which will allow an improved surface area unique to filters. Another difficulty is spinning fibers without remedies and creating filter media that is environmentally sustainable. So it can be assumed that due to their materials, nonwovens and nonwovens systems can play a significant role in the filtration field.

12.9 Conclusion

Even though cotton is not in a significant portion in nonwoven application fields till now but recent COVID-19 outbreak, it has attracted consumers and nonwoven suppliers to use biodegradable, sustainable, and disposable cotton fiber in their products. Different types of cotton (greige and pre-cleaned) can be used in diverse fields such as composites, home furnishing, bedding, and pads. With the use of hydroentanglement technology, on the other hand, as also mentioned in this chapter, the significant market share of pre-cleaned cotton is in personal care and medical nonwoven products. Cotton possesses unique properties like breathability, hypoallergenic, comfort, and good wet strength, which increase its value in medical textiles, especially. Cotton can be recycled, reused, and dispose-off by the biodegradation process and the recent pressure from the buyers to push nonwoven manufactures to enter the circular economy campaign, and undoubtedly, cotton is the leader in this regard. Therefore, many of the manufactures and researchers are focused on making it economically viable and fit for a broad level of applications by improving the cotton processability. The market share of cotton is increasing day by day, and innovations are being made periodically to put cotton in a significant portion of nonwoven products.

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Chapter 13
Pretreatment of Cotton

Abdul Khalique Jhatial, Hanur Meku Yesuf, and Bewuket Teshome Wagaye

Abstract Cotton is the most widely used natural cellulosic fiber by the textile industry. Due to natural growth conditions, transportation, and processing of cotton fiber (in spinning and weaving industry), it gets impurities, consequently making difficulties in the chemical processing of cotton. Therefore preparatory processes are necessary for their distinct importance in subsequent processes. Cotton preparatory processes include singeing, desizing, scouring, bleaching, mercerization, and biopolishing. Conventional preparatory processes utilize higher consumption of energy, water, and chemicals, affecting the environment and increases the cost of manufacturing. Therefore, alternative processes of cleaner production are getting more extensive attention to conserve water, energy, and reduce chemical usage to decrease the effluent load. The processes, such as enzymatic treatments, integrated processing, electrochemical processes, and plasma technology, are potential alternatives. These processes developed on the lab scale. However, only a few of them, such as enzymatic processes, have been widely accepted at an industrial scale. This chapter briefly describes the conventional and latest non-aqueous processing preparatory methods of cotton and their importance concerning the environment and their impact on cotton fiber.

Keywords Cotton · Pretreatment · Preparatory processes · Enzymatic processes · Desizing · Plasma

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13.1 Introduction

Cotton fiber is a natural and most widely used fiber in the Textile industry due to its comfort characteristics such as higher moisture absorption and good mechanical properties, making it the right choice for apparel applications. It is composed of 88–96% cellulose and up to 10% by weight of natural impurities such as proteins, pectin's, waxy esters, waxy alcohols, and hemicellulose and lignin substances [1–3] as given in Table 13.1. These impurities vary greatly depending upon the variety, origin, growth conditions, ripeness, and harvesting time. Besides these natural impurities, some external impurities are also added with the picking, transportation, and during the processing of cotton fiber in the spinning and weaving industry for yarn and fabric manufacturing, respectively. Therefore cotton fiber with these impurities becomes water repellent and yellowish in appearance [4]. It is difficult to process it for the coloration and finishing processes directly. This emphasizes the necessity to prepare the fibers to eradicate these impurities to avoid any severe problem in the subsequent processes.

Pretreatment is a preparation process for cotton textiles for subsequent processes of coloration and finishing. It is the series of cleaning operations for removing the impurities that can cause adverse effects in dyeing, printing, and finishing. The process of preparing cotton textiles is the chain of processes in the wet processing industry. It involves the wet treatment of cotton by using different chemicals and auxiliaries for removing the impurities and yellowness [1]. The degree of cleaning depends on the amount of impurities present and depth of shade required in the dyeing process, i.e., the higher degree of whiteness for lighter shades and wise versa depending on the customer requirements. However, for white finished fabric, high values of whiteness, along with fluorescence brightening agents (FBAs), are often used.

Table 13.1 The proportion of non-cellulosic matters in cotton fiber and cuticle [5]

Components	% composition of whole fiber	% in cuticle
Cellulose	88–96	–
Proteins	1.1–1.9	36.4
Pectins	0.7–1.2	19.6
Waxes	0.4–1.0	17.4
Ash	0.7–1.0	6.5
Seed coated Fragments	0.5–1.0	–

13.2 Cotton Pretreatment Processes

Cotton has different types of impurities; therefore, pretreatment of cotton is performed in stages intended to remove certain impurities in specific processes [3]. However, it is not necessary to subject the given textiles to all of them. Suppose if a fabric will be dyed with black color afterward, it's of wasting money and time on achieving a higher whiteness degree in the bleaching process. Therefore the process selection is mainly dependent on the quantity of impurities, end product, and customer requirements. It is necessary to achieve the required quality of fabric at the end of the pretreatment. The cotton pretreatment is followed by the sequence of processes, i.e., singeing, desizing, scouring, bleaching, bio-polishing, and mercerization processes. The process sequence is entirely dependent on the required fabric properties and end-use.

13.2.1 Singeing

This is usually the first process carried out in the wet processing industry, although it never involves the wet treatment, this preparatory process mostly performed on woven textiles to remove protruding fibers from the fabric surface. These protruding fibers on the surface of fabric trap air inside, therefore reduce the wettability of fabric. As textiles will further be subjected to wet treatments, therefore it must have good wettability to uptake the chemicals and auxiliaries. Singeing creates a smooth fabric surface by burning the surface fibers, as shown in Fig. 13.1; this smooth surface is required for printing. It helps to achieve brighter shades without frosty appearance. Cotton fabrics and other cellulosic fibers behave ideally during the singeing as they form light dusty ash, easy to remove afterward.

There are different methods of singeing textiles, such as roller singeing, plate singeing, and gas singeing. However, the most widely used successful method is gas

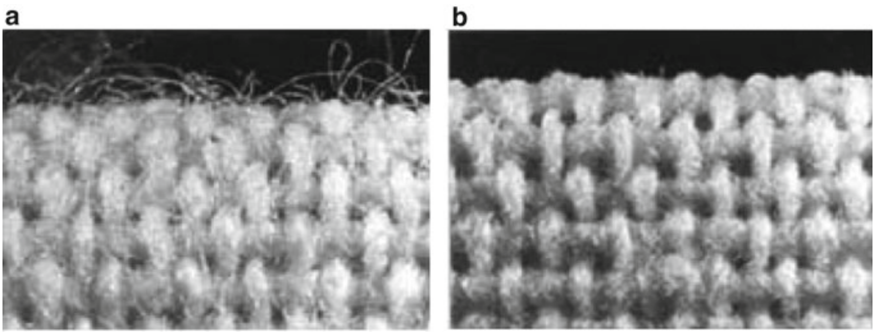

Fig. 13.1 **a** Fabric before singeing, **b** fabric after singeing

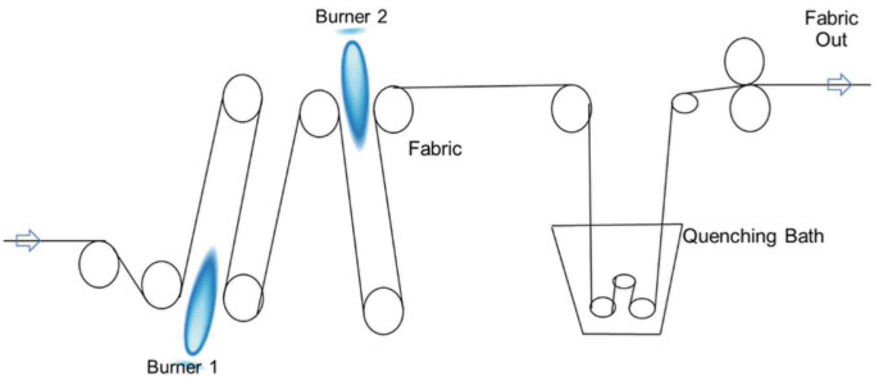

Fig. 13.2 Process flow diagram of gas flame singeing machine

singeing. The most widely used type of gas singeing machine uses the gas flames, as shown in Fig. 13.2, it is a continuous process performed on one or both sides of the fabric as per need. Textiles are allowed to pass in open width form through these flames at high speed 150–400 m/min to burn the protruding fibers [6]. Singeing effect is controlled to preset values. The speed of the singeing machine depends on the twist in the yarn, and the structure of the fabric, compact the structure severe will be the singeing. The fibers that are sensitive to heat, they form the hard black residue or melt, can be processed on modern singeing machines but with particular care and at specified parameters. The speed for protein fibers is much lower than the cellulose fibers, and woolen fabrics are singed at a speed of about 45–70 m/min [6]. Felt covered rollers are used instead of quenching chamber, or any other spark extinguisher can be used.

The latest singeing machines should be versatile to process tall types of fabrics, e.g., blends, synthetic filaments, and spun fabrics [6]. The singeing position (flame angle) can be varied depending on the type of fabric. Normally singeing can be performed with following three flame positions, as shown in Fig. 13.3.

The positions of the flame are dependent on the type of fiber, the density of the fabric, and the weight of the fabric. The tangential singeing, flame impinges at an angle, as shown in Fig. 13.3a only affecting the protruding fibers, the fabric surface is not affected directly. This position of singeing is suitable for lightweight and sensitive fabrics such as synthetic filament fabrics as they require mild singeing. Another case, as shown in Fig. 13.3b, the flame impinges directly to the fabric against the water-cooled roller situated behind the fabric. This cooling effect of roller forms inside the fabric an elastic steam air cushion. It resists the deeper penetration of flame, hence singeing occurs only at the surface of the fabric. This is also suitable for heat-sensitive fabrics as the fabric remains cool. Therefore the most synthetic and blended fabrics can be processed with this position.

In the third case, as shown in Fig. 13.3c, the position of the flame is at the right angle, flame passes through the fabric, therefore, resulting in good singeing on both sides of the fabric. This is very suitable in singeing the cotton, its blends,

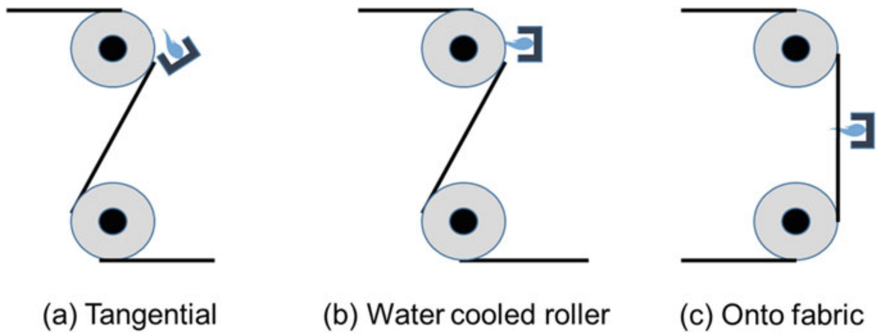

Fig. 13.3 Different Burner positions in modern gas singeing machine, **a** is tangential singeing, **b** singeing on water-cooled rollers, or with counteracting cold air and **c** singeing onto fabric [6]

and other manmade blended fabrics with higher GSM (grams/square meter) values. This method of singeing is also suitable for industrial and technical fabrics.

The most significant development made in the direct singeing of woven fabrics is the design of burners to produce a high-intensity flame with uniform temperature using natural gas, butane, propane, or LPG [4]. The direct singeing has a problem such as uneven temperature, flame heights, and chocked flame jets. The indirect singeing system has been developed to avoid these problems. In the indirect singeing system, the heat generated is transferred to specially designed heat retention zones, which are made of ceramic stones and form diffused infra-red radiations. These diffused rays are directed to the fabric surface. The heat of rays create ignition temperature and burns the protruding fibers present on the fabric surface evenly. The indirect system has high production speeds with automated process control and safety.

The cotton fabrics due their comfort are widely used in knitted high-quality products, as knitted fabrics could not be processed on the gas flame singeing machines or flat singeing machines made for woven fabrics, knitted fabrics will have the problem of edge-center-edge irregularities. Therefore circular singeing machine for the knitted fabric was developed by Donier et al. [4]. The method of opening the tubular knitted fabric is different in each of these manufacturers [4].

13.2.2 Desizing

Desizing is the process of removing size from the fabric. Size is the material, normally applied to warp yarns before the weaving process. The applied size gives the warp yarn sufficient strength and flexibility required to withstand the weaving operation forces acting on the warp yarns. Although sizing is good for the weaver to run the smooth production, it is a problem for the wet processor, the sized fabric has lower wettability, making dyeing and finishing processes difficult and non-uniform [7]. Therefore desizing is one of the initial wet treatments on grey fabric for removing

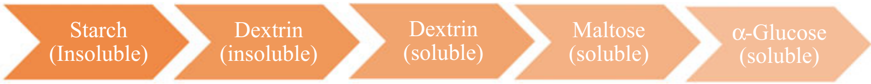

Fig. 13.4 Hydrolysis process of starch into soluble product

the size, the desizing is performed on fabric as per the type of applied size, and there are different types of sizes applied as per fiber type.

The typical sizing materials are:

1. Natural starches from potatoes, maize, rice or tapioca.
2. Chemically modified starches (ethers or esters).
3. Organic polymers, e.g., polyacrylates, carboxymethylcellulose, methylcellulose, polyester, or polyvinyl alcohol.
4. Solvent soluble materials, e.g., copolymers of methyl methacrylate.

Most of the textile fabrics are treated with starch or its derivatives, as its economical and efficient method of sizing textiles [7]. Cellulose and cellulosic blends with manmade are usually treated with starch-based sizes such as carboxymethyl cellulose (CMC) [7]. These products have poor solubility in water and are difficult to remove using water and detergent at boiling. Whereas manmade fabrics are mostly sized with a variety of water-soluble sizes such as polyvinyl alcohol (PVA) and polyacrylic acid (PAA), the removal of water-soluble sizes is easier as compare to insoluble starch [6, 7]. The removal of starch is only possible by converting the insoluble size into soluble products [6]. The solubility of starch can be achieved by the actions of acids and oxidizers, alkalis, and enzymes. However, during the process, proper care is required as starch and cellulose are composed of glucose, starch is formed by alpha glucose, whereas cellulose is formed by beta glucose. If care is not taken instead of starch, cellulose will be degraded by the sizing agents (acids and oxidizers), resulting in the formation of hydro-cellulose and oxycellulose, making the fabric weaker [8, 9]. Therefore under controlled conditions, starch can be progressively hydrolyzed to products with varying solubility in water as shown in Fig. 13.4.

In desizing, the hydrolyzing reaction is carried out up to the soluble dextrin, not up to the α-glucose to avoid the degradation of cellulose. The desizing process is carried out with lower concentrations of desizing agents to avoid degradation of cellulose [6]. However, the destruction of cellulose will be minimized, but the time required to complete the process will be increased. The efficiency of sizing depends upon breaking down the size molecules into smaller soluble fragments. It requires some key steps to follow, irrespective of the sizing agent. Such as Immersing the fabric into the desizing agent, allow time to desizing agent to degrade the size to solubilize it and washout the degradation Products. Starch desizing methods are classified as Hydrolytic methods (Bacterial desizing, acid steeping, enzyme steeping) and oxidative methods (Chlorine desizing, chlorite desizing, bromite desizing, and Peroxy compounds).

13.2.2.1 Hydrolytic Desizing Methods

Hydrolytic methods consist of degradation of starch into soluble products by using bacterias and enzymes. Hydrolytic methods are comparatively, safer desizing methods than oxidation processes [10]. However, hydrolytic methods are mostly batch processes and slower, requiring significant time. Desizing with oxidizing agents such as chlorine, chlorite, and bromite breaks the glucose rings or the ether linkages of starch into water-soluble products. Oxidative processes, therefore, requires careful degradation of starch [11].

Bacterial Desizing

This is the oldest and cheapest method of hydrolyzing the starch. The main advantage of this method is chemical less processing, and this process uses warm water. The fabric is immersed in the water and padded at 100% pick-up by using pad mangles and winded on the batcher, and the wet fabric is stored in the open space for 24 h at 35–40 °C. The microorganism present in water and air will hydrolyze the starch. The fabric is finally washed with water to remove the solubilized starch. The drawbacks of this process are its slow speed, and it requires more space for the storage of the fabric for hydrolysis of starch.

Acid Steeping

This method of desizing involves the use of a diluted sulphuric acid or hydrochloric acid. The cloth is impregnated with the acid solution with 2.5 g/l concentration and left for 6–8 h at room temperature (30 °C). For rapid desizing (within 1–2 h), the concentration of an acid solution can be increased to 10 g/l. This method has the advantage of removing metal contamination present in the grey fabric. These metal contaminations could lead to a serious problem in the bleaching process. Acid treated fabrics should never be dried before wash. Otherwise, acid at high temperature reacts with cellulose forming hydro-cellulose, resulting in a decrease of fabric strength.

Enzyme Steeping

Enzymatic desizing is the most widely used method of hydrolyzing starch. Enzymes are biochemical products sensitive to the condition of their use. They are naturally occurring biological catalysts in nature; they are protein catalysts for catalyzing the specific chemical reactions. Enzymes have a specific action on specific compounds for changing their chemistry. For example, the role of enzymes in the digestion of food. Amylase, a family of enzymes, has a function of hydrolyzing the starch. They convert the starch for a variety of different saccharides (sugars), a water-soluble product that can easily be washed out.

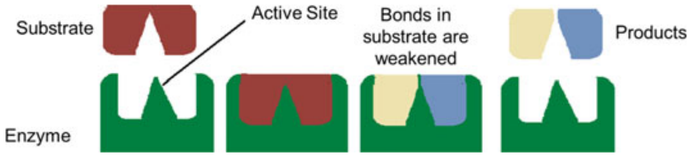

Fig. 13.5 Lock and key model of enzymes working

There are two types of amylase enzymes α-amylase and β-amylase, both perform the same function of hydrolyzing the starch, both attack the glucoside link in the starch molecule. However α-amylase has been used in the textile industry for many years for the removal of starch [8], the exact mechanism of hydrolysis of cellulose by enzymes is complicated to understand. The enzymes have a specific three-dimensional shape and have active sites, and they are adsorbed onto the surface of the substrate (starch) in the lock and key fashion, as shown in Fig. 13.5. The hydrolysis of the substrate is accelerated at the active site of the enzyme. Once the substrate is decomposed into water-soluble products enzyme is released, it reabsorbed onto the other locations. This process of hydrolysis continues until the enzyme is deactivated by the conditions of processing bath such as pH and temperature. Some chemicals called bogies are also used for deactivation.

Sizing agents are applied with additives such as oils, waxes, and allows to enhance the flexibility and softness of the yarn. Approximately 10–15% of the weight of yarn is added as size to cotton warp yarns and about 3–5% of the weight of yarn for synthetic filament. Due to these additives, the removal of size becomes a little complicated hence other desizing agents such as catalyzing lipase enzyme can be combined with the amylase to function efficiently; lipase hydrolyzes the fats and oils into products glycerol and fatty acids. The combination of two enzymes results in the efficient removal of starch. These oils and fats are also removed in the scouring process after desizing.

13.2.2.2 Oxidative Desizing Methods

Oxidative desizing method for depolymerization of the sizing agents by using oxidizing agents such as hydrogen peroxide and some persulphates has been used to degrade the starch by breaking the ether linkages and forming the carboxyl or aldehyde groups. However, the formation of oxycellulose is inevitable due to similar structures of cellulose and starch. Therefore this method of desizing starch requires intensive care to avoid the formation of oxycellulose [11]. In these methods, the fabric is treated with hot solutions of oxidizers and batched up for several hours or steamed for 20 min at 100–105 °C [6]. This method is done on fabrics with lower size percentages, sometimes desizing and bleaching were combined into one with increasing the concentrations of the chemicals. However, this method is not economical and environmentally friendly, due to high chemical usage resulting in higher chemical oxygen demand (COD) and biological oxygen demand (BOD) in the effluent, extreme pH, high concentrations of chemical used in the process and high temperatures [11]. The other chemical methods of desizing such as chlorine gas, sodium chlorite, and sodium bromite are not eco-friendly; therefore, no longer used for desizing.

13.2.2.3 Peroxy Compounds

The possibility of using sodium persulphate or hydrogen peroxide has been suggested, but their commercial use to date is small. Ammonium perdisulfate $(NH_4)_2S_2O_8$ and acid hydrogen permonosulfates are efficiently used as desizing agents for PVA slashed fabrics. Although PVA is water-soluble after the heat setting of fabric, it is polymerized and becomes difficult to wash off without using desizing agents. Three commonly known as persulphates, sodium persulphate ($Na_2S_2O_8$), Potassium persulphate ($K_2S_2O_8$), ammonium persulphate $(NH_4)_2S_2O_8$, these are salts equally useful for desizing, but potassium salt has poor solubility whereas ammonium salts liberate ammonia in alkaline desizing liquor; therefore sodium salts are preferred for the use [6].

13.2.2.4 Desizing Efficiency

After desizing, it is necessary to check the performance of the process by removal of size. This is referred to as desizing efficiency. The percentage of size present in the fabric is determined before and after the desizing process by using a potassium iodide solution. The starch content percentage in the fabric is determined by placing the drop of the solution on the fabric surface. The change in fabric color at the spot of the drop is then assessed by comparing it with the Tegewa scale or Violet scale having a 1–9 rating. Where rating of 1 denotes almost no removal of size rating of 9 indicates complete removal of size from the fabric. The commercially acceptable rating is 6–7 [12]. This test has been converted into a quantitative assessment of size content in the fabric. There is another method of determining the percentage of size removed by calculating the weight loss of fabric after the desizing process.

$$\text{Weight Loss } \% = (W_1 - W_2)/d$$

where W1 is the weight of fabric before desizing, W2 is the weight of fabric after desizing, and d is the amount of size present in the fabric. By using this formula, the size percentage removed can easily be calculated [6].

13.2.3 Scouring

The scouring is the process of improving the absorbency of textile materials by removing the non-cellulosic natural maters present in cellulose, such as fats, waxes, proteins, and pectin [8]. This process also breakdowns the seed and husk fragments trapped inside the structure of the yarn, and then in fabric, yarn manufacturing processes could not remove them [13]. During processing in weaving mills and transportation to the wet processing industry, the grey fabric gets some soils and stains, and these stains are also removed in the scouring process. This gives the fabric even wettability for the successful bleaching and dyeing. The process uses the clever usage of chemical properties of fats and waxes present in the fiber. Therefore traditionally a strong alkali, sodium hydroxide is used, it reacts with the fats and waxes, and sodium salt is formed. This salt is soap, and the reaction is called saponification. The process uses the emulsification and detergency reactions for assistance in the removal of dirt, stains, and other insoluble impurities present in the fiber. During scouring, water-insoluble impurities are converted to soluble impurities. Fats and waxes are soluble in solvent but insoluble in water. Therefore a solvent such as trichloroethylene cyclohexanol and methylhexanol can be used, and due to the use of these chemicals, the process may not be ecofriendly.

The process essentially consists of soap or detergent with or without the addition of alkali, when soap is added it reacts with the metal ion such as ferrous and calcium present in hard water and pectin of cellulose forming insoluble soaps. This becomes severe during the batch processes with lower baths (low L:R) as material to liquor ratio (M:L) is lower in the batch process, therefore, chelating or sequestering agents are used in the process to avoid the scum film formation.

Scouring processes depends on the type of fiber. Among natural fibers, cotton is a widely used fiber. Fortunately, cotton is not affected by the strong alkaline treatments up to 2% concentration for prolonging the time in the absence of air. This is very helpful in removing the pectins and proteins present in the lumen. The total impurities removed in the scouring process are less than 10% of the weight of the fabric. Other cellulosic fibers such as flax and jute cannot withstand the severe scouring by using strong alkaline treatments. Strong alkalis may remove the non-fibrous components of fibers resulting in damaging the properties of the materials. Therefore bast fibers are treated with soap or detergents with a mild alkali such as sodium carbonate (soda ash). Regenerated cellulosic fibers or manmade fibers are mostly clean and are sensitive to alkali; therefore, non-ionic or anionic detergents are sufficient for scouring them.

The scouring process can be performed on textiles at different stages such as fiber form, yarns/skeins, fabric. But due to ease of handling fabric form is preferred. However, the stage of scouring depends on the application of textiles. Such as surgical cotton is scoured at fiber form. The scouring process can be performed in two forms, the exhaust process by using Kier, Jigger, winch and overflow machines, and the continuous process by using J box, high-pressure reaction chamber, conveyor, and roller chambers.

Sometimes if textiles have less amount of impurities, scouring, and bleaching processes are merged into a one-bath process called solomatic bleaching. Currently, the majority of process houses do a one bath scouring and bleaching process. In the present time, the solomatic bleaching process seems ideal concerning conventional separate processes. Although this process has drawbacks as well, giving the scope for further developments. Much research has been directed to replace this process with an enzymatic process considering the energy and environmental demands for ecofriendly sustainable processes.

13.2.4 Bleaching

Bleaching is the process of removing the natural color pigments from the cellulose for whiteness. As cotton has yellowish appearance due to the presence of these pigments, therefore it is necessary to remove the pigments for achieving true color tone and brightness, especially with the lighter shades. The bleaching process also removes the natural impurities left during the scouring process in the fiber. Although the scouring process increases the absorbency and flexibility of the textiles, still some impurities are left in cotton required to be removed in the bleaching process. The bleaching process is performed on textiles after desizing and scouring. It is one of the processes that increase the aesthetic appeal of textiles by bringing the whiteness and removing the natural impurities. The bleaching process is performed mostly on all the natural and blended fabrics, the method of bleaching textile materials, the extent of bleaching, and conditions vary greatly to the extent of natural pigment present in fiber and amount of impurities. This emphasizes the need for selecting proper bleaching agent and processing conditions, and any error may lead to damage of fiber. There are the number of bleaching agents used since the roman and dutch times to bleach cotton and other vegetable fibers. These agents broadly classified as oxidative and reducing agents for bleaching. The problem with the reductive bleaching agents was oxidizing in the air and sunlight once exposed to such conditions, resulting in the yellowish tint appearing on textiles after bleaching [1, 6]. Therefore reductive bleaching agents are rarely used, whereas oxidizing bleaching agents, especially hydrogen peroxide, is mostly used to bleach the cellulosic textiles.

Hydrogen peroxide is one of the widely used oxidizing bleaching agents for cellulosic textiles. It has the advantage of having higher whiteness values with permanent whiteness. It is a colorless liquid soluble in water in all proportions. It is activated in alkaline pH, although it is stable at acidic pH for storage purposes. Cotton is usually bleached at boil using the hydrogen peroxide. The most important factor in bleaching is to achieve the right degree of stability in the bleaching liquor. If the pH of liquor is very low, no per hydroxyl ions are set free, and bleaching will not take place, this results in the lower bleaching liquor stability because whole oxygen is liberated and escapes into the atmosphere before acting upon the cotton. Therefore bleaching liquor must be made alkaline, to achieve the required degree of whiteness, for stabilizing the pH below 10 a stabilizer is added in the liquor as hydrogen peroxide is not stable above 10 pH, above pH 10 [12], it is precarious when it gets decomposed underwater and oxygen [12]. It is, therefore, necessary to add a stabilizer, and of all the substances, which have been tried sodium silicate is the most effective. Hydrogen peroxide is a stable chemical under acidic conditions and needs the addition of alkali for activating it. Above pH 10, it is precarious when it gets decomposed underwater and oxygen.

13.2.5 Bio-Polishing

Bio-polishing is an enzymatic process of finishing fabric to improve its quality by removing the protruded fibers from the surface, the modification of fabric surface structure to reduce fuzziness, and pilling property of cellulosic fiber. These protruding fibers create problems in the later processes. The objective of the process is the elimination of micro-fibrils of cotton through the action of cellulases enzyme [14, 15]. The enzymatic removal of fibrils imparts the main characteristics to the fabric during biopolishing treatment, such as it improves pilling resistance, a clearer lint and fuzz-free surface, soft and smooth feel, improved absorbency, and long-lasting effect along with fashionable effects.

Cellulose fibers are degraded by fungi and bacteria; during this degradation, they produce an enzyme (Cellulases) [16]. This enzyme degrades the polymer chain resulting in the chains become shorter. The diffusion of the enzyme to the interior of the fabric is the greatest operational limitation associated with enzymatic treatments. Therefore fabric surface enzymatic treatments have received greater acceptance; in these treatments, enzymatic action is performed on the surface of the fabric. During the bio-polishing, mostly, the cellulase enzyme is used for degrading the surface protruding fibers [17]. As enzymes are sensitive to process conditions and parameters; hence, therefore, it is necessary to use a buffer system during the process to control the pH and temperature. The physical or the chemical methods of removing the fibers from the surface of the fabric are temporary. The fibers returns on the surface of the fabric after a few washes and fuzz is formed on the surface of the fabric [18]. This fuzz creates a frosty appearance and dissatisfaction. Bio-polishing is a permanent effect, and it keeps the fabric in good condition after repeated washes along with enhanced feel, brighter color, and appearance. Therefore bio-polished products become more attractive to customers with higher sale prices.

13.2.6 Mercerization

Mercerization is a preparation process which is performed only on cellulosic fibers and cotton in particular. All the fabrics made from fibers that can resist the mercerization conditions can also be mercerized. Cotton polyester blends are mercerized, but cotton wool blends cannot be mercerized as wool is not resistant to strong alkali.

The process is named after John Mercer, who, in 1884, made a study of the effects of strong caustic liquors on cotton for improving the luster and absorbency [19]. This process is carried out to alter the chemical and physical properties of the cotton fiber. In the presence of strong alkali cotton fiber swells frequently brings the morphological changes in the cross-section of the fiber, a cross-section of cotton fiber is improved from elliptical to circular shape in the presence of strong alkali and tension [19]. The process helps increase the dye uptake in the dyeing process, the presence of immature fibers in cotton with high proportion results in uneven dyeing. It causes speck's appearance in the fabric. To avoid this defect, this mercerization process helps in bringing even dye pick-up, and level dyeing, reducing dye consumption.

Similarly, the luster of the fabric is enhanced by mercerization, which further increases fabric appearance by reflecting more light. This change is not temporary but permanent in nature due to permanent change in crystal orientation of fiber brought about by the mercerization process. The mercerization process has two major types, chain mercerization or chainless mercerization, also referred to as caustisization. These processes can be distinguished as a process with tension or without tension. Caustisization process achieves all the same results as with tension except the luster of the fabric.

13.3 Advancements in Pretreatment of Cotton Textiles

A basic and important purpose of the pretreatment is to remove most of the impurities from textiles and to make them ready for the subsequent processes, such as textile dyeing, printing, and further finishing. In general, textile pretreatment includes chemical, physical, and physicochemical processes [20]. The advancements have been made in processes either by modifying the chemistry of process or by reducing the process steps to make processes economical and sustainable. For the last three decades, after the restrictions on the use of chemicals and auxiliaries adversely affecting the environment, such as hypochlorite bleaches and other harsh chemicals along with the increase in manufacturing cost, there was the need for the development of sustainable and ecofriendly processes [3]. This demand forced the academia and industry to find the alternative sustainable and economic processes and chemical agents meeting the needs of the industry. Scientists and researchers are developing novel processes to accomplish the pretreatment of grey fabric without affecting the environment, the processes such as enzymatic pretreatment [17], one step pretreatment process [9], low-temperature pretreatment, electrochemical processes, plasma treatment, advanced oxidation treatments, and use of liquid carbon dioxide as an attempt to make the grey preparatory process economical and ecofriendly. These all processes developed on a lab-scale; however, only a few of them, such as enzymatic processes, have been widely accepted at an industrial scale.

13.3.1 Enzymatic Processing

Currently, enzymes are becoming increasingly important in sustainable technology and green chemistry. The textile industry is using enzymes at commercial scale at the early stages of preparatory processes such as enzymatic desizing with amylase, bio-polishing, and stone washing with cellulase, peroxide removal after bleaching with catalase, bio-scouring with pectinase and oxidoreductase for bleaching [17]. The applications of enzymes are increasing and spreading into all areas of textile processing. Due to this, intensive academic and industrial research has been carried out for making the preparatory processes economical and sustainable. Enzyme manufacturing companies are consistently working and spending on research and development to improve their products for more flexible applications, conditions, and uses. The textile industry can take benefit from these economic and sustainable products for expanded applications. It needs a better understanding of products and their working conditions, mechanisms, and effects on the fabric for better results. Enzymes have specific actions under certain conditions. They provide the safest processing conditions without any undesirable effect on fabric [20]. However, they are sensitive to process conditions; therefore, it requires care and monitoring during the processing. The enzymes are used in various textile processes, the class of enzyme and its function and applications are given in Table 13.2.

The desizing process is performed commercially by using the amylase for a few decades, and it has reached the state of an art process [11]. However, more work was conducted to substitute the chemical scouring and bleaching processes with enzymes. Enzymatic scouring (bio-scouring) combines the Cellulases and Pectinases for the removal of non-cellulosic material present on the surface of the cotton. During the process, pectinase destroys the cotton cuticle structure by digesting the

Table 13.2 Different types of enzymes and their application in textile processes [11]

Enzyme class	Function	Application in textile
Lipases	Split fats into glycerol and fatty acids	Scouring, desizing
Amylases	Split starch into dextrin and sugars	Desizing
Pectinases	Hydrolysis of pectins	Scouring
Cellulases	Degrade cellulose to soluble products	Scouring, bio-finishing, bio-stoning
Catalases	Degradation of residual H_2O_2 after bleaching	Effluent treatment of peroxide
Laccases	Bio-bleaching of denim, to catalyze the breakdown of the chromophore	Stone washing effect without loss of fabric strength
Glucose oxidase	For generating hydrogen peroxide	Bleaching
Laccases	Flavonoid degradation	Bleaching
Xylanases	Degradation of starch	Desizing
Cutinases	Hydrolysis of wax and pectin	Scouring

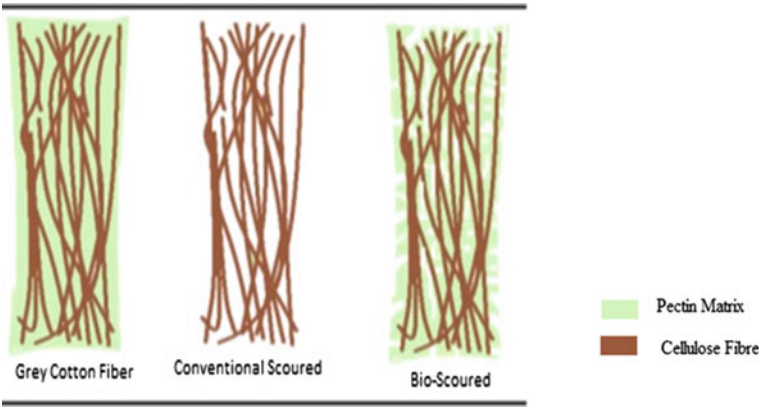

Fig. 13.6 Comparison of pectin removal in conventional and Bio-scouring [6]

pectin and removing the connection between the cuticle and the body of cotton fiber. In contrast, cellulase can destroy cuticle structure by digesting the primary wall of cellulose immediately under the cuticle of cotton. The conventional process eradicates these pectins resulting in lowering the binding strength of fiber, as shown in Fig. 13.6 [6]; this complete removal also increases the harshness and hairiness on the fabric surface. Therefore bio-scouring process removes the pectins to the level where absorbency is achieved without affecting the strength and hairiness. Bioscouring has lower wastewater parameters comparatively than alkaline scouring such as Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and Total Dissolved Solid (TDS). Fabric characteristics such as handle is soft in enzymatic scouring compared to alkaline scouring process.

The bleaching process is performed to increase the whiteness of the fabric. Conventionally hydrogen peroxide is used as a commercial bleaching agent. It requires higher amounts of alkali and chemicals; consequently, the process uses huge quantities of rinse water. This chemical process also pollutes the environment heavily [14], Hydrogen peroxide itself does not present an environmental pollution problem as it decomposes into water and oxygen. However, its processing needs the care of metal ions as it undergoes a radical reaction in the presence of metal ions. Therefore, the replacement of hydrogen peroxide by an enzymatic bleaching system would not only lead to better product quality due to less fiber damage but also to substantial savings on washing water needed for the removal of hydrogen peroxide [21]. An alternative to this process is to use a combination of suitable enzyme systems. Amyloglucosidases, pectinases, laccases, and peroxidases are selected that are compatible concerning their active pH and temperature range [11]. The enzymatic bleaching process is an emerging enzymatic process. There is a need for development to reduce the process cost to make it suitable for commercial, industrial applications.

13.3.2 Integrated Enzymatic Processing

The integrated enzymatic process can expedite the preparatory process of cotton preparation. The processes such as desizing, scouring, bleaching, finishing, and dyeing can be combined in a single bath or in one step to conserve water, energy, chemicals and can reduce effluent loads. Enzymatic technology has made it easy and advantageous as compared to the conventional process. However, there is a need for collaboration and understanding to plan as it requires multidisciplinary knowledge properly. The bioengineering specialists, textile technologists, and stakeholders in textile industries have to assess the sustainability issues, economic aspects, and environmental impacts of modified processes in comparison with currently used technologies [11].

Focusing on the sustainable and economic growth textile industry is becoming the main field of industrial application of enzymes. The integration of enzymatic processes is also another novel and economical approach of pretreatment of cotton textiles. It has an advantage over the conventional process concerning cost and sustainability. The newly integrated processes such as enzymatic desizing and bio-washing by one step using the amylase, cellulase, and laccases enzyme in denim garment manufacturing, single-step enzymatic desizing, and bleaching in a single bath [9]. Rapid enzymatic single-bath treatment (REST) used glucose oxidase enzyme to combine desizing, scouring, and bleaching processes in one bath to prepare the cotton fabric. This is an economical process as it conserves energy and time. Another approach used the combined one-step bleaching and dyeing in the same bath. The same approach has been used to integrate desizing, bleaching, and reactive dyeing processes in one bath using the gluco-oxidase enzyme, as the cost of gluco-oxidase enzyme purification are high; therefore, this process is not commercialized yet [11]. An enzyme alternative to the gluco-oxidase enzyme (Aspergillus Niger) is needed for the cost-effectiveness of the bleaching process.

13.3.3 Plasma Technology

Plasma technology is a novel non-aqueous and effective method to improve the surface properties of materials surface, by reducing or eliminating the use of water and chemicals as compared to conventional processes. It is a very attractive physical process used to enhance the quality of textiles at preparation, coloration, or finishing stages. For the textile fabric treatments, mostly cold plasma is used at ambient treatment atmosphere. Plasma can be produced in the glow discharge in a vacuum process or by using the atmospheric plasma devices. Plasma is partially ionized gas, composed of highly excited atomic, molecular, ionic and radical species with free electrons and photons. It can be obtained between the electrodes of devices having a high frequency, 40 kHz, 13.56 MHz, or with microwave generators (2.45 GHz).

Plasma processes modify the textile surface via four processes i.e cleaning, activation, grafting, and deposition. The plasma-cleaning process removes the organic contaminants from the surface of the material by using inert (Ar, He) and oxygen plasmas. The activation plasma process activates the surface of the material with the functional groups such as hydroxyl, carbonyl, peroxyl, carboxylic, amino, and amines. All fibers or polymeric surfaces can be functionalized for specific functions using the plasma activation process. The polymers activated in such a manner provide greatly enhanced adhesive strength and permanency; this is a great improvement in the production of technical fabrics.

Plasma technology has wide applications for textiles such as it enhances mechanical properties of cotton, softening of cotton, hydrophilic and hydrophobic functions, and desizing of cellulose-based polymers. It also improves the surface wetting properties of synthetic polymers such as poly amid (PA) polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and Polytetrafluoroethylene (PTFE) with treatment in the presence of gases such as oxygen, air, ammonia, and plasma. Hydrophilic treatments also serve as the antistatic finish for the synthetic polymers. Increased absorbency also increases dyeing uptake.

Desizing of the cotton fabrics, sized with carboxymethyl cellulose (CMC) and polyvinyl alcohol (PVA) can be accomplished using the plasma. An atmospheric pressure glow discharge (APGD) reactor is used with air, oxygen, and helium (O_2/He) or air helium (air/He) plasma to remove the size. The fabric size can be removed up to 99% using the APGD with both air/He and air/O_2/He plasma treatments followed by cold and hot washing. Atmospheric plasma treatment may greatly increase the solubility of PVA on cotton in cold water.

The grey cotton fabric contains a lot of natural and added impurities, which are high molecular weight substances [22]. For changing the solubility behavior of cellulosic polymers, dielectric barrier discharge (DBD) plasma applied in atmospheric conditions for modifying the surface properties of fibers [17]. It uses two electrodes (at least one of them coated with an insulating dielectric material), which are placed parallel to each other. The fabric surface is altered by placing fabric between these two electrodes in the presence of gases, i.e., oxygen, nitrogen, or air [23]. DBD plasma technology is an efficient technique for altering the surface properties of textiles, such as cotton and cellulosic fibers, synthetic polymers, and their blends [5].

13.3.4 Electrochemical Technique

Electrochemical techniques have been used for the synthesis of compounds and metal recovery treatments earlier; recently, the application range of the electrochemical process has been extended to various technical applications. One such application is the use of this process for textile applications to find economical and sustainable alternative processes. It is applied in textiles such as to produce smart textiles or conductive fibers, conductive polymers, functionalized fabrics, cotton bleaching process, finishing of denim fabrics, sulfur/vat dyeing of cotton, color removal of textile wastewater by using electrochemistry [24].

The application of the electrochemical technique in the dyeing of vat/sulfur dyeing is interesting as it is used to reduce the dyes without using sodium hydrosulfite, removal of nonbiodegradable dyes such as reactive dyes makes it an economical and cleaner process. Electrochemical methods are cleaner than physicochemical and membrane technologies. Nowadays, there are only a few applications on an industrial scale, as most of the electrochemical treatments are still being studied at a laboratory scale. The electrochemical technique has been used for bleaching the cotton fabric to achieve the whiteness. It is done by in situ electrolysis of oxygen in the presence of an alkaline electrolyte to produce oxidant. The results obtained by this process were comparable to those obtained with conventional bleaching methods.

13.3.5 Supercritical Carbon Dioxide Processing

Supercritical carbon dioxide medium based preparation of grey cotton fabric has been reported by researchers by using enzymes in supercritical carbon dioxide fluid, especially for degradation and removal of additional and natural impurities on grey cotton fabric in supercritical carbon dioxide medium. However, it is a very desirable and promising process for the cleaner production of cotton textiles due to waterless or very less water involved [3].

13.4 Conclusion

Pretreatment processes have a more significant influence on the subsequent processing of dyeing, printing, and finishing. The conventional pretreatment processes have significantly contributed to the textile industry and cotton fiber for the improvement of human life and comfort. However, due to the current demands of industry, the development of innovative strategies and advanced tools are crucial to moving towards a greener and sustainable textile production processes. The application of enzymes at commercial scale such as enzymatic desizing, denim washing, and bio-polishing processes are the distinct areas of enzymatic processes reaching the state of the art level. The enzymatic bleaching is also emerging. However, it still needs improvements to be adopted at the commercial level. Enzymatic processes have reduced pollution and are conserving energy and auxiliaries. The researchers are also trying to utilize the non-aqueous methods such as plasma technology, electrochemical processing to replace the conventional processes with the novel processes. However, these processes are still under experiments at the lab scale. This needs research and further developments to be commercialized.

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Chapter 14
Cotton Fiber and Yarn Dyeing

Sudev Dutta and Payal Bansal

Abstract Cotton is one of the most popular natural fibers around the globe with the purest source of cellulose. Cotton fiber is often dyed to obtain a wide range of colors and provide an integral component in modern society for human comfort and sustainability. Dyeing is the process associated with the coloring of fiber, yarn and fabric using different types of chemicals and dyes. Color is an essential aspect of our lifestyle and dyeing is the process to achieve that in the desired way. For the dyeing of the cotton substrate, different dyes like reactive, vat, sulfur, azoic, basic and natural dyes can be used. During dyeing, the dye molecules get attached to the fiber by various physical and chemical forces depending upon their molecular structure. There have been various developments in dyeing methods and relative machinery over the years to achieve optimum dyeing of the textile substrate in different forms. This chapter gives a brief overview of different dyes used for cotton fiber and yarn with suitable dyeing techniques and relative machinery.

Keywords Dyeing theory · Yarn dyeing · Fiber dyeing · Hank dyeing · Dyeing machines

14.1 History of Cotton Dyeing

In everyday clothing, cotton is one of the most widely used textile fiber, which is soft, staple, natural and cellulosic; it can be spun into yarn or thread to fabricate various textile materials such as suiting, shirting, breathable materials, etc. [1]. For better application of these constructed materials and their value addition, dyeing plays an extremely vital role. The process of treating fiber, yarn, or fabric with dyes or chemical pigments for coloration, is known as dyeing. A dye mainly comprises of

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two groups viz. chromophore and auxochrome in which chromophore is the primary coloring agent that reveals color on to the material and auxochrome helps in deepening the color provided by chromophore [2, 3]. Dyeing is an ancient art that has been in existence even in the bronze era. During ancient times natural dyes were extracted from crushed fruits, berries and other plants like madder, saffron plant, and dogwood. Stigmas of the saffron plant were used to extract different dyes such as blue indigo, red and yellow. Initially, sticking and rubbing methods were used for the dyeing process, but with the passage of time, a drastic evolution in dyeing methods has been noticed to get cost-effective and improved quality products [4, 5].

The indigo and other plant-based dyes came into existence around 4000 BC. Tyrian purple and blue dye were the most famous and highly prized color during the bronze era. From the murex shellfish, Tyrian purple dye was extracted [6], carmine (Bright red) was obtained from aluminum salt of carminic acid. Around the era of the mid-19th century, dyestuffs were made from vegetable and animal matter. Initially, only natural dyes were used for cotton such as indigo and madder dye. The archaeological pieces of evidence reveal that dyed cotton was considered as a luxury material. Cotton has a unique feature of dye uptake ability through bonding with different classes of dyes due to the presence of hydroxyl groups in its structure [7, 8].

14.2 Theory of Dyeing

As already mentioned previously, the process of application of color on textile material using dye (natural affinity and permanence to textile material) is called dyeing. For the success of the global market, dyeing is the foundation of the textile product. To meet customer requirements, the dyestuff must have some salient features such as good affinity, resistance against the light, uniform application over the material surface, better transport of moisture to reduce perspiration and laundering fastness. In the quest to satisfy these requirements, there have been various improvements in textile products over the years allied to the dyeing process. For achieving the final color on the textile material, initially, diffusion of dye particles in the interior of fiber structure occurs. During diffusion, dye and fiber molecules have some attraction for each other; however, some dyes react with fiber and get retained on the fiber surface. The strength of this retainability depends upon the physical and chemical attraction of specific dye and its fiber; the relative term to show this characteristic is called fixation [9]. Specific fibers have an affinity to particular dyes depending upon their structural compatibility; therefore, it is for this structural compatibility the dyes which are applicable to cotton may not work for other fibers such as polyester, nylon, acrylic, wool, etc. Cotton being a cellulosic fiber, same dye can be used for other cellulosic fibers like linen, ramie, rayon, and lyocell, but their hue may differ from the cotton. It is also essential that dye distribution must be even throughout the textile material for attaining a uniform shade. So it is necessary to get well known with the factors responsible for uniform dye distribution. Fiber properties, especially fiber porosity and pore size, influence the dye uptake. Dye and fiber involve mainly in four types

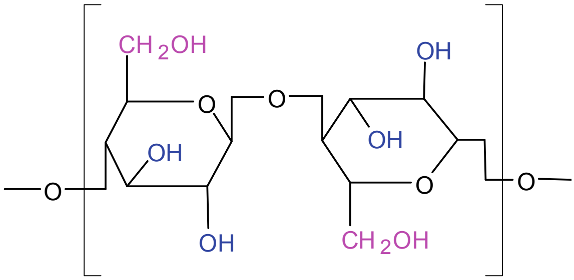

Fig. 14.1 Chemical structure for cotton

of interaction forces viz. ionic, van der Waals, hydrogen bonds and covalent bonds [10]. The dye—fiber interaction can be explained by six types of theories which are described as follows.

14.2.1 Physical Theory

In the dyeing process, when the dye is applied to the cotton, the presence of hydrogen and oxygen groups in its structure causes there to occur hydrogen bonds. There are also van der walls forces generate between fiber and dye particles. These both are purely physical attractions that help the dye molecule to get retained with fiber. The cellulose fiber like cotton has many OH groups as given in Fig. 14.1.

When dye diffusion occurs, some physical interaction between the dye molecule and cotton fiber takes place. The cotton fibers and dye molecule form several hydrogen bonds, as shown in Fig. 14.2. When the dye molecule during the affinity process gets attracted to the fiber by the van der Waals force of action, they get anchored to the fiber instead of making an actual bond. A typical example of this theory is when cotton is dyed with direct, vat and sulfur dye [10, 11].

14.2.2 Chemical Theory

When the dye molecules get diffused in the fiber, during the dyeing process, then both get attracted to each other by chemical forces of action, which suggests dye attachment on fiber through chemical bonding. The chemical bond can be ionic or covalent. For example, in the dyeing of cotton with reactive dyes, a covalent bond takes place where dye as an electrophilic group and fiber as the nucleophilic group performs.

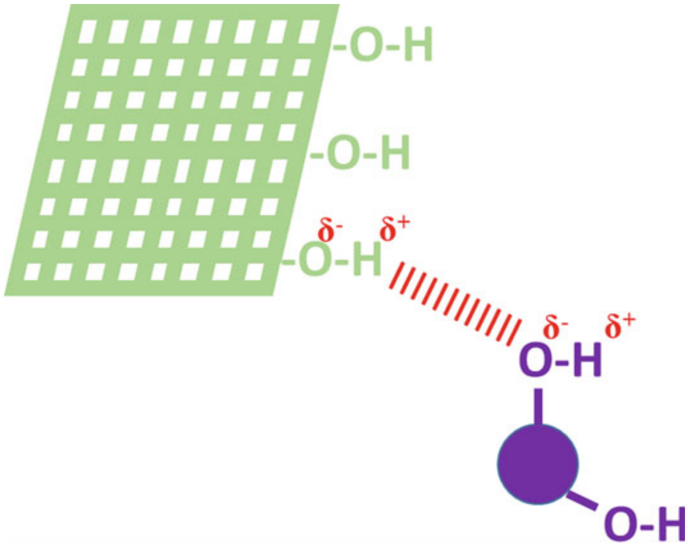

Fig. 14.2 Physical theory of fiber and dye molecule attachment

14.2.3 Physical-Chemical Theory

According to this theory, after the dye is applied to the textile material, initially, it forms a physical bond with the fiber, but the dye molecules get reacted with other chemicals/agent that binds them with fiber to enhance the fastness properties. So there are both physical and chemical bonds that occur in the dyeing process. The physical-chemical theory is a way to show how well the dye penetrates the fiber structure; its typical example can be cotton dyeing with basic dye or mordanting of cotton done before the dyeing process [11–13].

14.2.4 Fiber Complex Theory

When the dye molecules are more abundant in structure, then they have a lower affinity for fiber, which makes them incapable of entering the fiber structure and forms in situ by reacting to two different chemicals under favorable conditions. The best example relating to this theory may be the dyeing of cotton with insoluble azoic mineral, oxidation and phthalocyanine colors.

14.2.5 Solid Solution Theory

When dyestuff and fiber both are in solid form, but under suitable conditions, the dye is applied within the fiber using physical forces is described as solid solution theory, which is the solid-solid solution mechanism. In the hydrophobic fiber structure matrix, dye molecule solubilization occurs due to which it forms a solid-solid solution. The mechanism is done at higher temperatures; as a result, fiber structure is opened up for dye uptake. During the cooling process, dye diffuses inside the fiber and is trapped due to collapsing inside the fiber structure.

14.2.6 Mechanical and Pigment Theory

When the coloring materials have no reactive site, no affinity for fiber, and are insoluble in water/other solvents, then the binder is used in the aqueous emulsion for carrying out the dyeing process. The fiber and coloring material engages with each other mechanically [11, 14].

14.3 Dyes Used for Cotton

It is a known fact that demand for cotton has globally been increasing day by day due to its comfort, softness, lightweight, absorbency, and good strength characteristics. All types of apparel and household materials such as towels and linens are manufactured using cotton as it is versatile in colored fiber, yarn, fabric and garment form. Cotton can be dyed in fiber, yarn and fabric form by using reactive dyes, sulfur dye, Azoic (Naphthol) dye, basic dye, indigo, vat dye, direct dyes, and natural dye. Various dyes compatible with cotton have been discussed so forth [15, 16].

14.3.1 Reactive Dyes

These are the widely used category of dyes providing ‘fast dyeing’ on textile materials due to its cost-effectiveness, easy to apply the technique and to achieve brighter shades. These are mainly of two types of nucleophilic substitutive and nucleophilic additive dyes; this can also be further categorized as alkali-controllable dyes, salt controllable dyes, and temperature controllable dyes [17]. The Nucleophilic substitutive dyes are Mono-fluoro-triazynylamino, Dichloro-triazynilamino (Cold reactive dyes brand), Mono-chlorotriazynylamino (hot brand reactive dye), Mono-fluoro-triazynylamino dyes, Bis–Triazinyl dyes, Supra type of dyes, Di or trichloro-pyrimidylamino dyes. The Nucleophilic additive dyestuff is containing the

Vinyl sulfone group, Dyes containing Acrylamido group, α- chloroacrylamido dye. The general arrangement of reactive dye can be described as S-R-B-X in which S stands for water solubility group, R for chromophore, B for the bond between reactive system/chromophore and X for the reactive system. The reactive dye reacts directly with the structure of the cellulose and makes a power covalent bond between dye and fiber. This covalent bond is created between the dye molecules and the terminal –OH (hydroxyl) group present in the cellulosic structure and becomes an internal component of fiber structure. The bond is created with the help of nucleophilic substitution or nucleophilic addition mechanism. Reactive dye molecular structure comprises several groups, such as water-solubilizing groups, chromophore groups, bridging groups, reactive groups, and the leaving group. The chromophore group has pendant groups that are skilled in forming covalent bonds with nucleophilic sites in the fibrous substrates. Triazynil reactive dyes react with the cellulose by nucleophilic substitution [18, 19]. The chemical reaction of a mono-chlorotriazine reactive dye with the hydroxyl group of cellulose is the nucleophilic substitution process, as shown below in Fig. 14.3.

In the case of nucleophilic additive dye, a nucleophilic group in the fiber gets attached across an activated carbon-carbon double bond in the reactive group. The two-stage process related to fiber fixation via Nucleophilic addition to a Vinyl sulfone dye is shown in Fig. 14.4.

The reactive dye dissolves in water to form the dye liquor solution and then alkali (sodium carbonate, bicarbonate, and caustic soda) is added to the dye liquor

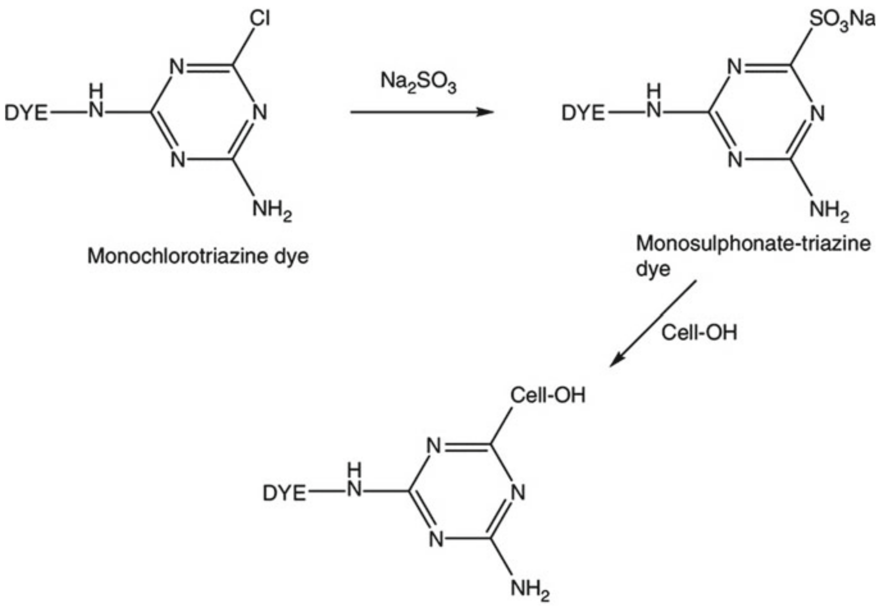

Fig. 14.3 Reaction of monochloro-s-triazine dye with cellulose [17]

$$(1)\ \text{Dye-SO}_2\text{-CH}_2\text{-CH}_2\text{-OSO}_3\text{Na+NaOH} \longrightarrow \text{Dye-SO}_2\text{-CH=CH}_2\text{+Na}_2\text{SO}_4\text{+OH}_2$$

$$(2)\ \text{Dye-SO}_2\text{-CH=CH}_2\text{+ Cell-OH} \longrightarrow \text{Dye-SO}_2\text{-CH}_2\text{-CH}_2\text{–O-Cell}$$

Fig. 14.4 Fixation via Neucleo philic addition to a Vinyl sulfone dye [20]

for accelerating the reaction. When reactive dyestuff is applied to the cotton, dye exhaustion from the dye bath to the surface of fiber occurs, causing the adsorption process. Salt is added for better exhaustion in the dyeing process after that dye diffusion from the surface of fiber into the fiber pore takes place, for achieving better migration and dye uniformity in an equilibrium condition between the dyestuff in the solution and the dyestuff inside the fiber. In the last stage is dye fixation through covalent bond formation between the dye and fiber takes place. The reaction using reactive dyes can be done at room temperature or specific temperature. The wash fastness, crock fastness of reactive dye is excellent and have acceptable lightfastness. Poor fixation of dye has been a big problem with reactive dyes, especially during the batch dyeing process, where a significant amount of salt is generally added for improving dye exhaustion. Reactive dyes can be available in powder, liquid, and print paste from at commercial level [21].

14.3.2 *Sulfur Dye*

Sulfur dyes are the most cost-effective dyes among all the dyes. These are water-insoluble in their normal form and have no affinity for the cellulosic material. It can be converted into soluble form when treated with reducing agents like the alkaline solution of sodium sulfide, which forms a water-soluble leuco compound, as shown in Fig. 14.5. This leuco compound enables the dye molecules to penetrate the fiber

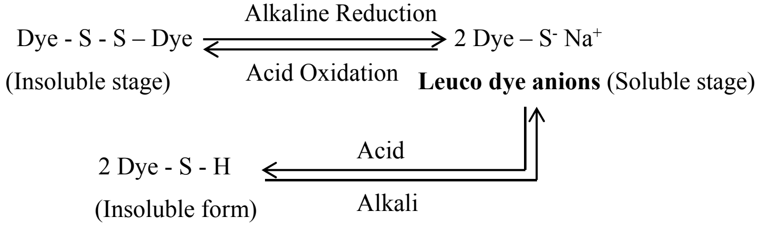

Fig. 14.5 Chemical reaction of water-soluble **leuco dye** [23]

easily. As the dye molecules are absorbed inside the fiber structure, it again oxidizes back to their water-insoluble form. A considerable amount of dyestuff is required for producing deep shades as sulfur dyes have a low color power. Wide ranges of shades are available for sulfur dyes, but the problem associated with it is dull color formation. The dyeing techniques like exhaust or continuous are applied during the sulfur dyeing process. The sulfur dyes exhibit poor lightfastness, especially for light shades. These are mostly used for dark colors like navy, blacks, and greens. The main disadvantage of sulfur dye is that it forms sulfurous and sulfuric acids in hot, humid conditions, which destroys the cellulosic structure and reduces the fabric strength [22, 23].

14.3.3 Azoic(Naphthol) Dye

Azo dye is a large class of synthetic organic dyes which contains nitrogen as the azo group –N = N– as a primary chromophore; the molecular structures are shown in Fig. 14.6. During the azoic dyeing process, a water-insoluble dye is formed directly within the fiber, which can be achieved by treating the fiber with both diazoic and coupling with suitable aromatic compounds. These two components react under suitable conditions of dye bath to form an insoluble azo dye.

During synthesis, diazotization is done, followed by azo coupling. Diazotisation includes a primary aromatic amine (diazo component) to create an unstable diazonium salt; this aromatic amine is processed at low temperature, acid conditions with sodium nitrite. After this, the diazonium salt is reacted with an aromatic amine and it produces stable azo dye, as shown in Fig. 14.7.

Azo dye is further classified based on the number of azo groups. Most azo dyes comprise only one azo group, but some of them contain two (disazo), three (trisazo), or more. There forms geometrical isomerism between planar –N = N– bond and which gets affected when exposed to UV radiation as its changes from trans (preferred) to cis. This method of dyeing cotton is not widespread due to the usage of chemicals with toxic nature [26–28].

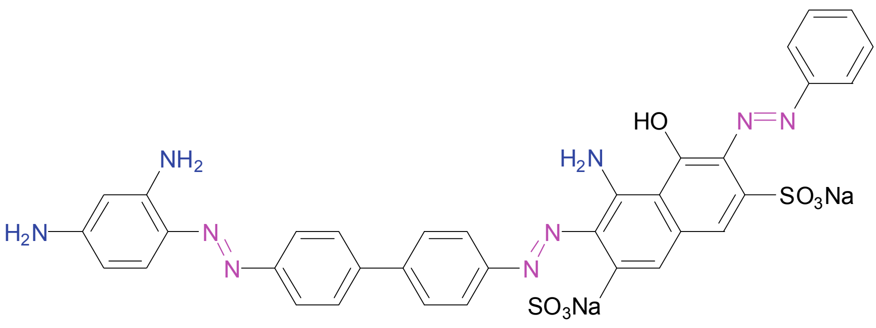

Fig. 14.6 Structure of CI direct black 38 azo dye [24]

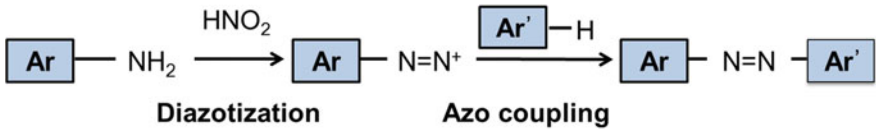

Fig. 14.7 Stable azo dye reaction [25]

14.3.4 Basic Dye

Basic dyes dissociate into cations and anions when dissolved in solution due to which it is known as basic group dyes. It consists of amino groups (primary amines, dialkyl amines, trialkyl amines, nitrogen-containing heterocyclic ring) and is usually aniline dyes, as shown in Fig. 14.8. In basic dye structure, there is less hydrophilic group present; hence it is insoluble in water. Colored cationic salts are produced by basic dye when made soluble in water, and these cationic salt react with anionic sites of the substrate [29]. The cellulosic fibers have no compatibility with basic dyes as the cotton structures do not show sufficient substantivity or affinity for dye. Suitable mordanting agents are used to make cellulosic fiber dye with basic dyes more compatible, as shown in Fig. 14.9. Dyeing of cotton with basic dyes is done after the

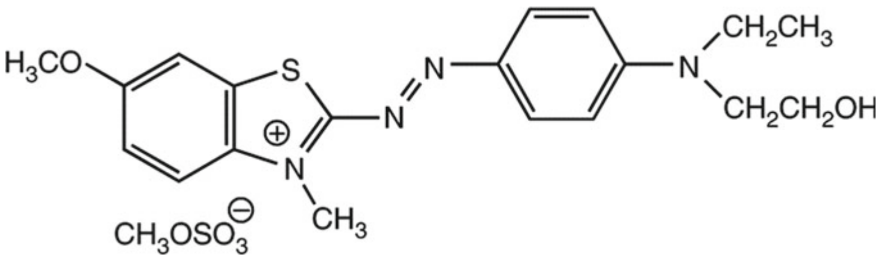

Fig. 14.8 Chemical structure of the CI basic blue 41 (astrazon blue FGGL 300) dye [32]

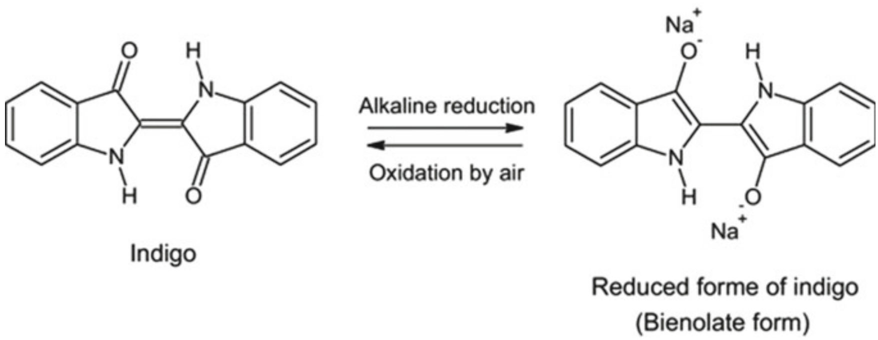

Fig. 14.9 Chemical structure and redox reaction of the indigo dye [34]

treatment of cotton fiber with tannic acid anions as it attracts the cations present in dye molecules and makes water-insoluble ionic complexes on the fiber. This method of dyeing is time-consuming and hazardous to the environment. In another method, polyacrylamide ($-CONH_2$) is used for pre-treatment of cotton, which increases the reactivity of cellulose substrate for basic dye [30, 31].

14.3.5 Indigo Dye

In ancient times Indigo dye was extracted from the plants, nowadays nearly all indigo dyes are produced synthetically, and most of them are used in textile/garment industries. It is a vital dyestuff with a unique shade of blue color, which is reduced to a soluble form by chemical reaction with suitable reducing agents like thiourea dioxide (thiox), sodium hydrosulfite, Zinc, or bacteria in the presence of alkali. After the reduction of indigo, it becomes water-soluble and has a high affinity for cellulosic fibers due to which it enters the open spaces of fiber. Dye molecule converts back to the insoluble mode when the dyed fibers are exposed to air due to oxidization. The dye molecules permanently color the fiber blue as dye particles get trapped inside the fiber by mechanical bond [33].

Dyeing of cotton with indigo dye can be done by an exhaust dyeing process where indigo can be converted into a water soluble leuco form with glucose used as a reducing agent. However, the case of Indigo dye with cotton is not famous as it generally does not yield appropriate results as far as color yielding and level dyeing are concerned. Hence for achieving a good dyeing quality, the affinity of cotton with indigo can be improved by enhancing to bienolate or leuco-indigo reduced form, as shown in Fig. 14.9. This is possible when a chemical modification through the cationization process is activated on cotton through a cationic agent. Dyeing with indigo dye can also be done by other various techniques such as one sheet dye slashing, Indigo double sheet dyeing, Loop dye (continuous dye slashing), Loop dye with dyemer [35]. The significant use of indigo is for the manufacturing of denim cloth.

14.3.6 Vat Dye

Vat dye is one of the oldest types of water-insoluble dye, which is most suitable for cotton or cellulosic fibers. They can be converted into a soluble form by the reduction process. Dyeing of cotton with vat dye includes mainly three steps as reduction, dyeing, oxidation, and soaping. In the reduction process, reducing agents like sodium hydrosulfide (Na-S-H) or caustic soda is used to the conversion of insoluble form to the soluble form of dye called leuco vat dye, after that leuco vat dye is applied on cotton during dyeing process as shown in Fig. 14.10. This class of dye has a high affinity to cotton fiber and gets highly absorbed inside the fiber structure. In

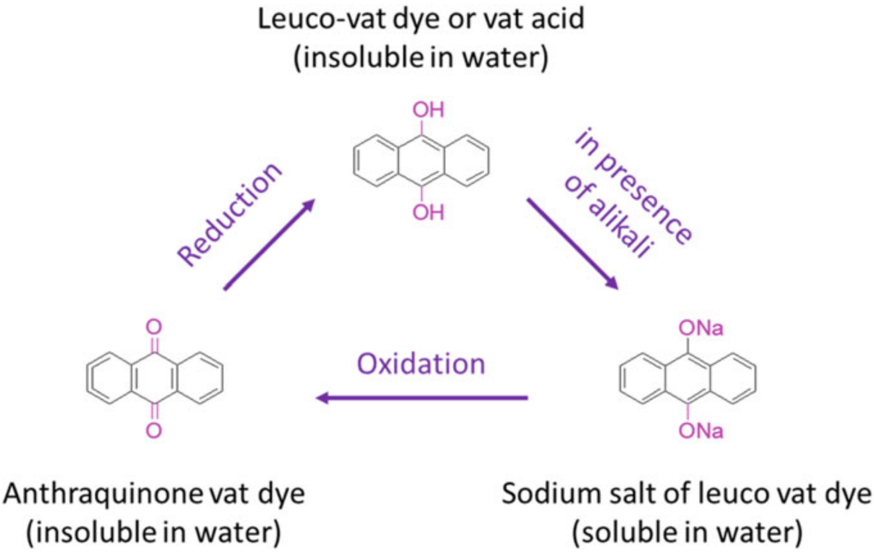

Fig. 14.10 Insoluble form to soluble form of dye [36]

the oxidation process, when dye penetrates fiber structure, this leuco dye is oxidized back to insoluble form on exposure to air. During this process, the dye molecules which are not soluble in the water sometimes traps inside the fiber structure. The vat dyes have excellent colorfastness properties on cotton fiber [36].

14.3.7 Direct Dye

Direct dyes are one of the most versatile dyes and are applied directly to the substrate in a neutral or alkaline bath. This type of dye can apply to cellulose, wool, silk, nylon fibers. Direct dyes are soluble in water and form colored anions that are directly applied to cellulose fibers. There is no need for mordant action for cotton. In the cotton dyeing process, aqueous solutions usually contain electrolytes such as NaCl or Na_2SO_4. These types of dyes are temperature sensitive and used mainly in exhaust dyeing. The dye molecules do not attach chemically with fiber structure but are mainly dependent upon dye to fiber associations like hydrogen-bonding and dipolar moment. The direct dyes on cotton fibers have poor to fairly good light fastness and low wash fastness [37, 38].

14.3.8 Natural Dyes

These dyes are derived from plants, minerals, or other natural sources like roots, berries, bark, leaves, wood, fungi, and lichens. Natural dyes are eco-friendly, and it is easily extracted. They are classified based on their chemical structures like Carotenoids, Xanthophylls, Flavonoids, Flavones and flavonols, Anthocyanidins, curcumin, and anthocyanins. The most common anthocyanidins structures are shown in Fig. 14.11. It can be used in the dyeing of cotton, wool, and silk [39–41].

14.4 Dyeing Process

As already discussed or the successful trading of textile products, the dyeing process plays a vital role. In the dyeing process, water is the medium in which dye is dissolved to form a dye solution, and water should be pure or clear to achieve good results. Alkali is mixed with the dye solution for enhancing the reaction between dye and fiber molecules. When the dye is applied to cotton, dye exhaustion from the dye bath to the surface of the fiber occurs, for conveying the dye molecules from the dye bath to the fiber. Proper heat must be supplied to the dye bath after this adsorption of dyestuff on the fiber surface occurs, and diffusion of dye is achieved. Leveled dyeing can be achieved by maintaining equilibrium between the dye in the solution and the dye inside the fiber. Finally, the fixation of dye occurs. [7, 12].

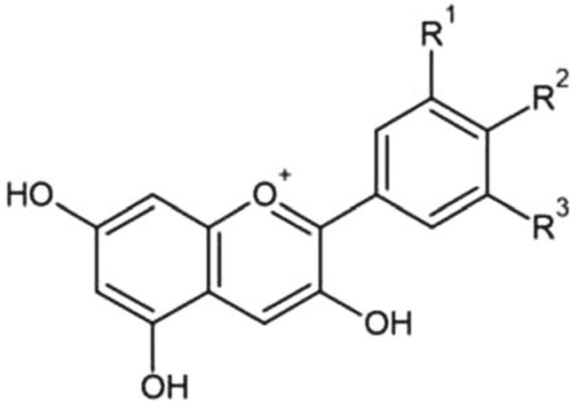

Fig. 14.11 General structure for an anthocyanidin and where R 1 = OH R 2 = OH R 3 = H [42]

14.5 Different Principles Involved in Dyeing

There are many different principles involved in dyeing based on their application. During the dyeing process, dyestuff and fiber have some kind of attachment, which may be physical or chemical due to affinity between them. The quantity of dye in the dye bath formulation can be used to obtain the actual color of the textile material. The depth of shade can be explained as the weight of dyed material in percentage. A specific dye is used for a particular fiber, and the same dye reacts differently with different fibers. Cotton has an affinity for direct, reactive and natural dyes. In contrast, other dyes like vat, azoic, indigo, basic and sulfur are water-insoluble dyes that require some process to convert them into water-soluble form Basic and sulfur dyes in insoluble form have no affinity for cotton [7, 10, 12].

14.6 Factors Influencing the Dyeing Process

The primary factors which affect the dyeing process are the type of fiber to be dyed, dye type, dye medium, type of salt, process time, temperature, pH, wetting agent, sequestering agent, leveling agent, etc. These all factors need proper optimization to achieve the desired shade on the material. The main task is to achieve a shade with good colorfastness. Other key factors are convenient blending with other dyes and chemicals, leveled dyeing features, dusting issues while processing powdered dyes, and environmental influences [7, 10, 12].

14.7 Preparation for Medium

In the dyeing process, water is the medium in which dye is dissolved to form a dye solution. The process is widely used for cotton yarn and its blend, which includes singeing, desizing, scouring, bleaching, mercerizing and cellulose enzyme treatments and all these processes except singeing require water baths. A low-quality water medium generates all types of hindrance during the preparatory or at the dyeing process. Water hardness is another influencing factor as a high proportion of calcium and magnesium present in the water plays an essential role in the cleaning process. Preparatory processes are key to superior quality, but this is often neglected. The purification or cleanliness of the water is essential for avoiding dyeing errors like unevenness, dye precipitation, dull shades, and harsh handling [7].

14.8 Preparation for the Dyeing Process

During dyeing, different types of chemicals are used, such as solubilizing agent, reduction agent, alkali, binding agent, wetting agent, antifoaming agent, anti-migrating agent, an electrolyte which aims to increase the attraction between the dye molecule and fiber. In this process, unwanted impurities like naturally occurring impurities that get added during yarn or fabric production are separated before dyeing. Dyeing is carried out in any of the forms like fiber, yarn, fabric, and garments, followed by the preparation process. Preparation is often carried out by bleaching of fabrics with hydrogen peroxide or chlorine-containing compounds aiming to separate its natural color and other alternate preparatory processes such as singeing or mercerization can also be other options for yarns or fabrics to make it suitable for dyeing. [7, 10, 12].

14.9 Cotton Fiber Dyeing Method

Fiber dyeing can be termed as a styling technique, and it is done before the fibers are spun. Fiber dyeing can be done by stock dyeing, which gives deep penetration of the dyestuff within the fiber structure. Cotton fibers are dyed in the stock form before they are spun into yarn form. During the yarn manufacturing process, these fibers are often blended with other fibers to get the desired shade. In stock, dyeing fibers are processed in loose form into large vats containing the dye bath. The fibers are placed in a perforated cylindrical basket (On the side) further the packed fibers are conveyed into a detachable fiber carrier, which is placed on a central spigot underneath the vessel. The dye solution is circulated by an external pump, which enables dye solution to circulate either from the bottom or on top of fibers, hence the mechanism is based on the liquor movement principle. Lubricants are added in final rinsing some to increase the flexibility. In this method, the chances of achieving uniform shade are more prominent. Fiber dyeing is the comparatively more expensive technique of all the methods [43, 44].

14.10 Yarn Dyeing Methods

Dyeing of yarn can be done either by a batch process or by a continuous process. Batch dyeing, as the name suggests, is done in different batches; this process consumes a large amount of water as materials are immersed in the dye solution for a longer time for molecular attachment. This process requires a different machine at different stages. In the continuous method, the material is dyed at one go, all the types of machinery are arranged in a sequence. This process is very fast, and a small amount of water is required. Afore said processes have been further mentioned as follows:

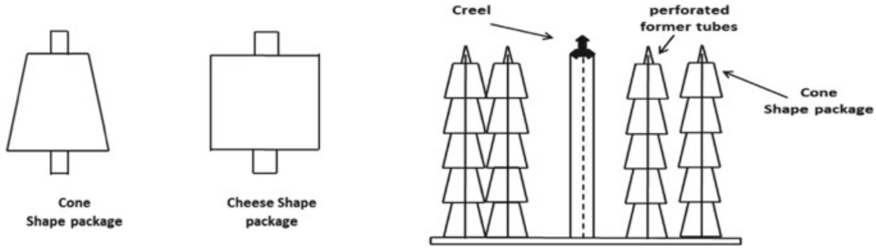

Fig. 14.12 Different type of packages

14.10.1 Batch Dyeing

In yarn dyeing, yarn is wound onto a different type of packages to carry out dyeing in different batches, as shown in Fig. 14.12. The package can be in the form of cheese, cone, or cake package having perforated form tubes. In this method, dye liquor is step by step, conveyed from liquor bath to the yarn for a comparatively longer time. In another technique, the package of yarn is inserted onto perforated spindles in vertical columns of packages. The packages may have a stocking over them to protect them, which acts as a filter during dyeing. The spindles in screwed into the holes at the base of the hollow, circular frame, which is connected to the pump.

14.10.2 Hank Dyeing

This is one of the costly methods. The hanks are processed in a loose form on the machine. The dye bath flows like a waterfall on the yarn loops, which enables the yarn to add up more bulk while dyeing. Hank dyeing is suitable for end applications such as sweaters and rugs. Generally, soft yarns are processed during the hank dyeing process.

14.10.3 Beam Dyeing Method

During beam dyeing number of yarns ranging from a hundred to thousand are wound on a solo beam having perforated slots. In the process, one beam is positioned over the dyeing pot, and the dye liquor follows an into out and out to in route. The yarns dyed on beams are often used for manufacturing striped woven fabrics. During this technique, a total warp beam is wound onto a perforated cylinder and positioned over the machine where the flow of the dye solution occurs alternately at the inner and outer area of the package [45, 46].

14.11 Continuous Dyeing Method

14.11.1 Rope Dyeing Method

Rope dyeing machine works on the principle of the form of rope. The ropes are fed into the machine through various guides and tension arrangements. The process results in even dyeing as the dye molecules are penetrated properly inside the yarn structure [47].

14.11.2 Slasher Dyeing Method

Slasher dyeing is also known as sheet dyeing. In this process, dyeing and sizing of yarn are accomplished in one process. To make warp yarns ready for weaving, they are processed in warp beams via several baths containing liquor solution one after the other. The dyeing is uneven and of low quality compared to the rope dyeing method.

14.12 Machinery Used for Dyeing

Different kind of types of machinery is employed for dyeing according to the material characteristics and their application area. The basic requirements of dyeing machinery are, it should provide sufficient liquor movement for uniform dyeing, heating throughout the liquor, and material of the machinery should not be affected by the dye or other chemicals. The materials used for the construction of machinery are chemical resistant stainless steel containing high quantities of chromium, nickel, tungsten, and a small amount of carbon.

14.12.1 Dyeing Machine for Loose Cotton Fiber and Sliver

The dyeing machine used for the dyeing of a loose form of raw cotton is shown in Fig. 14.13. In this machine, loose fiber is stationary, and the dye liquor is pumped/spray onto the packed fibers. The container in which loose fibers are placed has perforated walls that enable proper circulation of dye liquor from inside and outside of the material. In some of the other machines, the top plate is perforated, and the container wall is solid so that the liquor circulates vertically through the packed fibers. Fibers must behave equal access to the dye liquor to obtain leveled dyeing.

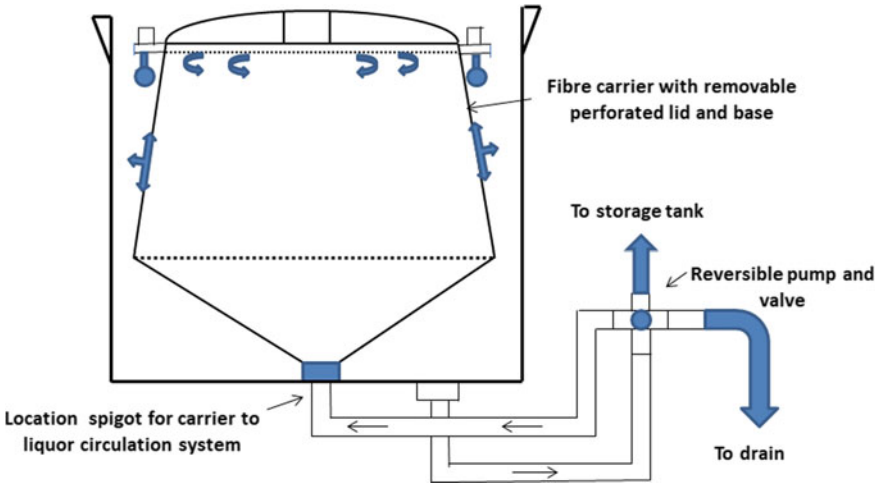

Fig. 14.13 Loose fiber dyeing machine

14.12.2 Machines for Dyeing Cotton Yarn

14.12.2.1 Hank Yarn Dyeing Machine

In this machine, the hanks of yarn, which are usually suspended by the poles, are fitted into a frame that is lowered into the dye bath in the dyeing machine, as shown in Fig. 14.14. The frame has a perforated top and bottom to allow liquor container dyes and chemicals to circulate either down through the hanks, or in the reverse direction. At the front of the machine, the impeller is placed in a compartment that circulates dye liquor, and it is separated from the hank frame. The steam and cooling pipes are

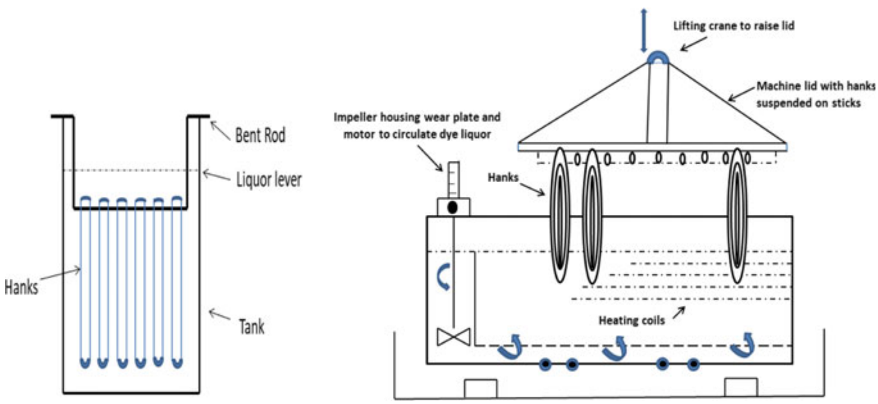

Fig. 14.14 Hank dyeing machine

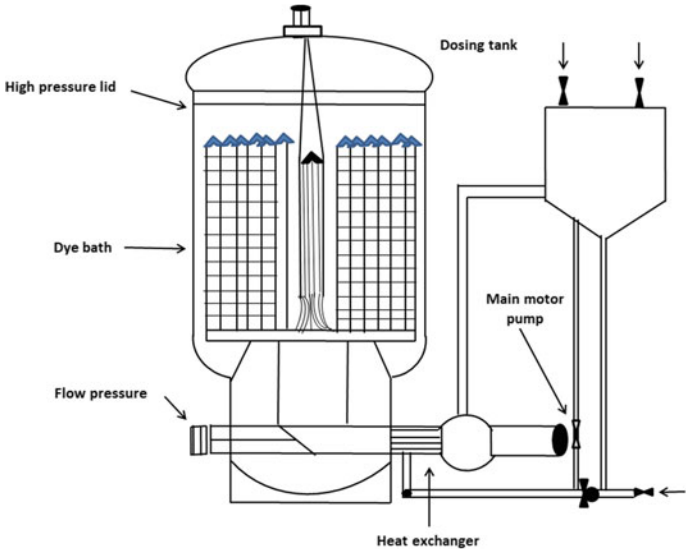

Fig. 14.15 Schematic diagram of package dyeing

placed beneath the compartment. Even packing of the skeins helps to achieve leveled dyeing by equal exposure of all the yarn to the dye liquor [48].

14.12.2.2 Package Dyeing Machine

Yarns are wound into various package forms (i.e., cheese or cone) for dyeing. The package dyeing machine consists of a vertical vessel that is closed, and their tubes are perforated. The yarn packages are arranged one above the other on these perforated tubes, as shown in Figs. 14.14. The dye liquor is circulated inside or outside of the tubes through a liquor pump, and the direction of the flow of the liquor can be reversed automatically from time to time [49, 50] (Fig. 14.15).

14.13 Conclusion

The above chapter provides a brief insight into the significance of the dyeing process. The theory of dyeing has been discussed considering various dye class and their application techniques over cotton fiber and yarns. Different dyeing machines, their features, and mechanisms have also been discussed. From the detailed study of various dyes and their treatment with cotton, it can be summarized that due to structural compatibility with cotton, the reactive dye class is best suited for dyeing of cotton material as far as quality and economic aspects are concerned.

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Chapter 15
Cotton Based Clothing

Haleema Khanzada, Muhammad Qamar Khan, and Saleha Kayani

Abstract Cellulose is a natural polymer and is being used in various textile applications due to its sustainable nature (as compared to synthetic polymers). Cotton is also a cellulose-based polymer, and almost 70% of cotton is converted into apparel and more than third into home textiles and remainder into industrial products. The share of cotton in retail apparel and home furnishings market has grown from a historic low of 34% in the early 1970s to more than 60% today. Cotton is being used for almost every type of apparel, from jackets and coats to foundation garments. Its apparel usage is mostly is for men and boys' clothing. 70% of cotton-based products constitute shirts, pants, and jeans. For home textiles, cotton-based products range from bedspreads to window shades. Cotton based products are dominative in the apparel industry due to its low price, comfort, and mechanical properties. As clothing comfort is the most crucial attribute of any textile material, it absorbs moisture and is breathable, which makes it's a perfect material for apparel. As cotton is a natural polymer, so it is less toxic and hypoallergenic and is used in undergarments to decrease the chances of infections and other health risks. Market trends are suggesting. Organic clothing will gain more popularity in the future.

Keywords Hypoallergenic · Air permeability · Thermal comfort · Softness

15.1 Introduction

Cotton is natural fiber supplying the global demand for the clothing industry [1]. The world uses cotton fiber more than other natural fiber [2]. It is mostly grown and used to manufacture apparel. According to a market survey, the world-wise consumption of cotton fiber in clothing material is 48%. The United States is the largest producer and exporter of raw cotton [1, 2]. Due to the increase in natural fiber demand, cotton is contributing significantly to the growth of the textile market. In Pakistan, cotton

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has a significant contribution to our economy. Worldwide, Pakistan is the 3rd largest consumer and fourth-largest producer of cotton [3]. Cotton fiber is known as the "king" of fibers because it is used in most of the world's apparel as it combines the physical and chemical characteristics that make it desirable in use [2].

Cotton is plant fiber and covered in a case that surrounds the seeds. Its other parts are used for other purposes, such as the production of food, plastics, and paper products and could be woven [4, 5]. Cotton based cloths/Apparel can control moisture and insulate because of natural fiber. It is hypoallergenic, weatherproof. Cotton based cloths are not only soft but comfortable and durable, too [6]. It is easy and straightforward to maintain cotton cloths. Cotton made garments/apparels were already in fashion, even thousands of years ago. Cotton clothing does not contain any synthetic compound as it is chemically organic [7]. The natural properties of cotton offer unparalleled comfort to textile and apparel consumers. Many consumer groups indicate that physical and psychological comfort is associate with cotton. 75% of summer wear items for women contain cotton fiber. Cotton fabric has good breathability than synthetics fabric, so it is ideal for wearing cotton-based clothes when you are working out. Cotton is a cellulose-based natural polymer, and fabrics made from them are made breathable with allows the air to circulate and discourages the formation of fungi in the dark and moist environment. Fabrics made from synthetic filament yarns do not have interfibrous spaces, so their moisture absorbency is poor as compared to the natural fiber polymers. There are numerous techniques to enhance the raw cloth and make it more attractive and useful in the final garment [8].

The procedure initiates with the last phase of refinement and purification. The first step is singeing, in which the greige fabric is exposed to heat so that surface fibers can be burned off and lead to the soft and smoother cloth. Then the second is desizing; usually, the greige fabric has an enormous size. Certain enzymes and acid washes are utilized to bring those greige fabrics in to reasonable and manageable size. This is followed by scouring in which chemical washes purify the greige fabric, so any plant wax or left out seed fragments can be eliminated. Sometimes, bleaching is also carried out to eradicate colors from fabric and to attain white color, and bleach is applied. Finally, the mercerization: alkaline soda is applied to the fabric to form dazzling, softer, and swell up clothes [9]. There are two famous procedures for tinting fabrics. One is dyeing, and the other one is printing. Cotton fabric usually grabs colors very quickly and readily. So, it is quite more comfortable to add to a wide range of colors to the cotton fabrics [10].

15.2 Classification of Cotton-Based Clothing

Apparel products may be classified in several ways based on wearing, fit, material, and function. Figure 15.1 shows there are types of apparel that exist based on their utilization, and they may be classified into three classes.

Fig. 15.1 Classification of cotton-based apparel clothing

The cloths covering the upper parts of the body are called tops (top-wear), such as a jacket, coat, and shirts, whereas the clothes which are employed to cover the lower portion of the body are known as bottoms. The few examples of bottoms (bottom wear) could be shorts, trousers, or pants. The third category is of Undergarments, garments which people wear beneath apparent outer clothes, generally very next to the skin. All mentioned categories have numerous purposes and are employed for various body parts. The purpose of brassieres and underwear to give support to specific parts of the body. Vests are used, usually, in warm seasons to absorb sweat and to protect the outer dress from sweating [11].

Worldwide, the apparel industry can be divided into 14 products subsectors; dresses and shirts, trousers, sweaters, sweatshirts, knit shirts, woven shirts, coats, pajamas and underwear's, suits and formal wear, accessories, hosiery and socks; bras; and baby apparel, miscellaneous apparel.

15.3 Market Share of Cotton-Based Apparel

The apparel manufacturing accounts for all the clothing except leather, footwear, and other technical textiles product. The market size is estimated based on the value of domestic production plus exports and imports, all valued at manufacturing rates. The Global apparel manufacturing market is forecasted to reach $992 billion in value in 2021, an increase of 26.2% (from $785.9 billion) since 2016. The Asia–Pacific region accounted for 61% of the market value in 2016, and Europe accounted for a further 15.2% of the market.

The textile is one of the well-established industries in a competitive marketplace. Many countries are chasing textile and apparel exports for benefits such as boost local, federal economy, enhanced domestic competitiveness, and state economy to gain global market share, it can be shown statically in below Fig. 15.2 [12].

After agriculture, the Textile manufacturing holds its prominent share in Pakistan's GDP; and almost half of its exports are based on textile products. Pakistan is the 8th largest textile exporter concerning its competitors in Asia [13] (Fig. 15.3).

Production of readymade garments s also represents progress towards higher value addition in textiles chain. Textile and clothing have an outstanding market in the entire world, and it has been rising even more, day by day. In recent times it has been observed that China has dominated the market. However, the world market share of

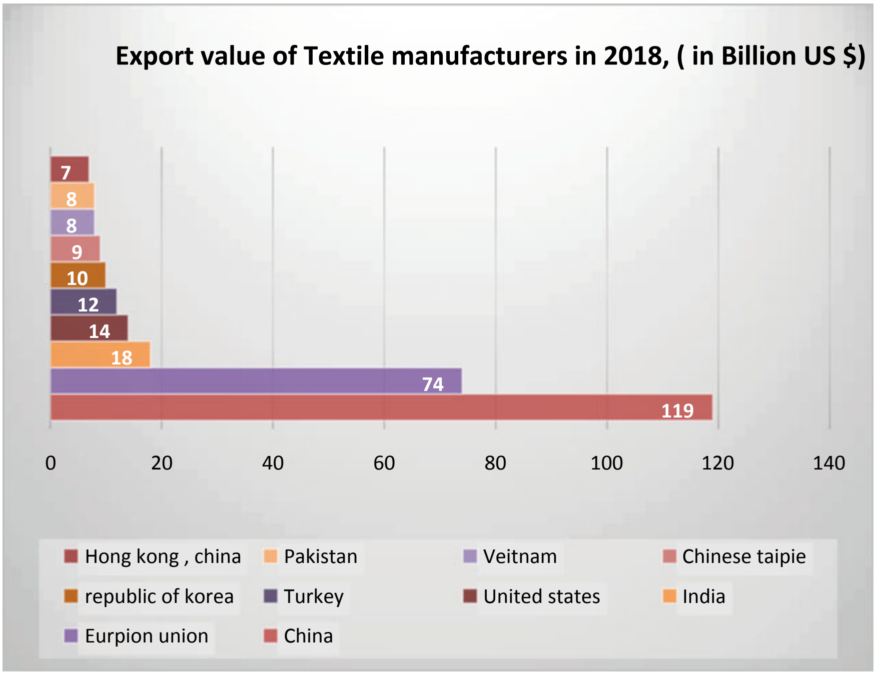

Fig. 15.2 The worldwide textile exporter 2018 [12]

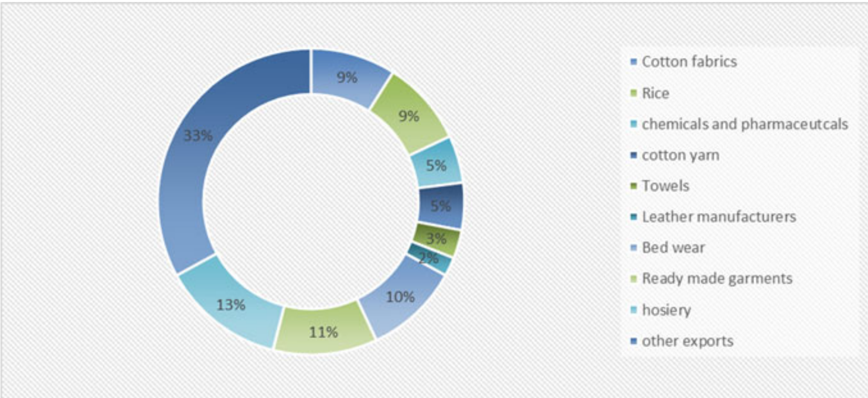

Fig. 15.3 Pakistan textile export (*Source* Pakistan trade)

the European Union is also significant. The demand for home furnishing applications and clothing has also risen; as a result, the market share of cotton is continuously found to be more than 50% [12].

Table 15.1 Worldwide export of apparel products

Product category	Value ($, billions)		World share (%)	CAGR %
	2014	2016	2016	2006–16
Total	402	377		2.6
Trousers	78	76	20	2.5
Coats	37	35	9	5.1
Sweat shirts	55	50	13	1.2
Knit shirts	52	49	13	2.3
Woven shirts	31	29	8	2.7
Under wears	21	20	5	1.5
Misc. Apparel	16	15	4	5.4
Bras	11	11	3	2.9
baby clothing	10	10	3	2.1
Dresses/skirts	29	27	7	5.2
Suits	20	17	5	−1.3

Source US (Comtrade 2006–2016)

Table 15.1 shows that Trousers have generally been the largest export category, with a 20% share of the world market in 2016. About 13% share of sweater and sweatshirts. Sweaters and sweatshirts were the second-largest at 13%. Dresses/skirts, coats, and miscellaneous apparel are all important growth areas for global markets, with growth rates of more than 5% in the period from 2006 to 2016 [5]. Table 15.2 shows the Pakistan export of apparel. The export share of Pakistan indicates that

Table 15.2 Pakistan export of apparel products source

Product category	Value ($, billions)		Pakistan share (%)		CAGR %
	2014	2016	2014	2016	2006–16
Total	5.4	5.7			6.3
Trousers	2.5	2.9	46	50	2.5
Coats	0.2	0.2	4	4	4.3
Sweat shirts	0.6	0.6	11	11	1.2
Knit shirts	0.6	0.6	11	10	2.3
Woven shirts	0.1	0	1	1	−0.9
Under wears	0.2	0.2	4	3	−0.2
Misc. Apparel	0.1	0.1	1	1	10.5
Bras	0	0	1	1	18.1
baby clothing	0.1	0.1	1	1	9.8
Dresses/skirts	0	0	1	1	0
Suits	0.1	0.1	2	3	6.3

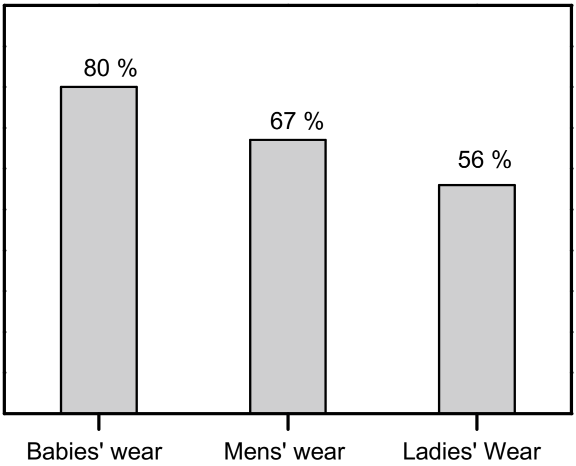

Fig. 15.4 Cotton-based clothing market share, according to US imports [14]

there is no significant improvement over the past years. Pakistani products are rising slowly as compared to their competitors. Pakistan, some products such as Men and boys clothing made by cotton fabrics, have a high annual growth rate than other world's top exporters.

It has witnessed that almost 54% of entire articles of apparel are represented by cotton, and, in 2015, the US market imported nearly 56% of home furnishings. In the clothing market, cotton competitiveness fluctuates with product divisions and end-user groups. In 2015 cotton served a demand for baby clothing more than 80%, whereas the demand for men and boy clothing was 67% (refer, Fig. 15.4) [14].

Cotton fabric enjoys the position of dominance in the segment of baby apparel. It is used and loved by consumers. They prefer and trust cotton, especially when buying baby wears. Whereas if one looks at women's clothing, the cotton industry faces a real challenge in this segment. Women's clothing segment is considered to be one of the most complicated segments because, in this category, there are numerous options available for consumers. Moreover, there is a vast range of fashion trends, and Women tend to change their taste and always look for "something new" or "what's in the market", and this is a solid challenge. Contrarily in the category of Men and boys clothing, the cotton industry has a better position. Cotton enjoys an outstanding market share in clothing categories such as tops, bottoms, underwear, and nightwear. According to market statistics, already mentioned above, it has been witnessed that the Cotton sector strives its level best to provide conventional textiles, keeping complete focus over end-users' protection and comfort. The selection of clothing depends on many factors, such as any specific application, personal desires [15]. People's preferences may also be dynamic with the environment, age, season, and type of activity. Fabric material used for human clothing must meet many requirements, depending on nature garments nature, purpose, climate, and many conditions under which it is worn. Fabric requirements for clothing can be categorized into four, i.e., aesthetic, drape, handle, and luster [16].

15.4 Comfort Properties of Cotton-Based Clothing

Comfort is the most important attribute of clothing; the factors affecting the comfort properties of cotton fabrics are illustrated in Fig. 15.5. As comfort is a subjective aspect of a wearer towards textiles, so it is entirely a perception in the mind of wearer individually; and thus, resist objective and quantified analysis. The definition of clothing comfort varies from person to person, day to day, and moment to moment [17].

Wick ability is most important as it factor as it indicates the amount of perspiration absorbed by the cloths. Wick ability is closely related to the air permeability (AP). There are two aspects of clothing comfort, i.e., sensorial and non-sensorial. Sensorial properties such as fabric handle, compression properties, electro-physical properties, and frictional properties define the comfort of fabric towards the wearer skin [18]. Non-sensorial comfort is comprised of air permeability, water repellency, and water resistance; other than these, the thermal and moisture transmission properties are also included in non-sensorial comfort properties.

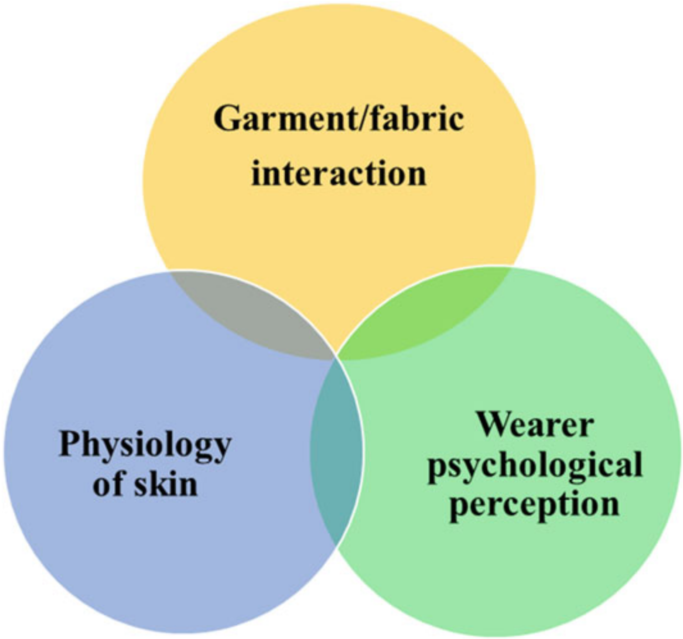

Fig. 15.5 Factors affecting the comfort properties of cotton fabrics

15.4.1 Softness

Fabric softness is the most important term used in describing clothing comfort. It can be related to fabric softness and fabric flexibility. Cotton is mostly used in clothing for its softness. It can stay soft over time; this makes it ideal for fabric for clothing from t-shirts to underwear [19].

15.4.2 Drapability

Fabric fall ness under r its gravity is known as a drape. In clothing, drape has enough importance as some fabrics like dresses, skirts, trousers, business suits; clothes are required for a good drapability. Drapability can be related to fibers' stiffness, yarn twist, fabric density, and organizational structure [20].

Strong friction between garment and skin results in more displacement of the skin during movements of the body leads to more discomfort. When polyester fabric used in clothing, it produces friction with the human skin and produces some sort of frictional sound, which may be the reason of feeling discomfort. In the case of abrasion, cotton does not produce any charge, whereas polyester generates a negative charge, which makes some sort of discomfort to the wearer. At the same time, cotton is soft and smooth fabric regarding this aspect. Besides, synthetic and manmade fabrics have the chance of any type of skin allergies like an itchy, tickling, rash, and harsh feeling, where cotton is less harmful from this point of view due to its hypoallergenic nature [19].

Fabric aesthetics also contributes to psychological comfort to the wearer. In the case of cotton, it has a much softer hand feel than polyester. Polyester fabric also gives a rough and tough noise if it is friction with different body parts.

Cotton is the most widely raw material used in the apparel industry. It has great condensation transmission capability; that is why it is getting well known gradually and attaining a great amount of admiration. The fabric of cotton is constituted of 94% of cellulose due to this; it is known as cellulose-based fiber. Cellulose is a characteristically occurring polymer, and cotton is formed of pure cellulose [18].

15.4.3 Thermal Comfort

Thermal comfort is a mental state that depicts a person feels relaxed and contentment with Thermal environment. Usually, in substantial activities, a human can release approximately 1200 ml perspiration/h. It is known that cotton has a moisture regain of 8.5%, and contrary to this, polyester fiber's moisture regain is only 0.4%. If one examines the cross-section of cotton fiber, it appears to be bean-shaped; and it contains almost 70% crystalline and 30% amorphous regions. The cotton fiber comprises of infinite polar-OH groups in its polymer chains that attract molecules of waters and thus absorbs water; these make cotton a very absorbent fiber. Whereas the considerable part of polyester has hydrophobic nature, which means it repels water, and it rarely permits or grants moisture over the fabric. In summers, most of the time, perspiration is experienced by almost everybody, and it brings an entirely unwanted feeling when sweats spots start appearing over a person's garments. In this situation, if the fiber lacks the capability of moisture regains then, it can be turned into even worst feeling. Cotton fabric can absorb sweat; that is why everybody loves it; people prefer and prioritize cotton fabric, especially in summers. People do not prefer polyester fabrics because they rarely can absorb sweat, and wearing polyester fabric brings a lot of unpleasantness and uneasiness [16].

15.4.4 Thermal Conductivity

Thermal conductivity gauges the ability of a material to conduct heat. The structure or arrangement of cellulose fibers, even it is natural or recreated, is wholly in charge of their thermal conductivity. The contact and space between the skin and the inner clothing layer make a microclimate region, and it determines the subjective perception of clothing comfort, especially at high skin humidity. Thermal resistance is the heat property that gauges the ability of material to repel heat. It is a prevention that a surface resists to heat flow. It is precisely reciprocal of thermal conductivity; both are essential parameters and are significantly influenced by fabric construction and raw material used [21]. For summer clothing, the rapid heat transfer is of importance to heat dissipation. Cloths with better moisture management, high thermal conductivity, open texture structure, and absorption to enhance the convection are highly desired. Cotton is majorly used in textile material in summer clothing due to its softness, moisture-absorptive features, although cotton has low thermal conductivity (0.026–0.065 wm/K), which limits its effective heat transfer [22].

15.4.5 Moisture Vapor Transmission

Moisture vapor transmission gauges the frequency of water vapor's motion over a fabric. It has the utmost significance in determining the ease because it has a substantial impact on human perception and feeling of cool/warmth [23]. As mentioned earlier, cotton is an excellent absorbent fiber due to the reason because it has strong hygroscopic nature, or in other words, it can be said that cotton is good hydrophilic fiber. In contrast, polyester has a hydrophobic nature that means it repels water on its surface. Moisture vapor transmission has a significant impact on the nature of the fiber. Cotton appeals moist vapor and later starts shifting away from the vapors through clothes because it is hydrophilic fiber. In cotton fabric, it is quite easier to move vapors through the holes of fabrics, but in the case of Polyester fabric, it is difficult because polyester does not grant moisture vapors on its surface due to its hydrophobic nature. A piece of fabric is called breathable if it permits water vapors transmission at quicker frequency. It can be said that a fabric's comfort and ease depend on how much it is breathable. The higher a fabric breath, the greater is its ease. In short, it can be said that cotton is much better fabric because it is breathable, and that is why it is most widely admired and used in the apparel clothing industry than polyester [24].

15.4.6 Air Permeability

Measurement of the textile material's ability to permit airflow through it. The rate of air volume flowing through fabric [25]. The microscopic view of cotton looks like collapsed and twisted tubes, or in other terms, it seems twisted ribbon. This structural property of cotton is known as convolutions. The cross-section shape of cotton is oval, and for this reason, the connection between cotton cloth and skin is higher. 100% cotton is highly preferable to use in the summer season clothing due to its air permeability. Fabric porosity and air permeability are interlinked and, in many factors.

Air permeability and porous fabric structure are linked and indicate breathability, which makes significant differences in the performance of materials. Air permeability depends upon many other factors of textile clothing, e.g., weaving structure of the fabric, chemically finishes on it, fabric cover factor, fabric, and GSM. The moisture regains of the fiber has a significant effect on the air permeability. 100% of cotton-based clothes have higher air permeability and higher thermal resistance values compared with synthetic blended fabrics [26].

15.5 The Durability of Cotton-Based Clothing

Cotton is famous for its durability. It has a high tensile strength, which makes it strong [27]. It is stronger in wet form. Cotton based apparel can withstand strong and hot washings. The durability of textiles is more important to be sold as apparel. If any textile product/apparel falls apart after a single use, it will be useless to the customer. Durability is a must for textile clothing. For sports apparel, durability is even important than conventional apparel items. Sports apparel is exposed to extreme wear and tear by consumers. Cotton has the only disadvantage that cotton always needs ironing. But technology and techniques have been developed. This makes easy care and able to skip ironing the 100% cotton-based cloths [18].

15.6 Value-Added Product

Nonwoven materials are gradually becoming part of our daily life. Nonwovens were once seen by the cotton industry, just as a process to reuse the cotton waste in the shape of nonwoven products. For example, the resin-bonded short cotton waste was used to manufacture the industrial wipes. Hygiene and next to skin nonwoven applications are usually made of cotton fibers as they have the good softness and absorbance properties. Bleached cotton is utilized in the wipes, hygiene, and health product category. In the medical sector, cotton is used in surgical clothing, gowns, bed sheets, pillowcase, and surgical hosiery. Its use in the medical sector is due to its mechanical and physical properties, as well as due to its biocompatible nature [28].

However, even considering these applications, cotton's market share is minute and does not exceed a few percentage points. Cotton fabric can be multi factional (anti-bacterial, flame retardant, UV resistant) textile by application of advanced material and chemical finishes on its surface [29].

15.6.1 Cotton and High-Performance Fibers Blends

Cotton serviceability and affordability can be improved by Nomex blending with cotton. By blending, not only cost reduces, but the comfort properties of resultant fabric also improve. Cotton is a highly flammable fiber. Cotton/Nomex blended fabrics, more than 20% of cotton content is not self-extinguishable [30]. The blending of cotton with Kevlar can improve fabric strength. Kevlar supports cotton at any extension-to-break. According to researchers, 85% cotton with 15% Kevlar fabric shows better strength than 50/50 poly-cotton blend. Cotton Kevlar blended fabrics have slightly improved in abrasion resistance and flex resistance as compared to 100% cotton fabrics [31]. Cotton Kevlar blend produces uniform yarn because the elongation of both fibers is similar, so the resultant yarn is drawn with less drafting tension deferential.

15.6.2 Cotton/Jute Blend

Fibers produced by chemical synthesis have nondegradability. Nowadays, textile technologist has been working on biodegradable materials. Mostly natural fibers are bridgeable and have wearable properties. Jute is a natural fiber that possesses high strength, Fiber length, and tenacity. It can retain heat that can be enhanced by the chemical treatment, which makes it suitable for winter clothing. Its main limitation is fiber brittleness, which produces high haired yarn in the result of spinning and has a harsh feel. Jute can be blended with cotton to produce winter clothing; a certain amount of jute with cotton can be spun [32].

15.6.3 Cotton Blends with Other Technical Fibers

Fibers' blend ratios are significantly impacted by the parameters of water vapor permeability and air permeability thermal resistance. The comfort of textile clothing can be improved 12 times by blending cotton with polyester and other regenerated fibers by permitting more wicking action.

Cotton and polyester blend mostly used in the production of sportswear. Moisture management in sportswear concerns a lot nowadays. The cotton/polyester blended apparel are long-lasting, less shrink than 100% cotton, more wrinkle resistant. Workwear clothing is one more well-known area where blended cotton fabrics are customarily used. Poly/cotton blends are durable and yet still comfortable, have easy-care properties, dye consistently, and stronger to stand up with high-temperature laundering. Such type of fabric has superior performance characteristics than fabrics made up of 100% cotton [33]. With increasing demand, there is a need to look at substitutes for the traditional fabrics instead of cotton and polyester blended fabric that are used today. Flax is an attractive candidate as a substitute. Flax is a sustainable crop resource that has numerous required performance and comfort characteristics. The blend of cotton with flax absorbs and transport moisture away from the wearer body. Flax is 2–3 times stronger than the cotton, so it allows durable clothing and retains skin cool by enhancing moisture wicking. Wearing 100% cotton clothing during physical exercise can make skin feel sweaty; meanwhile, it does not dry quickly. The addition of flax to the blend allows for better moisture management with high air permeability, which allows the fabric to dry more [8].

15.7 Conclusion

Since the last two hundred years, cotton has been dominating and ruling the entire worldwide market of textile fiber due to the reason that it comprises distinctive qualities which form cotton as the most desirable raw material. It was and is loved, preferred, and admired by processors. Moreover, it is also considered as the most used trustworthy fabric in the views of customers. According to customers, it is the most comfortable, perfect option in every wear from work to play. It has versatile applications; it can be knitted, woven into distinctive fabrics. It is admired by customers, especially in the section of babywear and undergarments clothing. If one talks about other applications of Cotton fabric, it has been used in categories such as Tops (t-shirts or dress shirts) due to its anti-allergenic characteristics.

Moreover, it is used in denim and cotton jeans as well. Denim is a by-product of cotton; it differs from cotton made products just because of the distinctive weaving and finishing technique. Consequently, cotton is continuously flourishing in the worldwide market of textile fibers. Cotton has an enormous scope, and its use shall be increased, especially in unconventional markets such as the nonwoven sector as well. However, continuous research is needed so that new opportunities can be discovered, and cotton can serve as best in the textile sector.

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Chapter 16
Biomedical Application of Cotton and Its Derivatives

Mina Shahriari Khalaji and Ishaq Lugoloobi

Abstract Cotton and its derivate are widely studied and used as a medical and biomedical product in the "Health care textile" aria. The cotton-based materials have been used in external (surgical clothing, surgical covers, and beddings) and internal (traditional and advanced wound dressing, tissue engineering, drug delivery, surgical area, and dental applications) application. For the use in the internal application, the biomaterials have to pass many in vitro and in vivo tests due to the final application. Cotton is used to cover the wound as a barrier for bacterial penetrate and keep the wound aria warm since 19 century. Due to different medical demands, the modification of cotton has been developed to meet the diverse requirements with different biomaterial applications. The cotton has unique properties such as high surface area, favorable mechanical property, gas permeability, cellulose fibers, etc. which makes it a good candidate for use in medical and biomedical applications. Nowadays, due to innovations, novel and ultra-modern biomaterials are available. The researchers are developing new functional cotton base biomaterials at an incredible rate. The health care textile aims to bring comfort and better treatment for patients in their painful days. The huge study has been physically and chemically modified the structure of cotton gauze. Chemical modifications such as etherification, oxidation, and phosphorylation of cotton gauze have been studied to develop wound dressing for different kinds of wounds. Cotton has the capability to deliver the drug in the wound area, which can be stimulation responsive or non-stimulation responsive. In the surgical application, the cotton is used as surgical sutures and cotton rolls. It has been widely used in tissue engineering and dental application also. This study aims to summarize the development of the biomedical use of cotton and its derivatives.

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Keywords Cotton · Wound dressing · Tissue engendering · Drug delivery · Biomaterials

16.1 Introduction

"Health care textile" is any textile material and products that offer a medical or biomedical advantage. Cotton and other naturally produced fibers, for instance, silk, hemp, and flax widely used as health care textiles. Most of the hospital textiles are made of cotton and their derivatives [1]. Cotton in the medical and biomedical applications can be divided into two categories: Internal applications such as wound dressings, drug delivery, surgical applications, dental application, and tissue engineering, external applications like surgical clothing (gowns, masks, uniforms, caps, etc.), surgical covers (covers, drapes, etc.), and beddings (pillowcases, blankets, sheets, and so on) [2]. As presented in Fig. 16.1, the researchers have shown increasing interest in wound dressing and dental application of cotton and its derivatives over the last couple of decades, while the use of cotton and its derivatives in tissue engineering application and drug delivery systems is a new concept. To be used as an internal biomaterial, the composite has to achieve the utmost standard properties and must pass many in vitro and in vivo evaluation (Fig. 16.2) [3]. The word "biomaterials"

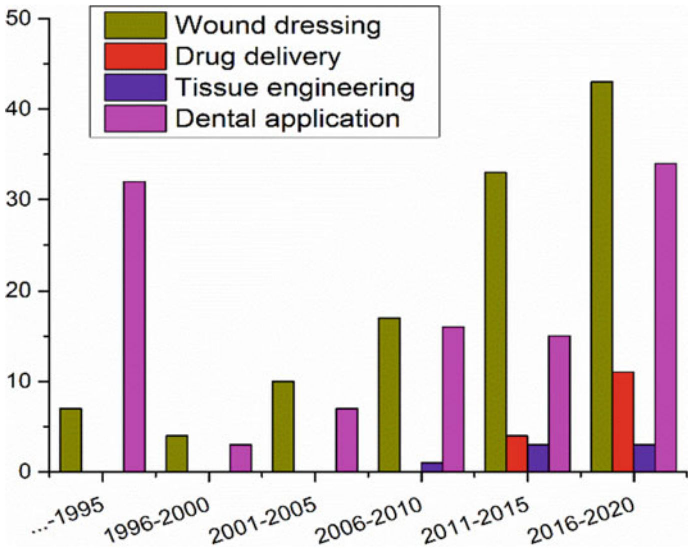

Fig. 16.1 Bar-chart of the number of the published articles in cotton-based biomaterials vs. year of publication in a 5-years' time-frame. Web-of-science was used as a reference website for literature search, with keywords such as "cotton," "wound dressing," "drug delivery," "tissue engineering," and "dental."

is a combination of the "bio" (everything alive) and "materials" (including chemical or components with unique properties that can be used as functional products). Biomaterials can be defined merely as natural or human-made (synthetic) materials that replace the function of body tissues or organs, in other words, the biomaterial is a composite that comprises all (or part) of a biomedical device or living structure [4]. "Biomaterial" word is used in the mid-twentieth century, but biomaterials products have been used much earlier [5]. It had been reported in 3000 BC Egyptian doctors used linen sutures to treat the wounds, and it was the first use of biomaterials in medicine [6]. So, biomaterials are mostly developed, used, and improved for medical applications. A few decades ago, only traditional cotton base biomaterials were available, but nowadays, due to innovations, novel and ultra-modern biomaterials with different functions are available. The researchers are developing new functional cotton base biomaterials at an incredible rate. Many biomaterials products are made from polymer fiber components and their modified structures. Developments of all biomedical textiles aimed to increase the comfort to patients and end-users during the painful days [7]. For successful synthesize of health care biomaterial products, the vital requirements are non-toxicity, non-carcinogenesis, non-allergenic response, strength, mechanical properties, durability, elasticity, and biocompatibility [8–10]. The natural fibers same as cotton can be improved significantly in their properties by the use of chemical and other advanced modification by different methods of processing to overcome their drawbacks and production new and functional biomaterials for clinical use. This chapter provides the latest information on the main properties of biomedical use of cotton and its derivatives for internal application.

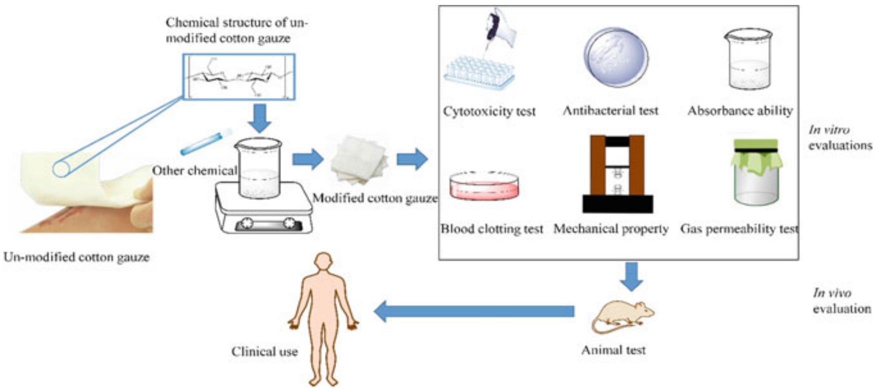

Fig. 16.2 Schematic illustration representing the modification and evaluation of cotton gauze-based biomaterials *in vitro* and *in vivo*

16.2 Wound Dressing

The human and animal external body layer is skin, which is the largest (around 15% of body weight) organ of the body [11]. Skin is a complex organ that has vital functions for human and animal physiology and homeostasis [12, 13]. It shows a variety of applications such as: protecting against environmental damage and preventing a microbial attack to the underlying muscles, nerve, bones, and internal organs from diverse sources [14], preventing water loss [15], and balance the body temperature [13]. It is the largest sensory organ, which can profoundly sense the light, touch, and deformation [16], and skin is taking part in the early stage of vitamin D3 synthesis [17]. Any unfavorable change in skin structure, same as wounds, cuts, burns, and surgical ulcers, are capable of letting germy enter the body and begin to multiply. The result depends on the pathogenicity of the bacteria, and the host's immune system can be a pain, chronic wounds, infections, deep tissue inflammation, cellulitis, tenderness, abscess, deep tissue and bone infections, blood poisoning, and even death [18]. To prevent bleeding, avoid bacterial access to the wounds, and help the skin to recover the use of dressing material is necessary. Cotton had been widely used for different types of injuries since the 19th century as cotton gauze. The thin layer of fiber was made of cellulose fiber and occupied from years ago, but however nowadays still the cotton gauze has its prevail position for managing the surgical wound, chronic wound, burns and diabetic ulcer etc. [19]. Researchers are developing a different derivative of cotton with different properties to help patients to overcome their painful days. To be used as a functional medical wound dressing, a dressing material depend on the wound type must possess four essential properties:

(1) Protect the wound from infection in advance dressing material even providing antibacterial activity
(2) Keep the environment of wound moisturized and absorb exudates while providing gas permeability
(3) Acceptable mechanical characteristics
(4) Easy applicability and removal from the wound (non-adherence) [20].

Cotton is impressively used as a wound dressing materials due to its favorable property, such as reasonable gas permeability, highly water absorbent, and quickly absorb the wound fluid such as blood, plasma, and other exudates in wound area. Highly exudates absorption is an essential approach in chronic and burns wound because most of these wounds are highly exudative, and healing requires frequent dressing changes [21]. However, cotton gauze has few disadvantages, for example, it is unable to protect the wound against infection and contamination (antibacterial activity), and it sticks to the wound site. While removing, it will damage tissue and will create the second injury. These drawbacks can be overcome easily by using a chemical or physical modification of cotton gauze. Other advantages can be achieved by modification of cotton structure such as increase healing rate, antibacterial activity, non-adherence property, good degradability, and cost-effective synthesis process, which makes functional dressings for different wound requirements. Nowadays, the research base on wound dressing modification is a hot topic in medical and biomedical research and innovations made by researchers are developing much different dressing with different properties under the title of advance wound [22].

16.2.1 The Traditional Cotton-Based Wound Dressing

Cotton gauze is one of the widely used traditional wound dressing products, which consider as a dry wound dressing. A cotton gauze dressing is applicable in wound area as a primary or secondary dressing that protects the open wounds from bacterial attack (barrier) and keeping the wound warm [23]. Some sterile cotton gauze due to their fiber structure is used as a dry dressing to absorb the exudates in wound aria such as fluid, plasma, and blood in the wound area. In the wounds contain more exudates, the dressing must changes frequently because the absorbed fluid causes saturated dressing and damage the healthy tissues through maceration. Due to the rapid saturation of cotton gauze, it is not efficient and cost-effective, and another drawback is its tendency to adherent to the wound area, which makes the second injury while removing the cotton dressing [24].

It had been reported that the healing process in the presence of wet dressing is much faster in comparison to dry dressing. Wound area should be physiologically moist, not dry, not wet, dressing with 85% water content is a suitable candidate for functional dressing, and it promotes faster healing [25]. Traditional cotton dressings are used to cover the wounds either with a neat and low level of exudate wounds or used as secondary dressings. Due to its failure to provide a moist environment, prevent infection, promote healing, and tendency to stick to the wound tissue, traditional cotton gauze dressings have replaced with more modern formulations, which named advanced dressing.

16.2.2 The Advanced Cotton-Based Wound Dressing

Advanced wound dressing was developed in the 20th century. The first aim of advance dressings material is keeping the wound area moist, and the second aim depends on wound type is providing some property, which helps to improve the healing rate [26]. Based on the wound type, huge products are available in the market that offers different advantages for different wound requirement. For instance, improve collagen synthesis, faster healing process by stimulating re-epithelialization, promote angiogenesis, and decrease the pH of the wound, which reduces wound infection rather than only covering the injury [24]. Cotton had been modified and combined innovatively with chemicals and materials with specific properties to build the functional wound dressing, which provides a favorable environment to facilitate wound healing. Cotton can be modified through a physical or chemical modification to gain different properties and act as a functional dressing. After modification depends on the dressing requirement, the new dressing should pass laboratory tests. Such as cytotoxicity test toward human fibroblast cells, antibacterial activity against *Escherichia coli*, and *Staphylococcus aureus* (two common bacteria which cause wound infection) and evaluation of gas permeability, mechanical property and blood clotting ability. After laboratory test (in vitro tests) the material has to be examined on the animal model (in vivo test). If the material can pass those steps successfully would be ready for clinical use.

16.3 Physical Modification

Polymers' composition is designed to achieve performances of their constituting ingredients, rather than single ones. The composite of two or more polymers that are proficient in providing favorable properties has gradually become an extraordinary approach to develop new dressing materials exhibiting new functional properties [27]. Physical attachment refers to the entanglement of more than one component by physical interaction, which makes composites with the aim of production single functional wound dressing. Physical treatments of the cotton change structural and surface properties of the fiber through a reversible procedure. The physical modification is achieved by the attachment of selected polymers onto the cotton surface. The physical modification is performed by:

1. Direct adsorption, which occurs due to reversible noncovalent interactions such as hydrophobic, van der Waals, electrostatic interactions, or hydrogen bonding [28].
2. Adsorption of carrier particles where a component does adsorb onto cotton fiber because of physical interactions, but it is not the biomolecule itself. It is a carrier particle into (or onto) where the biomolecule is immobilized [29].
3. Confinement in which, after adsorption onto the cotton fiber, the biomolecule deposit is covered with a semipermeable film, which will adsorb as well as hold biomolecules in place [30].

The physical modification of cotton is considered as a simple, fast, and cost-effective process, which does not use any chemical modifications of the cotton gauze. The challenge is to choose the polymer with suitable property and maintain its effect after impregnation with cotton gauze as a composite material. The main drawback of physical modification is random, weak, and non-specific interaction of polymer and surface of cotton gauze. Xeroform™ is considered a non-obstructive dressing and is a famous cotton gauze dressing that contains Bismuth tribromophenate (3%). Xeroform™ is used to dress wounds with low exudate or clean wounds (non-exudation). Melolin* is another commercially available cotton dressing which is also used for non-exudation wounds. Jelonet, Bactigras, Paratulle are cotton gauze impregnated with paraffin, and these dressing are also commercially accessible and suitable for neat and non-exudate wounds [20, 24, 31]. Table 16.1 briefly summarizes the physical modification of cotton gauze for the wound dressing application.

Table 16.1 Physical modification of cotton gauze, properties of the obtained new functional dressing

Material	Cytotoxicity test	Water holding and Absorption property	Mechanical property	Antibacterial activity	Adhering evaluation	Reference
Cotton gauze/Ag nanoparticle/chitosan/alginate		Improved	No significant change	Increased		[21]
Cotton gauze/vaseline	Improved	Improved			Improved	[32]
Cotton gauze/carboxymethyl chitosan/alginate	Improved			Improved		[33]
Cotton gauze/chitosan/Ag/ZnO		Improved		Improved		[34]
Cotton gauze/Alginate/Ag nanoparticle		Improved		Improved		[35]
Cotton gauze/chitosan/polyethylene glycol/poly N-vinyl pyrrolidone	Improved	Improved	Improved	Improved		[36]

16.4 Chemical Modification

The three hydroxyl groups contain one primary and two secondary hydroxyl groups at C-6, C-2, and C-3 respectively can participate in various functional modifications. Etherification, oxidation, and phosphorylated are chemical modifications which are providing desired cotton products for novel and practical applications. These hydroxyl groups are controlling the water content, and moisture of material and can engage in different chemical reactions [37]. Chemical modification has many advantages, such as providing a stable and robust bond between polymer and cotton fiber. The drawback of this method is a complicated process, expensive chemical, and the possibility of an unfavorable change in cotton fiber. For achieving functional wound dressing, the most used chemical reaction is etherification, phosphorylation, and oxidation cotton fiber.

16.4.1 Etherification

Carboxymethylation of cotton cellulose (CMCC) had been widely described since it is cost-effective, simple, and readily available, which leads to various products with desired properties and new functions. It had been popularly used in multiple industries such as wound dressing, paper industry, drag delivery, detergent production, foods industry, textile applications, and in the operations drilling of the oil-well [38]. After etherification, the cotton gauze will gain unique properties such as impressive improvement in water absorbance and water holding capacity, gelation behaviour, high bio-degradability, and bio-capability. Due to all the above properties and rapid blood clotting ability of etherified cotton gauze, it had been used extensively in the field of medical and biomedicine, especially as a wound dressing [39].

Aquacel® (ConvaTec, Princeton, NJ, USA) are commercially available wound dressings consist of sodium carboxymethyl cotton cellulose in the form of soft and non-woven with silver ion, which provides antibacterial activity and moist wound healing environments [40]. In etherification, the cotton with the degree of polymerization up to 2000 is preferred. CMCC was produced in two steps, alkalization and etherification. Chloroacetic acid ($ClCH_2COOH$) was used as an etherification chemical, and sodium hydroxide (NaOH) was used as alkalization [41]. The degree of substitution (DS) is considered as a critical index in reaction progress characterization. In one study, the effect of chloroacetic acid, sodium hydroxide, and reaction time on the DC of carboxymethylation cotton fiber were evaluated. The result showed that both chemical concentration has a direct effect on reaction efficiency. Also, by increasing the reaction time, the rate of reaction was improved, but the concentration of chloroacetic acid plays a more critical role in the final DC index [42]. Siriwan Kittinaovarat et al. [43] compared two different methods of CMCC preparation, pad-dry-cure method, and the exhaustion method. In the Pad-dry-cure method, all chemical was mixed. Cotton gauze was placed in a solution. In the exhaustion method, firstly, alkalization had been done and then adding monochloroacetic acid carboxymethylation reaction was started. In this research also the effect of different concentrations of chemical and reaction time on DS, physical and chemical property of modified cotton gauze were evaluated. The result showed that when the DS value was more than one, the CMCC surface turns to jelly form. In the exhaustion method, by the use of 25% (w/v) and 45% (w/v) of monochloroacetic and sodium hydroxide respectively, after 4 h, the DC was 0.85, which does not show ant unfavorable surface gelation property. In contrast, in the pad-dry-cure method, the maximum DC without gelation surface was about 1, which achieved after 3 min reaction time at 120 °C and 35% (w/v) and 25% (w/v) of sodium hydroxide and monochloroacetic acid respectively.

The water absorption property did not impressively change by the use of two methods and in different DS, but when CMCC is prepared by exhaustion method, water absorbance property remarkably increased within DS values higher than 0.68 [43]. The favorable DC value for wound dressing application is 0.2 or less, which can quickly achieve in chloroacetic acid and sodium hydroxide reaction. The CMCC can act as a functional dressing with a different property, which is significantly improved in comparison to un-modified cotton [44]. For instance, it had been reported that the hemostasis effect of CMCC is better than unmodified cotton. Because the CMCC contains negatively charged particles that will encounter iron ion, and the result is the precipitation of blood to provide a protecting layer around the wound. Besides, the negatively charged particles can activate factor XII and promote thrombin production. When the thrombin is present in the plasma fibrin will be produced rapidly by conversion of fibrinogen, and the result is adequate hemostasis [44]. Table 16.2 shows different research that uses CMCC for wound dressing applications, and the property of obtained dressing is shown.

Figure 16.3a and b show the fiber structure of the un-modified cotton gauze and the CMCC, respectively [42]. Figure 16.3c shows the FTIR result of cotton gauze and CMCC, the strong pick in the range of about 1600 and 1800 cm-1 is confirming the stretching vibrations of the carbonyl group in CMCC, which is observed after modification of cotton. The result of FTIR indicated the hydroxyl groups in the anhydrous glucose unit of cotton cellulose in replaced with carboxymethyl groups [45].

16.4.2 Oxidization

Oxidized cotton (OC) is to produce carboxyl groups in anhydroglucose units with intermediate aldehyde stage, the oxidation is selective and will involve the C6 of anhydroglucose. In the oxidation process, nitroxyl radical production affects the oxidation from the alcohol to the aldehyde oxidation state. Besides that, hypochlorite and bromide produce hypobromite causes further oxidation of the aldehyde to the carboxylic acid. It had been reported bio-compatible, and bio-absorbable cellulose, which showed biodegradability in the human body, can be achieved by oxidation

Table 16.2 Etherification of cotton gauze, properties of the obtained new functional dressing

Dressing material	Cytotoxicity toward fibroblast cell of animal test	Blood clotting index	Absorption property	Antibacterial activity	Degradation	Reference
CMC		Improved	Improved		Improved	[42]
CMC/chitosan	Improved	Improved	Improved	Improved		[46]
CMC/silver				Improved		[47]
CMC/Carboxymethyl chitosan		Improved	Improved			[48]
CMC/silver			Improved	Improved		[49]

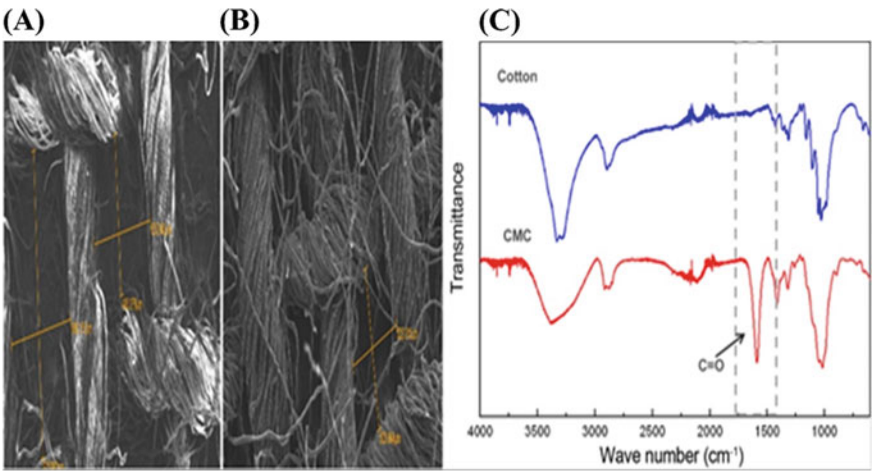

Fig. 16.3 SEM result of un-modified cotton (A) and CMC (B), the FTIR result of un-modified cotton and CMC(C)

of cellulose-containing 3 till 25% of the carboxyl group [50]. The carbonyl and carboxyl groups containing compounds are critical stuff and used for immobilization of positively charged biomolecule. As the carbonyl and carboxyl groups can react with primary amines of biomolecules to form imine and amide linkages and promote different useful properties [51]. Although the most studied method for oxidation of polymers including cellulose for preparation of carbonyl functionalized polymer skeleton is a periodate oxidation process, TEMPO oxidation is also another oxidation method which has weak oxidation ability and oxidizes the primary alcoholic group of cellulose selectively to aldehyde (cellulose aldehyde), without affecting the pyranose ring [52]. Due to some disadvantages, oxidized cotton is not preferred for wound dressing applications. J. Milanovic et al. [53] evaluated the degree of stability of TEMPO-oxidized cellulose fibers over time, and they have reported just the sample with CHO groups ranging from 40.4–82.2 mmol/kg showed strong stability after five years of storage in natural condition [53]. Another research has reported the other drawback of cotton oxidation, which is weight loss of cotton with the severity of the reaction, which leads to low mechanical properties [54]. To date, there is one research used TEMPO-oxidized cotton incorporate with copper nanoparticle for wound dressing application. To avoid weight loss of cotton, the reaction time decreased to 15 min, which provides 169.9 $\pm$ 25.9 Aldehyde content (μmol/g) and 462.0 $\pm$ 9.2 Carboxylate content (μmol/g). The antibacterial activity of obtained material was tested against *E. coli*, *S. aureus*, and *C. albicans*, and the result confirmed high antibacterial activity against 3 examined bacterial strain [55]. Figure 16.4. A and B show the scanning electron microscopic (SEM) pictures of the un-modified cotton gauze and the OC, respectively, and Fig. 16.4c is the result of FTIR.

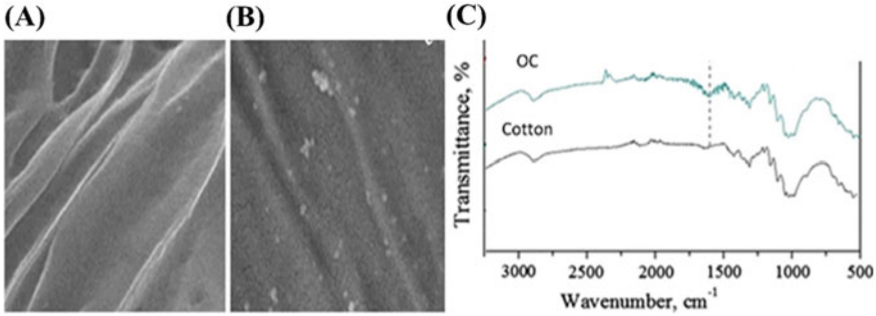

Fig. 16.4 SEM result of un-modified cotton (A) and OC (B), the FTIR result of un-modified cotton and OC (C)

16.4.3 Phosphorylation

Chronic wounds occur when a wound faces a long inflammatory stage of healing, or as a result of long incomplete healing. In this situation wound, an over-exuberant supply of neutrophils is commonly observed. The neutrophils have contained an armament of biochemical weaponry, which has an antibacterial effect of preventing the bacterial infection. It can become a significant threat for wound healing when the release of destructive specific inflammatory mediators and proteolytic enzymes from excess neutrophils is in high concentration [56]. Preventing the wound from healing by protein destruction is the result of a high concentration of protease human neutrophil elastase in chronic wound area.

In this regard, researchers have tried to develop wound dressing, which can absorb the proteases selectively from chronic wounds [57]. Through Phosphorylation, the cotton cellulose can gain the ability to absorb the protease human neutrophil elastase. Up to now, two phosphorylation method base on urea is developed. The reaction contains urea with sodium polyphosphate (SMP) solution or a diammonium phosphate (DAP) solution [58]. The result of one research that compares these two different methods of phosphorylation showed that higher protease absorption is achieved by DAP: urea when compared with SMP: urea solution. Although SMP: urea gives more whiteness index in comparison to DAP: urea, which makes cotton yellow [59, 60]. For the commercialization of cotton gauze as a wound dressing, whiteness is a vital index, and yellow appearance is a drawback need to overcome. In this regard in one research to improve the witness and retain the efficacy of phosphorylated cotton gauze combination of DAP and SMP were used to develop new dressing material. The result shows improvement in both whiteness and protease absorption in chronic wound areas [58] (Table 16.3).

Table 16.3 Phosphorylation of cotton gauze, properties of the obtained new functional dressing

Phosphorylation treatments chemical	Ratio	Protease-lowering activity	Absorption property	Reference
SMP/urea	2:1	Improved	Improved	[59]
SAM/urea	16:30	Improved		[60]
DAP/urea	10:30	Improved		[60]
SMP/urea + DAP/urea	1:1	Improved		[58]

16.5 Drug Delivery

Delivery of drugs is an important and vital aspect in the field of biomedicine. Drug delivery technology is one of the scientific areas in which chemists, biologists, and chemical engineers are trying to improve the quality of lives effectively, and the number of publications in this regard has rapidly grown. One of the popular choices for drug delivery is textile products due to their unique properties such as good mechanical property, high surface area, simple preparation, and great emphasis on slow - or controlled drug delivery applications. The drug delivery system based on textiles is promising many more advantages compared to conventional drug administration methods (tablets, ointments, or injectable solutions). For instance, the efficiency of treatment is improved, and it shows low toxicity as well as improvement in patients' connivance and complication. In many types of research, delivery of anti-inflammatory factors, antibiotics, and painkillers are performed locally and improvement in patients' comfort is reported without having side effects associated with their systemic delivery. In particular, novel dressings which carry the drug and acts as a delivery system (also referred to as finishes or coatings) provide new applications for functional medical textiles [61]. Textile based drug delivery systems are divided into two classes of drug delivery systems such as stimulation responsive drug delivery and non-responsive drug delivery.

16.5.1 Non-responsive Drug Delivery

Non-responsive drug delivery is a facile, simple, and economical method for the production of a cotton dressing to deliver a drug. In one research, antibacterial dressing with drug delivery properties was developed by grafting the betamethasone sodium phosphate loaded silica particles on the cotton surface. Chitosan and polysiloxane reactive softener was used as a soft and safe fixing agent. The obtained cotton dressing shows more than 99% antibacterial activity against E. coli and S. aureus; after five cycles washing the cotton still shows more than 92% antibacterial activity. The dressing material shows good gas permeability and mechanical property [62]. Angélica Lumbreras-Aguayo et al. [63] modified cotton gauze by grafting poly(methacrylic acid) (PMAA), zinc oxide nanoparticles, and nalidixic acid as antimicrobial agent. The antibacterial dressing shows good swelling property [64]. In another study, amino-functionalized mesoporous silica was chosen to carry tetracycline on cotton. The dressing showed the gradual release profile of tetracycline in phosphate-buffered saline (PBS) solution with excellent antibacterial activity [63]. Dariush Semnani et al. [65] have reported the release of fluconazole, which was loaded on the cotton surface with the electrospinning method. The obtained nanofiber was a mixture of polyvinyl alcohol (PVA), fluconazole, and ethanol. The results demonstrated that the morphology and structure of PVA nanofiber could influence the rate of drug release, which could be adjusted in the desired dosage [65]. Kangkang Ou et al. [66] were developed low-adherent cotton base wound dressings. The synthesized wound dressing provided a faster wound healing and favorable environment for re-epitalization, also the evaluation showed it has good biocompatibility, good mechanical property and low adhesion to tissue in wound aria [66].

16.5.2 Stimulation Responsive Drug Delivery

Some polymers are known as stimulation-responsive polymers (SRP) and considered as a smart polymer. These kinds of polymers can respond to environmental triggers such as a change in pH, temperature, ionic strength, chemical specie, and light with their sol-gel transitions [67]. Additionally, the change is reversible; after removing the environmental triggers, SRPs can return to their initial state [68]. In recent years, textile-based trans-dermal therapy using drug-loaded hydrogels, which used SRPs with a controlled drug release ability, has attracted researcher attentions. Critical solution temperature (CST) in an important feature in SRPs; in this temperature, the isotropic state of SRPs changes to anisotropic state, and polymer solution shows phase separation. When the polymer has a lower critical solution temperature (LCST) means over this critical temperature, the polymer solution becomes insoluble or forms hydrogels and shows phase separation. The polymers with LCST are preferred to occupy in drug delivery. Coating the SRPs on textile products is providing some advantages in medical use, such as their ability to balance skin moisture and actively balance body temperature [69]. The biomedical applications of SRPs coated on textile products impressively studied on infected sites of skin where the synthesized hydrogel can deliver drugs and provide moisture environment.

SRPs can be divided into two natural and synthetic groups. Chitosan, albumin, cellulose, and gelatin are in the natural stimuli-responsive polymers category. Synthetic SRPs contain PF127, pNIPAAm, poly(ethylene glycol) (PEG), polyacrylic acid (PAA), and poly(dimethylaminoethyl methacrylate) (PDMAEMA) and poly(diethylaminoethyl methacrylate) (PDEAEMA) [70]. Boxiang Wang et al. [71] Have developed thermo-responsive hydrogel. They applied chitosan and Poly (N-isopropyl acrylamide) (PNIPAAm) on cotton gauze. Glutaraldehyde was used as a cross-linker to fabricate antibacterial cotton gauze. PNIPAAm is a synthetic SRP which is widely studied as a thermos-responsive polymer. What makes PNIPAAm more interesting is the ability to highly response to slight temperature changes by sol-gel transitions. It has a unique LCST, which is around 32 °C and near to the physiological temperature of the human body. Coating PNIPAAm on cotton gauze showed high thermo-responsive behavior and antibacterial activity, which was more than 99% against two gram-negative and positive bacteria (S. aureus and E. coli) [71]. Pooria Mostafalu et al. [72] successfully delivered different growth factors and antibacterial drugs with developing textile base carrier contain cotton impregnated with alginate (Alg)/poly (ethylene glycol) diacrylate (PEGDA). The synthesized dressing was tested successfully in the infected skin in vivo [72].

Another research incorporated PNIPAAm/chitosan(PNCS) nanoparticle to cotton with the use of 1, 2, 3, 4-butane tetracarboxylic acid (BTCA), which is environmental friendly cross-linker. The results claimed that the cotton gauze would gain not only antibacterial activity but also temperature and pH-responsive ability. Increasing the PNCS concentration was directly influence on absorption property of modified cotton gauze [73].

16.6 Surgical Purpose

16.6.1 Cotton Roll

The surgery process always is causing bleeding in surgical place, which can increase the risk of unintentional injury around the surgical wound. In this regard removing blood during surgery is an important aspect that ensures the surgical area remains in the appropriate condition. Removing blood can also help the surgeon to identify the bleeding site, organs, or vessels [74]. Cotton-tipped with different functions and sizes wildly used to absorb blood from the surgical area by soaking them into the bleeding area. Three kinds of cotton products are available. Cotton dental roll, large cotton rectal swab, and standard 6” cotton-tipped. The application of standard 6” cotton-tipped is limited because of low absorption ability, which quickly becomes saturated and ineffective. The most useful cotton product in surgery is large cotton rectal swabs due to its high absorption ability. The dental roll can be used by placing it at the end of a cotton swab and can even be used to retract tissues within the surgical area. 6” cotton swabs, absorb 0.18 g of blood or any fluid of body in the saturated state and cost only $0.01 per swab. Large rectal swabs absorb 2.87 grams of blood or any fluid in saturated state and cost $0.10 per swab, which is 16 times more than the volume which 6” swab can absorb.

The price of dental rolls is $0.01, which can absorb 2.67 grams of fluid, which is 15 times higher than the 6” cotton swab. Cost-effectively analysis base on cost per gram of absorption demonstrates that the dental rolls are more cost-effective, which is 15 times better than 6” cotton swabs and nine times better than large rectal swabs for the absorption of an equal amount of blood [75]. Therefore, dental cotton rolls are cost-effective and efficient tools to remove blood from the surgical area during dermatologic surgery. In 2004 it was reported that a dental roll covered with viscous lidocaine was developed, which can reduce the pain of local anesthetic injections before nasal surgery also can absorb secretions that may drain down the nasopharynx canal [76].

16.6.2 Surgical Sutures

Sutures are implanted materials into foreign tissue. Although sutures are the most common implants used by surgeons and doctors all around the world, their biological and physical characteristics are usually not fully understood and appreciated. Sutures are letting the edges of the wounds come close, and this can help to wound closing and healing process [77]. At least 4000 years sutures have been used to close the wounds. In wound closure and tissue approximation, area sutures are the most frequently used biomaterial [78]. Sutures are used to close any skin cut, such as surgical cut, and wounds. They can be used in a different part of the body, such as internal tissues, blood vessels, skin, or organs.

Up to now, two kinds of sutures are clinically in use, absorbable and non-absorbable sutures. In contrast, absorbable, which dissolves on their own, non-absorbable sutures must remove from the body after a particular time. All over the word suture market is costing $1.3 billion per year. The most property of ideal sutures is to keep the edges tissue close and improve the healing rate before it absorbs or removes. In 1939 during the second world war, cotton was employed as a suture instead of silk [79]. Cotton is classified as a multifilament, non-absorbable, and natural surgical sutures. The cotton suture has good mechanical property and tensile strength when it is wet. The studies showed that cotton suture loses its mechanical property around 50% after six months, which reached up to 70% after two years. In comparison to silk, cotton has better knot security, however it has some disadvantages such as tissue reactivity, inferior handling ability due to electrostatic properties, and the ability to potentiate infection. Cotton base sutures are an effective strategy for the delivery of anti-inflammatory drugs or antibacterial agents to the surgical site [80].

16.7 Dental Use of Cotton: Iced Cotton Bud as a Pre-Cooling Method for Palatal Anaesthesia

The conventional way to give local anaesthetics to the patients in the oral cavity is the local injection, which has many disadvantages, such as pains and complainants of patients [81]. The use of local anaesthesia is a good solution to minimize the pain caused by the needle. Many studied have developed different methods to reduce the pain of needle during injection. The result of local anesthesia is not a pain-free injection, and several factors have a direct influence on the efficacy of local

Anaestasia. For instance, the speed of injection and the size of the needle can affect pain [82].

It is well known that Pre-cooling (Cyro anesthesia) can cause local and temporary Anaestasia and help to reduce the injection pain. Therefore scientists have developed a new iced cotton bud, which can provide effective pre-cooling for palatal anaesthesia. The preparation method was simple and easy. The cotton was firstly socked in water and then placed in the freezer for a particular time. Then iced cotton was used in the oral cavity for one minute while holding the iced cotton, and applying pressure injection was done(less than 0.5CC local anaesthetic solution) at a slow rate. The result clearly showed that all the patients were tested; this method reported 0% pain [83].

16.8 Tissue Engineering

Textile products demonstrate many advantages over other fabricate scaffolds, and it gained researchers' attention in regenerative medicine and tissue engineering. Textile products such as cotton providing high surface area, which is the main feature for tissue engineering applications. The high surface-to-volume ratio of textile producers promises vast areas for cell adhesion and proliferation [84]. Tissue engineering is a promising technology for damaged tissues, which can alternatively compensate for the scarcity of the tissue [85]. Except for high surface area, the ideal scaffold for tissue engineering must provide porosity structure, high pore interconnectivity, mimic the natural extra-cellular matrix (ECM), biocompatibility, and acceptable mechanical property. One of the simple and cost-effective methods which gave a high porosity structure with nanoscale fiber is electrospinning. In electrospinning, the obtained scaffold is closely the same as natural nano-fibrillar components (e.g., collagen) of ECM that naturally surrounds the cells of any biological tissue [86]. Xu He et al. [87] developed a cotton base electrospun scaffold for tissue engineering application. In this research, the cotton washed accurately and was added into 8% lithium chloride/dimethylacetamide (LiCl/DMAc) solution. The solution with 0.5–3% (in weight) of cellulose(with cotton source) were prepared, and as viscosity is a critical factor for electrospinning, the solution with 0.5 and 3% were not electrospinable due to that their viscosity which was 0.1 for 0.5% and non-measurable for 3%. The result of cell culture experiments showed the obtained scaffold from electrospinning was quite suitable for human dental follicle cells (hDFCs) attachment and proliferation in the entire scaffold [87]. Cheng hong Ao et al. [88] Have developed a scaffold base on cotton cellulose and different concentration of nano-hydroxyapatite (nano-HA). They have reported fiber diameter is increasing with increasing in nano-HA(Hydroxyapatite ($Ca_{10}(PO4)_6(OH)_2$) concentration. In this study, the synthesized dressing showed good proliferation and growth of hDFCs cells.

16.9 Conclusion

This chapter tried to summarize the use of cotton and its derivatives in biomedical materials. Cotton fiber is a type of natural cellulose which widely used in medical and biomedical applications as an internal and external material. To be used as an internal biomaterial, the newly synthesized material has to pass many tests and evaluations in vitro and in vivo. Cotton base gauze is used many decades ago as a primary or secondary wound dressing material, but nowadays, due to wound requires a new and functional cotton base, dressing material is available. For instance, developing non-adherence dressing or antibacterial dressing by the use of physical modification of cotton. A specific property can be achieved by chemical modification, which is more strung and stable modification. The dressing with good fluid absorbance is achieved by the etherification of cotton, which shows a high ability to absorb the fluid and is favorable for chronic wounds with a high level of exudate. The negatively charged cotton can be achieved by an oxidation reaction, which makes the cotton subject of chemically attached to positively charged molecules with different properties. Phosphorylation of cotton can absorb specifically protease human neutrophil elastase from the wound area.

Cotton is widely used in drug delivery applications due to its high surface area, porosity structure, and nano-size fiber. The drug which is loaded on cotton can be delivered due to stimulation response, which can be changed in pH, temperature, or light. Cotton gives enormous products in the surgical area, dental, and tissue engineering. The researchers are making more and more new products with different abilities which can be used in the different biomedical area. This new cotton base products make life easier for patients and reduces the pain and un-comfort during painful days and help the patients to recover in less time.

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Chapter 17
Chemical Structure and Modification of Cotton

Ishaq Lugoloobi and Hafeezullah Memon

Abstract Textiles are among the paramount universally used fabrics in homes and industries. However, the acquisition of scalable and eco-friendly multi-functional fabrics of high durability presents as an obstacle challenging their commercialization. The surface modification of textile fabrics, such as cotton, to integrate multiple operates has been recently researched as the primary solution. Cotton is part of the topmost omnipresent and expansively used fabric owed to its inexpensiveness, obtainability, breathability, and biodegradability. It is also a hydrophilic cellulose-based fiber with negatively charged hydroxyl functional groups that can be easily modified with different polymers or small chemical agents for advanced applications. In this chapter, therefore, we shall deeply describe the cotton structure, and highlight the different reaction mechanisms and techniques applied for modification of cotton fibers and fabrics, using various modification agents for diverse applications.

Keywords Textile · Cotton · Fiber and fabric · Modification mechanisms · Modification techniques · Modifying agents

17.1 Introduction

People are becoming more aware and have, therefore, demanded easy-to-care, disinfecting and disinfected, and body protective textiles [1–3]. Also, due to non-biodegradability, some conventional synthetic chemicals, and textile wastes, among others, have become toxic to the environment and human beings as a whole [4, 5]. Thus, the manufacturing of textiles with improved performance and value-added

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features has turned into the inevitability of the contemporary era. Consequently, textile industrialists are toiling to boost fabric features with considerable commercial intent. This has increased competitiveness and enhanced market dynamics, thus revolutionized science and technology for not only the development of advanced products but also the industry of economics.

In the latest centuries, the adoption of nanoscience and technology in the field of textile has been massively accepted to manufacture protective, efficient, hard-wearing, and cheaper textiles with advanced features for multiple applications [6]. Textile fabrics are treated with various synthetic and natural agents, such as essential oils, to equip these multi-functional attributes [7–10]. This is aimed at amending the physical, mechanical, and chemical characteristics of textile materials, to ascertain their imperfection extent to improve their inherent properties and incorporate novel functional features. The nature of textiles, chemical properties of the reactive agent, mechanism, and extent of fixation, alongside usage technique, are mainly the factors accountable for the enhancement of the introduced multi-functional features [11–14]. Also, potentials such as color-insensitivity, skin-friendly/dermal non-toxicity, absence of environmental concerns, fast activity, and resistance to repeated washing and stretching/folding, concentrated chemicals, harsh abrasions, among others, should be pondered when choosing chemical reagents for a particular modification [15]. This ensures the focus of developing green, decomposable, high performing and reasonable priced functional fabrics for advanced applications, for example, medical uniforms and hygienic textiles in homes and hospitals, clothing and home textiles (including beds/protective nets), textiles for food and agricultural industries, engineering and hotel clothings, tenting and camping gears, military uniforms and gears, automotive and automobile business, machinery and machine tools, electronics, and sports merchandises like field wears, nanocomposite fibers, aerospace [6, 16–19].

The unique properties added on advanced textiles include water and oil repellent, self-cleaning, ultraviolet shielding, stain proof, moisture control in synthetic fabrics, breathability, anti-static, toughness, antimicrobial and medical, insecticidal, ultra-violet (UV) protection, electrical conductivity, electromagnetic interference (EMI) shielding, chemical waste decomposition and photocatalysis [6, 20–25]. When another function is appended on a fabric, the outcome is envisaged as new material. Following the customer expectations, these clothing additives should have numerous valuable features, including comfort, easy maintenance, presence of biological and chemical toxins for microbes, moisture, and heat adjustability [26]. Textile treatment should, therefore, be an essential consideration to permit aesthetical approval, originality of textile properties, and profitable acknowledgment [27]. Textiles concocted from cellulose-based fibers, including linen, viscose rayon, and cotton fibers, are described as perfect for absorbability, smoothness, air perviousness, and abrasion relief [28–30].

Cotton is a portion of the most globally used natural fiber materials for a primary function of clothing, to provide body protection and relief. The current estimates for the world cotton consumption are about 120.5 million bales (26 million metric tons) annually [31]. Cotton is a unique textile fiber with a combination of properties, like high strength, durability, softness, high absorbency, biodegradability, ease of processing, and good dyeability [32, 33]. It is also skin-friendly and costless for wearers, compared to other natural textile materials. Therefore biopolymeric cot fiber materials have found many applications in textile and biomedical engineering [34]. Cotton is described as a natural hydrophilic cellulose-based fiber possessing hydroxyl functional groups. This enables its modification with chemical agents using different methods that are more reliable for clothing and other advanced applications [13].

17.2 Chemical Structure of Cotton

A fabric is acknowledged as a two-dimensional sheet of intermingled, interloped, or interlaced fibers/threads that emerge into shape by respective bonding, knitting, or weaving together [35]. Therefore, yarns/threads are formed by jointly twisting short and staple fibers. Expressly, cotton fabrics are made from their natural fibers.

Cotton fiber is a multi-layered biological cell consisting of structural features, in the order from outside to the inside layer as a cuticle, primary wall, secondary wall, and lastly lumen (Fig. 17.1). These layers differ structurally and chemically. They also have different degrees of crystallinity and molecular chain orientations. The primary and secondary layers comprise of elementary fibrils that are densely packed to form microfibrils and macro fibrils. There are strong hydrogen bonds that hold the layers together. In mature fibers, the primary wall possesses an annular shape and several fibrils, while the secondary wall consists of numerous concentric layers with a spiral shape [36]. Generally, cotton is characterized by a flat structure with a natural twist in the warp direction, to increase the fiber strength. The water absorption and heat retention capabilities are enhanced by the hollow structure [36].

The primary wall and secondary wall weigh 2.5% and 91.5% total fiber mass, have 30% and 70% crystallinity index and comprise of 50% and 92–95% cellulose, respectively. The entire cotton fiber, therefore, contains 88–96.5% cellulose, mainly located in the secondary cell wall [37–39], while the rest are naturally existing non-cellulosic components such as amino acids, proteins, fats and waxes, organic acids, pectin, sugars, inorganic salts, and natural colorants [40]. These non-cellulosic components constitute 10% of the total fiber weight and are principally located in the lumen, primary cell wall, and cuticle. After selective solvent treatments to get rid of the non-cellulosic constituents, the fiber content becomes over 99% cellulose. Thus, cellulose polysaccharide is almost the entire component in cotton. This cellulose is composed of crystalline fibrils that differ in complexity and length and linked by less ordered amorphous sections of crystalline and non-crystalline components, in an average ratio of 2:1, depending on the analysis technique.

Cotton cellulose is a linear polymer, constructed of monomeric glucose units of β-D-glucopyranosyl residues associated together via β-1,4-glycosidic bonds [41]. This polymer has numerous hydrogen-bonded attachments besides the stable glycosidic links [42, 43]. The constituent hydroxyl groups of cotton cellulose-macromolecule

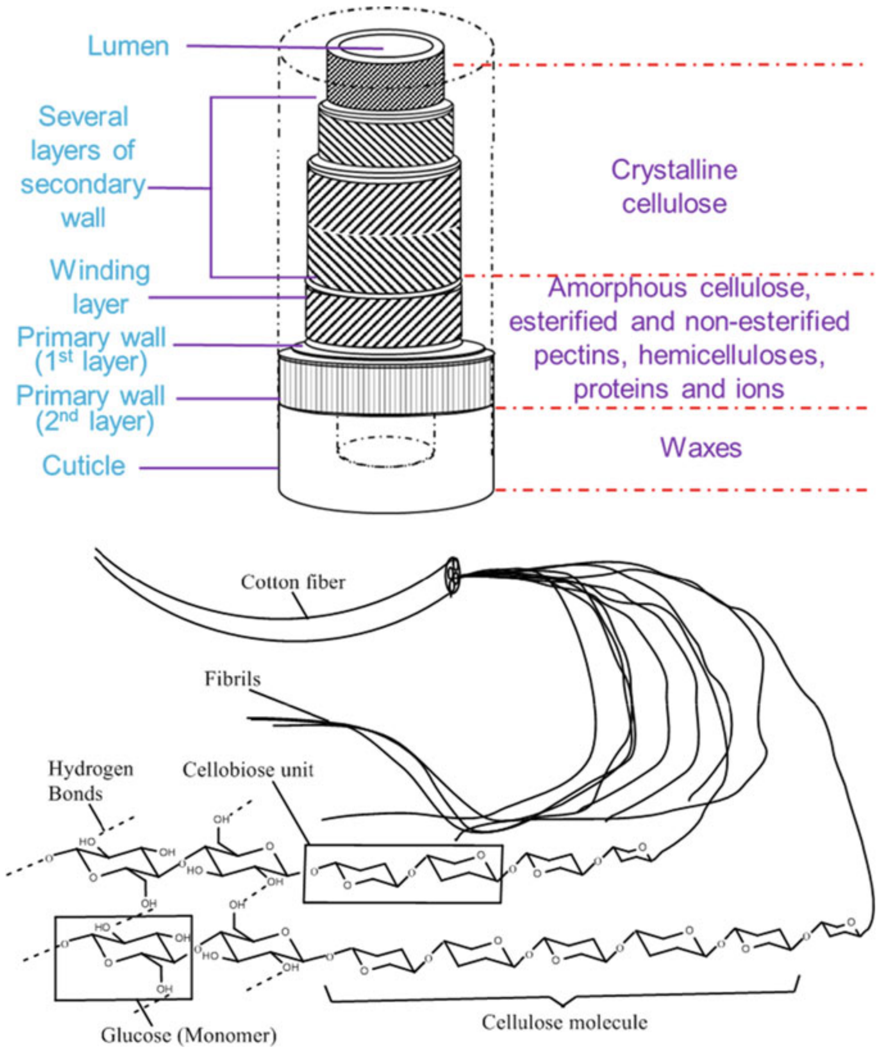

Fig. 17.1 Schematic illustration of the morphology of the cotton fiber

are mostly involved in hydrogen bonding, due to its length, which is almost more than 5000 nm [44]. Thus, increasing the number of intermolecular hydrogen linkages. The glycosidic and hydrogen bonds, therefore, promote stability in the cellulose polymer [45].

17.3 Mechanisms of Modification of Cotton Fiber and Fabric

The modification of cotton involves the treatment of the fibers and fabrics with synthetic and natural agents. These agents are imparted primarily during finishing, dyeing or printing action, or before, to provide additional values for advanced applications. The treatments may be physical, mechanical, thermal, and the most common chemical techniques, as illustrated in Fig. 17.2, or a combination of two or more. Physical methods may include gamma irradiation, which is applied to improve the cotton surface, to achieve high color intensity [46–48].

Chemically, cotton has marginally oxidized hydrophilic carboxylic groups and hydroxyl functional groups in its polymer chains, which makes it electronegative by nature when placed in an aqueous liquid [49]. Cotton fibers also have the same negative zeta potential with an IEP of 2.8 and about −15 mV plateau at pH 9 [50]. As a result, the active chemical groups and the surface charge on cotton can be finetuned via cross-linkage. Crosslinking of cellulosic cotton is an imperative chemical technique in textile, described as the stabilization of cotton fibers by reacting it with some chemical agents, to link their chains across. Crosslinkers in cotton cellulose exist in two categories, firstly, the self-polymerizing and/or cross-linking cellulose chains formed using agents like polycarboxylic acids [51], to create three-dimensional polymers. Secondly, those known as cellulose reactants that cross-link cellulose to various agents by reaction via the hydroxyl groups of cellulose to form covalent bonds [52]. Reactions such as esterification, ionic/electrostatic interactions [53], hydrogen bonding [53], carboxymethylation [54–56], thiolene click reaction [57], oxidation, etherification, amidation, carbamation, silylation, polymer grafting,

Fig. 17.2 The imparting techniques of cotton textiles

free radical polymerization, and nucleophilic substitution reactions, are involved in the attachment of chemical linkages, i.e., alkoxy(ether)-, amido-, ester-, epoxy-, carbamyl-, silyl- among others onto cotton and other cellulosic materials. These linkages are formed from reaction with agents such as imidazolium salts [58], polysilsesquioxane (POSS) [59], aliphatic, and aromatic acid halides, phenolic or mercapto-esters of carboxylic acids, acrylonitrile, anhydrides, alkenes, isocyanates, s-triazine derivatives. Also, polymerized di-acid chlorides and bisphenols, or between acid chlorides and diamines [60].

Chemical reactions with the functional groups of cotton may necessitate particular modifying techniques such as exhaustion, mist modification [61], solution-dipping/immersion, coating [33, 62–64], sol–gel method [65, 66], plasma treatment [67], electrostatic assembly [68], pad-dry-cure [69], in-situ synthesis [70, 71], foam techniques, spraying, direct addition to the fiber spin dope, weaving metal wires with fibers, layer-by-layer (LbL) assembly technique [72–75], copolymerization or grafting, micro-encapsulation technique [76, 77], vapor deposition [78, 79], drop-casting method, UV irradiation, corona discharge treatment, [80–83]. They may also require a variation of pH, temperature, and use of catalysts in the form of nanoparticles such as TiO_2 [84]. For instance, carboxymethylation of cotton involves treating its hydroxyl groups with monochloroacetic acid in an alkaline solution [85–87] by commonly using exhaustion and pad-roll methods [88].

Since some processes tend to impair some physical, chemical, and mechanical properties of textile fabrics [89], chemical methods have been deployed to alter the surface chemistry of cotton to increase their affinity for anionic agents. This method is referred to as cationization and, therefore, involves the incorporation of cationic groups onto cotton [90] directly or via a crosslinker. These cationic vectors are small molecular weight cationic chemical groups or cationic polymers/resins, the majority of which are secondary, tertiary, or quaternary amino groups [91–94]. The cationizing agents may occur as natural polymers, including chitosan [95] and cationic starch [96], or synthetic agents such as acid tannic, 3-chloro-2-hydroxypropyl trimethyl ammonium chloride (CHTAC), Sera Fast, Rewin Os, and Denitex BC [97]. Plasma treatment can also be applied to adjust the surface chemistry of cellulosic materials to increase the adsorption of chemical agents. For instance, oxygen was used for the plasma treatment of viscose fabric leading to hydrophilization of their surfaces by the formation of suitable binding sites [98]. Other gases applicable to plasma treatment may include nitrogen gas and sulfur hexafluoride (SF_6) [99]. Pre-irradiation techniques can also improve the incorporation of chemical agents onto fabrics, for example, Co-60 gamma rays irradiation enhanced the grafting of 2-hydroxypropyl acrylate, *N,N'*-methylene bis(acrylamide), styrene, 2-hydroxypropyl methacrylate, acrylonitrile, acrylic acid, methyl methacrylate, and acrylamide monomers onto cotton fabrics [100–102].

Some functional agents have been attached to cotton surfaces via intermediate crosslinkers to enhance compatibility. For example, AgNPs (Silver nanoparticles) were effectively immobilized onto cotton fabrics [103–106] through polymer binders such as amino-terminated hyperbranched polymers [107] and polydopamine [108].

Though chitosan doesn't offer pleasing durability to Ag NPs [109], owing to no covalent bond formation with the cotton fiber surface, it was utilized as a binder through various methods including plasma, cross-linking and oxidation of cotton [110–114]. Nevertheless, carboxymethyl chitosan was identified as a powerful linker of Ag NPs on the cotton surface, owed to the formation of ester bonds with cellulose hydroxyl groups, primarily when the pad-dry-cure method and "mist modification" process are utilized for functionalization [115]. On the other hand, chemical agents can also be modified for secure attachment onto cotton surfaces. For example, bifunctional itaconic acid with carboxyl and vinyl groups that can undergo esterification reaction and free-radical polymerization, respectively, was employed for modification of cyclodextrin [116]. The reactive groups of the cyclodextrin complex derivative, therefore, easily formed direct covalent bonds with cellulosic cotton. In general, by modifying cotton with these chemical groups, electronic, magnetic, catalytic, antimicrobial, fluorescence, thermal, and optical properties can be imparted to realize various advanced and multi-functional cotton textiles.

17.4 Conclusion

Cotton is an excellent substrate for facile polymer modification due to the high content of hydroxyl groups in its structure, which are associated with the existence of cellulose, a main component of the cell wall. These hydroxyl groups enable designing and precise synthesis of novel and advanced cotton fibers and fabrics with controlled architectures for specific functions, using specific modification mechanisms and imparting techniques. There are various methods for the construction of advanced cotton textiles, as described above. These are specially selected to ensure the incorporation of particular chemicals and polymeric chains to acquire absolute hybrid cotton textiles. The cotton structure makes it a superlative candidate for modification to create properties that enable its wider range of industrial applications. However, some of these agents and imparting methods may present unwelcomed properties in terms of loss of cotton's originality. Thus, it is imperative to utilize specific and highly efficient additives and techniques to achieve targeted final properties of the material. In the case of reaction mechanisms, some conditions such as pH, temperature, the presence of a catalyst may be inevitable for successful chemical modification. Also, modification of cotton surfaces may require prior alteration of its functional groups or those of the additive for a high scope of physical or chemical compatibility. This chapter has summarized the structure of cotton, the applicable mechanisms, and techniques for modification of its structure for potential advanced industrial applications, as extensively described in the subsequent chapters.

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Chapter 18
Advanced Physical Applications of Modified Cotton

Ishaq Lugoloobi, Hafeezullah Memon, Obed Akampumuza, and Andrew Balilonda

Abstract Today, modified cotton materials have become an important aspect of man's life since they can be utilized in various advanced applications. Among them, superhydrophobicity and flame retardancy are the most crucial improvements for advanced industrial physical applications. These are characterized by enhancement of the physical resistance of cotton textiles against water and fire, respectively, which are the most common physical conditions that favor the degradation of natural materials. This hence provides safety to human life and his property. The present chapter, therefore, summarizes the research progress of cotton fabrics modified for advanced physical applications, highlighting the different chemical agents used and their binding interaction, imparting techniques, the quality of the modified textiles, and the potential fields of usage.

Keywords Modified cotton · Superhydrophobicity · Flame retardancy · Chemical agents

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Abbreviations

Ag NPs	Silver nanoparticles
ATRP	Atomic transfer radical polymerization
BA	Butyl acrylate
BR	Bacterial reduction rate
CNTs	Carbon nanotubes
CVP	Chemical Vapor Deposition
EMI	Electromagnetic interference
DMAEMA	2-(dimethylamino)ethyl methacrylate
DD	Degree of deacetylation
DMSO	Dimethyl sulfoxide
DCM	Dichloromethane
FAS	Fluoroalkyl silane
GMA	Glycidyl methacrylate
GO	Graphene oxide
HEMA	Hydroxyethyl methacrylate
HFBA	Hexafluoro butyl acrylate
HFP	Hexafluoropropylene
HMDSO	Hexamethyldisiloxane
HPLC	High Performance Liquid Chromatography
LbL	Layer-by-layer
LODs	Limits of detection
LOI	Limiting oxygen index
MMA	Methyl methacrylate
MOFs	Metal-organic frameworks
NPs	Nanoparticles
NWs	Nanowires
OCA	Oil contact angle
PDMS	Polydimethylsiloxane
PDTS	1H,1H,2H,2H-perfluorodecyltriethoxysilane
PEDOT	Poly(3,4-ethylenedioxythiophene)
PEG	Polyethylene glycol
PEI	Polyethyleneimine
PFWs	Perfluorinated waxes
PMMA	Poly(methyl methacrylate)
POSS	Polyhedral oligomeric silsesquioxane
POTS	1H,1H,2H,2H-perfluorooctyltriethoxysilane
PP	Polypropylene
PSS	Poly(styrene sulfonate)
PTFMA	Poly(trifluoro ethyl methacrylate)
PVDF	Poly(vinylidene fluoride-co-hexafluoropropylene)
PVD	Physical Vapor Deposition
SA	Stearyl acrylate

RhB	Rhodamine B
rGO	Reduced graphene oxide
RSDs	Relative standard deviations
SDS	Sodium dodecyl sulfate
SP	Solid phase
UV	Ultra-violet
UPF	UV protection factor
WCA	Water contact angle
WSA	Water-shedding angle

18.1 Introduction

The commonly used materials for various functions are heavy, becoming depleted, costly, environmentally unfriendly, and not easily used for clothing on human bodies, owed to their high toxicity and discomfort. Therefore, modification of textiles such as cotton for advanced applications becomes one of the main solutions. These are versatile, inexpensive, easily woven, widely, and abundantly used. Cotton possesses a structure with hydroxyl functional groups that enable modification with different agents, as discussed in Chap. 17. The incorporated agents impart novel properties that contribute to different additional physical, chemical (Chap. 20), and biological (Chap. 19) applications of the modified cotton fibers and fabrics (Fig. 18.1).

The advanced physical applications of modified cotton that have been deeply studied include superhydrophobicity and flame retardancy. Therefore, these are the mainly discussed physical applications in this chapter. They are greatly achieved on enhancement of physical properties such as material resistance, affinity, rigidity, strength, by coating of cotton materials with various natural and synthetic agents. This ensures the reliability and safety of used cotton textiles against physical conditions such as water, fire, temperature variations, dirt.

18.2 Superhydrophobicity

Pondered as an outstanding character among worldly creatures, such as butterfly wings, beetle elytra, dragonfly wings, mussels and cicada [1, 2], and vitally the lotus leaves (from lotus plants) that bore the famous term "lotus effect" [3], superhydrophobicity has elicited enormous curiosity and interest of research in academic, industrial and engineering sectors, due to their hands-on applications [4–7]. Surfaces are considered superhydrophobic with WCAs higher than 150° and WSAs lower than 10° [8–10], and also for super-amphiphobic surfaces, the behavior is the same for low-surface tension liquids, with water and oily liquids having contact angles higher than 150° [11–13].

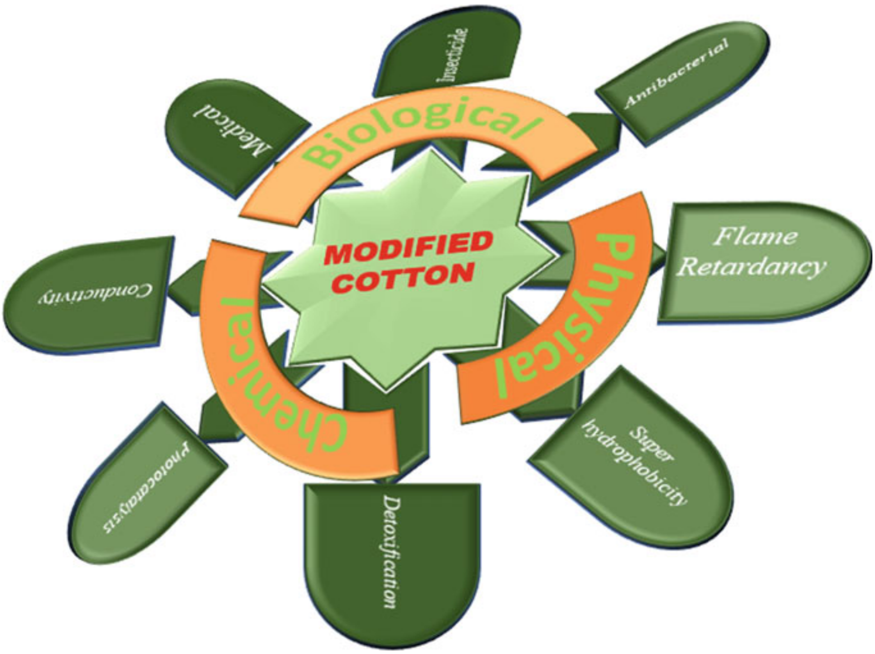

Fig. 18.1 Illustration of the different advanced applications of modified cotton fibers and fabrics

Universally, the crucial factors accountable for the desired superhydrophobic surfaces are the formation of hierarchical structures and the insertion of water repellent chemical groups [14–16] with low surface energy [17]. Unlike superhydrophobic coatings, the design of super-amphiphobic coatings is quite challenging, owing to the need for controlling both of their surface energy and surface structure [18–23]. Furthermore, the organic/oily liquids with WCAs higher than 150° tend to adhere securely to surfaces, without roll-off, thus elimination of the most relevant self-cleaning property [24, 25].

Importantly, wetting control systems are mainly towards waterproofing [26, 27]. However, they possess numerous superior features such as oil-water separation [28–30], self-cleaning [31–33], oil resistance [4], anti-corrosion [34], anti-icing [35], anti-fouling [36–38], thermal performance, antimicrobial and medical potential [39], as well as condensation for more efficient heat transfer and water harvesting, with durability [40, 41]. These are as well recently reaping popularity in research and application. Thus, a property developed for the protection of surfaces from impairment by harsh environmental components, such as bacteria, dirt, some chemical agents and rain [12, 42–46].

Cotton fabrics are susceptible to the absorption of a substantial amount of oil, water, and liquid mixtures, such as gasoline, wine, coffee, and tea. These liquids can easily infiltrate through their pores under minimal differential pressure. This is attributable to the high surface energy of cotton, leading to inherent hydrophilicity or expression of poor hydrophobicity. Nevertheless, superhydrophobic and super-amphiphobic characters have been added onto cotton surfaces by the introduction of functional agents including polymers and copolymers such as PMMA-*b*-PTFMA (paraffin) [47], fluorinated C6 and C8 compounds such as PVDF-HFP/FAS and fluorinated-decyl (F-POSS)/POTS mixture (C8/C6 fluorinated mixture) [34, 48], PFWs, silicon-containing agents, alkylamines, poly/mono-acrylates, nanoparticles like nanowhiskers, natural materials such as stearic acid. The above and other superhydrophobic imparting chemical agents are listed and precisely elaborated in Table 18.1.

Fluoropolymers made-up of long alkyl chains, with 8–12 carbon atoms, having all or most of their hydrogen atoms substituted with fluorine atoms (C8 chemistry), have been utilized to impart hydrophobic and droplet mobility properties on commercial cotton fabrics. C8 fluoropolymers possess a low surface free energy of 18 mN/m, and hence, material fabrics modified with C8 fluorinated chemicals generally exhibit WCAs above 150° and WSAs below 10° [32, 49–53, 138, 139], reliant on the quantity of fluorine atoms along the carbon chains. Moreover, C8 fluorinated anti-wetting superhydrophobic coatings are resistant to chemical and mechanical environments, hold superhydrophobic capacity [140], and efficient with lower coating.

As well, C6 fluorochemicals, also described as fluorinated polymers with shorter chains (≤6 fluorinated carbon atoms), were also developed. These environmentally benevolent fluoropolymers decompose into perfluorohexanoic acid with low toxicity and high bio-removable rate [141], thus attracted numerous interest from moneymaking manufacturers and scholars. Furthermore, C6 fluorochemicals may have substituent groups such as silicone, acrylics, and methacrylates, among others. For instance, Lai's group used POTS (C6 chemistry) and PDTS (C8 chemistry) for comparison, to functionalize cotton fabrics with the unique flower-like titanium(IV)oxide particles by applying a single-step hydrothermal reaction and after that post hydrophobization [54]. The titanium (IV)oxide/cotton fabrics exhibited a superhydrophobic nature with WCA of 160°, and WSA of 15° and 10° for fabrics modified with POTS and PDTS, respectively. The lower WSA of titanium (IV)oxide/PDTS cotton fabric is due to its longer fluoropolymer chain. However, fluoropolymer-modified cotton fabric without TiO_2 particles and functioning as a reference sample displayed WCA of 120°. Cassie-Baxter's model explains this behavior. The water repellent fabric also exhibited 50+ UV protection factor (UPF), oil-water partition and self-cleaning potential, and robustness with WCA slightly reducing from 160° to 148° after 30 abrasion cycles. Earlier on, Men's group had designed POTS C6-treated cotton, with successive addition of polyaniline using the vapor phase deposition process [55]. The coated fabric had WCA of 156°, and this reduced by 10° after 30 cycles of abrasion. Several scientists have also reported treated cotton fabrics with WCAs of 145°–150°, by applying POTS C6 chemistry [50, 56, 57].

Fluorinated acrylic and methacrylate monomers have also been utilized to impart super hydro-oleophobicity during the preparation of non-wettable materials. In particular, Zhang's group prepared 1 wt% emulsion solution of perfluorinated

Table 18.1 Summary of chemical agents, imparting techniques, and properties of hydrophobic and superhydrophobic cotton textiles

Chemical agents and imparting techniques	Highlights	WCA	WSA	Refs.
Fluoropolymers (POTS/C8)				
Heptadecafluorononanoic acid; fluoroalkyl silane; silica NPs. *By dip-coating or electro-spraying*	Superamphiphobic with 155° OCA; chemical resistance; durable for 120 abrasion cycles and 5 accelerated laundry cycles	166°		[49]
Tridecafluorooctyltriethoxysilane; tetraethyl orthosilicate; trimethylammonium chloride; silica NPs. *By dip-dry*	Superamphiphobic with OCA of 155°	145°		[50]
1,1,2,2-Tetrahydroperfluoro-1-decanol; tri-functionality vinyl perfluoro decanol; vinyl-terminated polydimethylsiloxane and octavinyl-polyhedral oligomeric silsesquioxane. *By Dip coating and UV-curing*	Self-healing; resistance to liquid pollutants and chemicals; durable to 10,000 abrasion cycles, 120 h of weathering test, and 12 h of exposure to 10–180 °C temperature ranges	153°		[51]
Poly-[3-(triisopropyloxysilyl) propyl methacrylate]-block-poly-[2 (perfluorooctyl)ethyl methacrylate]. *By dip-dry*	Oil repellency of 157° OCA; stability against simulated washing, and retained mechanical properties; durable to 50 washing cycles	164°	2°	[52]
Stearic acid; 1H,1H,2H,2H-perfluorodecyltrichlorosilane; silica NPs. *By pad-dry-cure*	Robustness of more than 1 h	170° (5 μL)	3°	[53]
C6 Fluoropolymers				
POTS (C6 chemistry); flower-like TiO_2 NPs. *By solution-immersion/soaking*	50+ UPF; oil-water partition; self-cleaning potential; robustness for 30 abrasion cycles or 5 laundering cycles	160°	15° (8 μL)	[54]
PDTS (C8 chemistry); TiO_2 NPs. *By solution-immersion/soaking*			10° (8 μL)	
POTS C6/polyaniline. *By solution-immersion and vapor phase deposition*	Oil-water separation under high temperature, high humidity, strongly acidic or alkaline solutions, and mechanical forces; superhydrophobicity for 600 abrasion cycles	156°	–	[55]

(continued)

Table 18.1 (continued)

Chemical agents and imparting techniques	Highlights	WCA	WSA	Refs.
Tetraethoxysilane; 1H,1H,2H,2H–fluorooctyltriethoxysilane; hexadecyltrimethoxysilane (C_{16}). *By sol-gel*	2 h wash durability	169°		[56]
Fluorosilane; fluorinated polysiloxane; guanidine carbonate; ammonium dihydrogen phosphate; melamine. *By sol-gel*	Flame-retardancy Thermal stability	143°		[57]
Poly dopamine; TiO_2 NPs. *By dip coating*	Vapor permeability; self-cleaning; dirt removal; thermal regulation for 30 laundering cycles; hydrophobicity for 50 abrasion cycles	150°		[58]
Fluorinated-decyl POSS; POTS; Cu NPs. *Using layer-by-layer assembly*	Self-cleaning; electrical conductivity; EMI shielding; electrothermal heating; superamphiphobicity (155° OCA and 8° OSA); resistant to 100 washing cycles and against acidic and basic solutions; healable superamphiphobicity by either heating at 135 °C or applying 1.0 V	166°	5°	[34]
Polyvinylsilsesquioxane; ZnO NPs. *By solution immersion*	UV shielding; antimicrobial; oil/water separation; self-cleaning; enhanced mechanical properties; superhydrophobic durability of 20 washing cycles	162°		[59]
Fluoroanion $CF_3(CF_2)_7SO_3Li$; Chitosan NP. *By spraying*	Antibacterial	157°	14°	[60]
Fluorinated acrylic and methacrylate monomers				
2-[[[[2-(perfluorobutyl)]sulfonyl]methyl]amino] ethyl methacrylate/stearyl acrylate copolymer. *By solution immersion*	Omniphobicity with OCA of 3°; self-cleaning	100°		[61]
Monofluoroalkylsiloxy polymethacrylate latex (C6)		149°		[62]
Bisfluoroalkylsiloxyl polymethacrylate latex (C6)		151°		

(continued)

Table 18.1 (continued)

Chemical agents and imparting techniques	Highlights	WCA	WSA	Refs.
Trisfluoroalkylsiloxyl polymethacrylate latex (C6). *By dipping and post-nip-dry-cure*		154°		
Perfluorinated acrylic copolymer (Capstone ST-100) (C6); acetoxy-cure silicone (PDMS) (C6); silica NPs. *By solution dipping.*	Hydrostatic head pressure resistance (2.65 kPa); breathability; resistance to 1 ultrasonic washing cycle and 30 abrasion cycles	150°	17° (8 μL)	[63]
2,2,3,3,4,4,5,5-octafluoropentyl acrylate(C4). *By surfactant adsorption*	Hydrophobic and oleophilic; separation of chloroform/water mixture	126° (20 μL)	–	[64]
Poly(2-(dimethylamino) ethyl methacrylate)-b-poly(hexafluorobutyl acrylate) (C3). *By solution immersion and dip-nip-dry method*		141°		[65]
2,2,2-trifluoroethylmethacrylate with 2-isocyanatoethylmethacrylate copolymer and CF_3 side chains (C1). *By mist and immersion treatment*	water adsorptivity and vapor transmissibility; durable for 30 laundering cycles and 100 abrasion cycles	151°		[66]
Glycidyl methacrylate (C3) and heptafluorobutyryl chloride; cotton-Br using 2-bromoisobutyryl bromide. *By solution-immersion*	Air permeability; durability to 40 abrasion cycles and 35 laundering cycles	163°	45° (10 μL)	[67]
Poly(methylmethacrylate glycidylester-co-dodecylheptafluoroethyl methacrylate); octa(aminophenyl)silsesquioxane; 9, 10-dihydro-9-oxa-10-phosphaphenanthrene 10-oxide. *By dip-cure-dry*	Flame retardancy; self-cleaning; separation of oil/water mixtures and emulsions for 100 cycles; chemical and heat resistance; durability to 16 h washing	154°		[68]
Perfluorinated waxes (PFWs)				
PFW (≤C6 chemistry); graphite fluoride complexes. *By solution-immersion*	Self-healing; dyeability; resistant to strong chemicals and harsh environmental changes; durable for 600 abrasion cycles; self-healable with continuous O_2 plasma etching	157°	5° (10 μL)	[69]

(continued)

Table 18.1 (continued)

Chemical agents and imparting techniques	Highlights	WCA	WSA	Refs.
PFW/BiOBr. *By solution-immersion*	Oil/water separation; photodegradation for 6 test cycles; resistance to ultrasonic chemical tests; durable to 2400 friction test cycles	154°		[70]
Other C6 fluorinated polymers				
Polyvinylidene fluoride; silicon carbide (C1). *By electrospinning*	Oleophilic; oil/water separation for 10 cycles	113°		[71]
Oleophobol CP-C (C6); Knittex FEL linker. *By dip-dry*	Amphiphobic with OCA of 109°; maintained fabric properties	125°		[72]
Oleophobol CP-C (C6); phobol; trimethyl methoxy silane; rubber. *By dipping-padding-knife-curing*	Super-omniphobic; breathability and comfort; oil and chemical resistance; durability for 30 washing and 2000 pilling cycles	150°		[73]
Other halogenated agents				
($BiOBr_xI_{1-x}$ ($0 \leq x \leq 1$)) nanosheets. *By dip-dry*	UV-blocking; self-cleaning; near-infrared reflectance	143°		[74]
Silicon-containing agents				
Octadecyltrimethoxysilane; silica NPs. *By solution-immersion*	Superhydrophobic and super-oleophilic; oil/water separation for 40 cycles; resistance to hot water and corrosive solutions; durability for 600 abrasion cycles	159°	–	[75]
Polyurethane sponges; octadecyltrimethoxysilane; silica NPs. *By solution-immersion*	Superhydrophobic and super-oleophilic; oil/water separation for 40 cycles; oil selectivity and storage; resistance to robust corrosive solutions and hot water; durability of 300 scratch cycles	158°		[76]
Trichloro(octadecyl)silane; silica NPs. *By modified sol–gel*	Oil/water separation for four cycles	152°		[77]
Octyltriethoxysiliane; dodecyltriethoxysilane; isooctyltriethoxysiliane; γ-mercaptopropyltriethoxysilane; silica NPs. *By electrodip-dry-cure*	Durability of 20 laundering cycles	162°		[78]

(continued)

Table 18.1 (continued)

Chemical agents and imparting techniques	Highlights	WCA	WSA	Refs.
Polysiloxanes/SiO_2 with aminopropyltriethoxysilane end-cap. *By dip-dry-cure*	Durability of 20 washing cycles; maintained color and softness	158°		[79]
Hexadecyltrimethoxysilane; polydopamine NPs. *By dip coating*	Resistant to 100 laundering cycles and 4000 abrasion cycles; self-healable against acid/base etching and plasma damage for 10 cycles	163°	8° (3 μL)	[80]
Hexadecyltrimethoxysilane; polydopamine; Fe_3O_4 NPs. *By dip-coating*	Magnetic responsivity; oil removal for ten cycles; resistant to 50 laundering cycles and 500 abrasion cycles	156°	5°	[81]
Monomer 1,1,1,3,3,3-hexamethyl disilazane; polydopamine; silica NPs. *By dip-dry*	Separation of oil/water mixture for 20 cycles; stability towards high temperature, UV irradiation, and organic solvents; resistance to 1 h ultrasonic washing, 50 abrasion cycles, and 250 tape peeling-off cycles	156°	6°	[82]
Acrylic resin; (3-amino-propyl)-triethoxysilane; SiO_2 NPs. *By spraying*	Self-cleaning property; acid corrosion resistance; durability of 30 abrasion cycles	165°	2°	[83]
Methyltriethoxysilane; γ-chloropropyltriethoxysilane; N-octyltriethoxysilane; dodecyltriethoxysilane; TiO_2 NPs. *By sol–gel electrochemical deposition*	Durable for ten washing cycles; Healable when irradiated in the dark	166°		[84]
PDMS; methyltrimethoxysilane (MTMS). *By dip-dry-cure*	Anti-fouling; self-cleaning; oil-water separation; retained fabric properties; chemical resistance; durability of 5 laundering cycles and 100 abrasion cycles	160°	8° (10 μL)	[45]
Hexamethyldisiloxane (HMDSO). *By gliding Arc plasma treatment*	High resistance to static wetting; durability of 3 washing cycles	143°		[85]
PDMS; ZnO NPs. *By dip coating*	Self-cleaning; UV protection; oil/water separation; chemical stability; UV and superhydrophobic durability of 20 washing cycles and 300 abrasion cycles	160°	5°	[42]

(continued)

Table 18.1 (continued)

Chemical agents and imparting techniques	Highlights	WCA	WSA	Refs.
PDMS; Poly-triethoxyvinylsilane. *By dip coating*	Superhydrophobic and super-oleophilic; self-cleaning; UV irradiation; photocatalytic degradation; oil-water separation for 10 cycles; resistance to harsh chemical corrosives; durability of 20 laundering cycles, 10 abrasion cycles, and 20 tape peel-off cycles	154°	8°	[86]
Poly[3-(triisopropyloxysilyl) propyl methacrylate] bearing PDMS block co-polymers. *By sol-gel method*	Oil-water separation; patterned superhydrophobic and hydrophilic fabrics	150°		[87]
Poly(dimethylsiloxane-co-methyl-hydro siloxane) co-polymers; rGO. *By dipping coating*	Resistance to strong corrosives for 30 days and hot water; durability of 200 laundering cycles and several abrasion cycles	157°	5° (10 μL)	[88]
Poly{dimethylsiloxane-co-[2-(3,4-epoxycyclohexyl) ethyl]methyl siloxane}. *By pad-dry-cure*	Breathability; mechanical strength; resistance to water infiltration at 22 mbar; durability for 5 laundering cycles	150°		[89]
Polydimethylsiloxane; copper sulfide. *By dip-dry-cure*	Photocatalytic activity; UV-blocking; 80 h UV and 20 cycles of laundering durability; retained fabric mechanical properties	157°	7°	[90]
Polymethyl siloxane; GO. *By dip-pad-dry method*	Electroconductive; self-cleaning	163°	7°	[91]
Methacryl-heptaisobutyl POSS; mercapto silanes. *By dip-dry*	Removing oil from water; tolerant to corrosives, UV irradiation, high temperatures, 1 h ultrasonic washing, and 40 abrasion cycles	159°	7°	[92]
Vinyl-POSS; 1-dodecanethiol; 3-Mercaptopropyltriethoxysilane. *By solution-immersion*	Durability for 30 standard laundering cycles	149°		[93]
3-Mercaptopyl trimethoxy silane; ZnO sol; dodecafluoroheptyl methacrylate. *By dip-coating*	UV protection; self-cleaning; oil-water separation for 20 cycles; resistance to corrosive and organic chemical solutions; stability to 20 launderings and 30 abrasion tests	156°	6°	[94]

(continued)

Table 18.1 (continued)

Chemical agents and imparting techniques	Highlights	WCA	WSA	Refs.
3-(trimethoxysilyl)propyl methacrylate; poly(ethylenimine); ammonium polyphosphate. *By pad-dry-cure*	Flame-retardancy; self-cleaning; Remained superhydrophobic and flame-retardant after 75 and 5 commercial washing cycles, respectively	160°		[95]
Alkylated with triethoxysilyl and dodecane groups. *By dip-dry*	Resistance to 15 standard washing and 70 abrasion cycles	146°	17° (8 μL)	[96]
N-halamine; graphene oxide. *By dip-dry*	Antibacterial activity; 132 UPF; self-cleaning; electrical conductivity	140°		[97]
Hexadecyltrimethoxysilane; Zinc oxide NPs. *By pad-dry-cure method and solution-immersion*	Durability for 35 washing cycles	152°		[98]
Hexadecyltrimethoxysilane; cellulose nanocrystal; epoxidized oil resin as a binder. *By dip-coating method*	Oil/water separation; Solvent and chemical resistance; reusable for ten extraction cycles; hydrolytically degradable in 10 weeks and renewable	157°		[99]
Hexadecyltrimethoxysilane; stearic acid; triethoxy(octyl) silane; silica NPs. *By dip pad-dry-cure*	Water uptake; stain repellency and anti-soiling; resistant to 1 h of ultrasonic washing in ethanol	161°	10° (13 μL)	[100]
Vinyl trimethoxysilane (VTMS); mercaptan carbon chains. *By solution-immersion*	Self-cleaning; Oil-water separation for 20 extraction cycles; resistance to organic chemical solvents, extreme temperatures, UV irradiation, and 20 abrasion cycles	156°	8°	[101]
PDMS; TiO_2 NPs. *By dip-coating*	Self-cleaning; catalytic photodecomposition; resistance against organic and inorganic corrosives, 48 h UV light exposure; durable to 30 washing cycles	153°		[102]
Hydroxyl-terminated PDMS; tetraethoxysilane ammonium polyphosphate. *By plasma treatment and sol-gel*	Flame-retardancy; self-cleaning	160°		[103]
Silres BS39A; polyethylene. *By simple dip coating*	Super-oleophilic and selective oil and organic solvents absorption; oil/water separation under various chemical solutions; reusability for ten extraction cycles	135°		[104]

(continued)

Table 18.1 (continued)

Chemical agents and imparting techniques	Highlights	WCA	WSA	Refs.
Vinyl trimethoxysilane; TiO_2 silanized with 3-methacryloxy propyl trimethoxysilane. *By combined immersion and spraying*	Self-cleaning; oil-water separation; photodegradation for 10 test cycles	150°		[105]
Octavinyl-POSS modified with 3-mercaptopropyltrimethoxysilane. *By dip-coating*	Oil/water separation; Resistance against 24 h UV light exposure, chemical corrosion, 60 min ultrasonic washing, and 180 scratch cycles	142°		[106]
Organosilicon sol and GO particles. *By sol-gel*	Surface resistance of 2.7 MΩ sq^{-1}; resistance against 30 cycles of strain forces and intense sonication in SDS	150°		[107]
Polydimethylsiloxane; carboxylated and aminated multiwalled CNTs. *Using layer-by-layer assembly*	Oil/water separation for 30 cycles; pressure sensor for human motions	162°		[108]
PEI; SiO_2; Polyphosphoric acid; REPELLAN FF. *By layer-by-layer deposition and dip-pad-cure*	Flame retardancy; thermal stability	142°		[109]
Chitosan; phytic acid; SiO_2 modified with hexamethyldisilylamine. *By layer-by-layer deposition*	Fire-resistance; thermal and mechanical stability; anti-fouling; self-cleaning; durability of 50 abrasion cycles	150°	˜5°	[110]
HMDSO/toluene. *By plasma modification*		174°		[111]
Alkylamines				
Octadecyl amine; octa decanethiol; polydopamine nanocapsules. *By dip coating*	Durability of 500 stretching cycles, 50 compression cycles, 1 min rubbing with hand and 5 min mechanical washing; self-healing	152°		[112]
Octadecyl amine; tannic acid; Fe(III) metalorganic hybrid. *By dip coating*	Self-cleaning; oil-water separation; resistant to corrosive chemicals and 25 washing cycles	145°	–	[113]
Octadecylamine; Laccase/2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPO). *By solution-immersion*	Resistant to 8 laundering cycles; retained mechanical strength	117°		[114]

(continued)

Table 18.1 (continued)

Chemical agents and imparting techniques	Highlights	WCA	WSA	Refs.
Dopamine and octadecylamine. By *solution-immersion*	Resistant to 1000 abrasion cycles	154°		[115]
Polydopamine encapsulated octadecylamine; Fe_3O_4 NPs. By *solution-immersion*	Durability of 40 h laundering in water and 500 abrasion cycles; Photoinduced self-healing	152°		[116]
Polypyrrole and polyaniline. *By solution-immersion and pad-dry*	Cell non-toxicity; Electrically semi-conductive; conductivity was resistant to laundry and friction tests	90°		[117]
Poly/monoacrylates				
Poly (2-dimethylaminoethyl methacrylate). *By dip-dry*	Self-cleaning; oil/water separation and oil release in acidic water for five cycles	130°		[118]
2-(dimethylamino)ethyl methacrylate. *By dip-dry*	Oleophilic with OCA of 30°; oil/water separation; Switchable hydrophilicity and hydrophobicity after CO_2/N_2 alternation for seven cycles; improved tensile strength; resistance to 600 abrasion cycles	140°		[119]
Stearyl methacrylate (SMA)monomers. *By dip-dry*	Resistant to 30 laundering cycles	149° (5 μL)		[120]
Lauryl methacrylate (LMA). *By mist treatment*	Water absorbability and vapor transmissibility; durable with 35 laundering cycles and 2000 abrasion cycles	150°		[121]
Alkyl acrylates like methylmethacrylate, polylauryl methacrylate. *By dip-dry*	Vapor transmissibility	150°		[17]
TiO_2 and ZnO NPs; MTP-acrylate commercial binder. *By dip-dry-cure*	Improved UV protection and mechanical properties; antibacterial action against *S. aureus*	160°		[122]
Ethyl-α-cyanoacrylate; SiO_2 NPs. *By spray coating*	Wound healing; self-cleaning; breathability; resistance against 40 abrasion cycles	154°	16° (10 μL)	[123]
Poly[(methyl methacrylate)-*b*-(trifluoroethyl methacrylate)] diblock copolymer. *By mist treatment*	Oil/water separation; flexibility; water absorbability and vapor permeability; durability against 2000 abrasion cycles and 60 laundering cycles; self-healable with perchloroethylene	160°		[124]

(continued)

Table 18.1 (continued)

Chemical agents and imparting techniques	Highlights	WCA	WSA	Refs.
Other silicone/fluorine-free treatments				
Derivatives of catechol with various alkyl chain substituents. *By dip-dry*	Selective oil-absorption; water/oil separation for 5 extraction cycles	133°		[125]
Graphene oxide. *By dip-dry*		143°		[126]
Silica NPs; silver NPs. *By dip-dry-cure*	Improved textile properties; UV protection; antibacterial properties against *S. aureus*	145°		[127]
TiO_2/Ag/AgBr. *By simple spray coating*	Antibacterial activity; selective oil adsorption from oil/water mixtures; UV blocking; photocatalysis; improved mechanical properties; resistance to 1 washing cycle	149		[128]
Diamond-like carbon. *By plasma-enhanced chemical vapor deposition*	Self-cleaning; durability of 12 months	146°	13°	[129]
Bismuth oxy-iodide (BiOI) nanosheets. *By dip-dry*	Photodegradation ability; UV shielding; self-cleaning	140°		[130]
Polybenzoxazine; SiO_2. *By dip-coating*	Oil/water separation; improved mechanical properties; heat and chemical resistance; durable to 30 abrasion cycles and five washing times	154°	3°	[131]
Naturally bio-based materials				
Stearic acid; epoxidized soybean oil resin. *By dip-dry-cure*	Oil/water separation for ten times reuse; thermal stability; resistance against solvent erosion and low/high temperatures; durability of 14 abrasion cycles, 100 tape peeling cycles, 60 min of ultrasonication	155°		[132]
Stearic acid; epoxidized soybean oil with sebacic acid; ZnO NPs. *By simple spray-coating method*	Selective separation of oil-water mixtures; resistant to chemical corrosives; superhydrophobicity after water and oil immersions for ten days	155°		[133]

(continued)

Table 18.1 (continued)

Chemical agents and imparting techniques	Highlights	WCA	WSA	Refs.
Stearic acid; Mg–Al layered double hydroxides linker. *By solution-immersion*	Oil absorption; reduced processing time; stability in alkaline medium	150°		[134]
Stearic acid (SA); ZnO nanorods. *By dip-dry*	Oil/water separation for 10 cycles; self-cleaning; Resistance to corrosive liquids and UV irradiation; biodegradability	164°		[135]
$SiCl_4$/stearic acid. *By immersion*	Removal of used cooking oil and motor oil	124°		[136]
$SiCl_4$/dimethyldichlorosilane. *By vapor deposition*		130°		
$SiCl_4$/POTS(C8). *By vapor deposition*		155°		
Poly(caffeic acid); Fe. *By dip-dry*	Oil-water separation for ten times; self-cleaning; resistant to 100 abrasion cycles and different chemicals	158°		[137]

homopolymer, PC_4SMA/SA through free radical polymerization of C_4SMA (2-[[[[2-(perfluorobutyl)]sulfonyl]methyl]amino] ethyl methacrylate), and copolymer, SA, using tetrahydrofuran [61]. Consequently, cotton fabric was treated with the emulsion through the solution immersion technique, to form a super water-repellent textile. The as-prepared cotton fabric preserved household liquids such as water, coffee, milk, rice wine, tea, ink, salad oil in beaded forms; thus, denoting omniphobicity. The as-prepared cotton fabric also presented water and oil repellency of 100 and 3 test ratings, respectively. In the same year, Li's group devised three C6 fluorinated alkylsiloxylmethacrylates by incorporation of short multi-perfluorinated alkyl groups on each silicon atom [62]. By applying emulsion polymerization, the authors then reacted to the fluorinated alkylsiloxylmethacrylates with additional acrylic monomers, including BA, MMA, and HEMA, to form three perfluoroalkylsiloxyl polymethacrylate latexes. Finally, they functionalized cotton fabrics with the fluorinated alkylsiloxyl acrylic latexes via solution dipping method with post-nipping-drying-curing steps. With an increase in the number of fluorine atoms on the respective latexes, the modified cotton fabrics presented a gradual increase of WCAs, while their adhesive forces and zeta potential decreased. This observation was attributed to each silicon atom having various fluorinated moieties, thus creating an air-film interface endowed with functional groups having lower surface free energy [62]. Later on, Bayer's group generated robust woven cotton fabrics with high water repellency by applying bilayer coatings [63]. Via a solution dipping technique, the authors first coated a single layer using a commercially available C6 perfluorinated acrylic copolymer (Capstone ST-100), merged with nanoparticles of silica and silicone (PDMS) resin. The coated cotton fabric presented 145° WCA, 19° WSA, and upheld hydrostatic head pressure resistance of 2.65 kPa. Conversely, it was susceptible to cycles of ultrasonic washing and mechanical abrasion. As a remedy, the authors effectively applied another layer of acetoxy-cure silicone resin of PDMS, and formed a new coated fabric with sustained hydrophobic and water-resistant properties, even after washing and exposure of up to 30 abrasion cycles. The new coated fabric had WCA of ~150° and WSA of 17°, slightly improved after the addition of the subsequent PDMS layer. In 2018, Maity's group generated both hydrophobic and oleophilic cotton fabric with C6 fluorochemical polymers with particularly four fluorine-containing carbon atoms, as-synthesized via admicellar polymerization [64]. The treated fabric had a low WCA of 126°, though its surface also sustained water droplet (10 μL) mobility. Surprisingly, the treated cotton fabric exhibited oleophilic behavior. Whereby, an octane droplet with the surface tension of 21.62 mN/m could easily spread when placed on the surface. This anomaly of the C4 fluoropolymer chains was attributed to the enhanced surface free energy after coating. Still, the treated cotton fabric was successful with the separation of chloroform/water mixture [64]. To study C3 fluorinated polymer chains, Chen, Zhou, and Ma prepared a hydrophobic cotton fabric by solution immersion and dip-nip-dry method, using cationic fluorinated polyacrylate (C_3F_6 side chains) emulsions without emulsifiers [65]. The authors first synthesized poly (DMAEMA)-b-poly(HFBA), acting as both stabilizer and macro-RAFT agent for initio-RAFT emulsion polymerization. With such a low amount of fluorine on carbon atoms (C_3F_6), the functionalized cotton fabric had WCA of 141°. Likewise, Liu's group exploited a copolymer of 2,2,2-trifluoroethylmethacrylate (TFMA) possessing 2-isocyanatoethylmethacrylate and CF_3 side chains, to impart superhydrophobicity onto the surface of cotton by mist polymerization [66]. The treated cotton fabric achieved a very high WCA of 151° at a concentration of 1.38 mol/L of TFMA. Unfortunately, the superhydrophobic character of the treated fabric lowered with prolonged contact. Lai's group prepared a superhydrophobic cotton fabric via ATRP of GMA and heptafluorobutyryl chloride (C_4F_7OCl), using Cotton-Br as a microinitiator [67]. Cotton-Br was first synthesized by reacting 2-bromoisobutyryl bromide with the cellulosic cotton, and then poly(GMA) (PGMA) and C_3F_7 functional groups were respectively implanted onto the surface after that. The Cotton-PGMA-C_3F_7 fabric exhibited unstable superhydrophobic character after some longer period, which inspired the authors to opt for a graft-on-graft method to increase the length of PGMA brushes, on the addition to further functionalization with C_3F_7 moieties. These graft-on-graft functionalized cotton textiles were characterized by PGMA-g-PGMA-C_3F_7 functional groups and excellent superhydrophobicity, unlike their counterparts. The elongated cotton fabric also demonstrated improved surface water mobility and minimal adhesion force. The authors attributed this upshot to change in conformation of lengthy PGMA-g-PGMA brush, in addition to a very high density of C_3F_7 moieties at the interface of the liquid and solid. The elongated cotton fabric also presented superior resistance against numerous cycles of laundry and abrasion, and high stability with 6.8° decrease in WCA, after 15 days [67].

Perfluorinated waxes (PFWs), also known as polyfluorowax, normally possess short and long fluorinated carbon chains (≥C3–C24). They have been prepared for the main use as skis, to purposely reduce wet friction for a better performance during winter sports [142]. They are rarely used in textiles and hence less researched. Zhang's group assembled PFW (≤C6 chemistry)/graphite fluoride (GF) complexes onto the cotton surface to prepare durable and self-healable superhydrophobic cotton fabrics in a single step [69]. The PFW/GF functionalized cotton fabric presented excellent superhydrophobic character with WCA and WSA of 157° and 5°, respectively. They also exhibited a lotus leaf-like silver mirror effect when submerged in water. Nevertheless, the treated fabric was self-healable when damaged by O_2 plasma etching for several times. The functionalized cotton fabric allowed dyeing property and was resistant to harsh environmental changes and numerous cycles of wear abrasion [69].

Other C6 fluorinated polymers have also been studied. For instance, Balasubramanian's group innovated an approach for preparing hydrophobic-oleophilic nano-engineered Janus cotton textiles, comprising of electrospun nanofibrous mate sandwiches of polyvinylidene fluoride (PVDF), in the presence and absence of silicon carbide (SiC) [71]. The modified Janus fabrics with only PVDF possessed WCA of 113°, whereas those with PVDF/nano-SiC coating, had a reduced WCA of 96°. On the converse, both cotton fabric coatings had OCA of 0° and, therefore, easily absorbed the oil in machine oil and oil/water mixtures such toluene/water and ethanol/water mixtures. This was owed to the large surface area of the porous structure, interconnected network and facilitated capillary action of the electrospun Janus fabric.

Silicon monomers/polymers such as silanes, siloxane or silicone resins, and polysilsesquioxanes (POSSs) are also popular water repellent agents. The cotton fabrics treated with the long alkyl chained resins exhibit extremely high WCAs on their surface. Hence the extent of hydrophobicity being dependent on the chain length of the alkyl group coated on the fabric. These silicon-based materials are frequently melded with NPs to impart superhydrophobicity onto cotton fabrics. Since silicon-encompassed agents have no fluorine and accessible as waterborne dispersals [143], they have a high potential for industrial application. Li's group engineered silica NPs from tetraethyl orthosilicate (TEOS) via a one-step sonochemistry irradiation technique and modified with octadecyltrimethoxysilane (OTMS), to assemble superhydrophobic and super-oleophilic cotton/spandex fabrics (~0.90% spandex) [75, 76]. The functionalized cotton/spandex fabric presented a high WCA of 158° and OCA of 0°, thus confirming its superhydrophobic-super-oleophilic modification. These silica-coated cotton/spandex fabrics achieved high oil/water separation capacity from various mixtures, for example, separation efficiencies of 99% for kerosene and 98% for chloroform from mixtures of 1:2 oil/water ratio, and >98% efficiency for n-hexane, heptane, chloroform, toluene, and petroleum ether. The cotton/spandex fabrics demonstrated a durable oil absorption capacity with a small WCA reduction, from 158° to 150° after 40 absorption cycles, and slight WCA alteration after abrasion cycles of 300 times. The cotton/spandex fabrics also expressed resistance against numerous harsh settings such as 1 M NaOH, 1 M HCl, 1 M NaCl, and hot water immersion for 12 h. Jadhav's group exploited the pad-dry-cure method to coat zinc oxide nanoparticles onto cotton fabric. Then post-coated shorter chains of hexadecyltrimethoxysilane (HDMS) to obtain durable superhydrophobic fabric. The ZnO-coated and HDMS-post coated cotton fabrics exhibited high WCA of 91° and 152°, respectively, even after several washing cycles [98]. Vinyl groups were attached to a cotton fabric surface using vinyl trimethoxy silane (VTMS), followed by incorporation of superhydrophobic mercaptan carbon chains, via UV irradiation catalyzed thiolene click chemistry reaction. The as-prepared fabric had WCA of 156° and WSA of 8°, which remained stable under harsh conditions due to resistance to mechanical friction, extreme temperatures, UV irradiation, and organic chemical solvents. It also presented excellent oil-water separation execution, even after several separation cycles. This confirmed the efficient application of this novel technique for further functionalization of modified cotton surfaces with different polymers/chemical groups [101]. To innovate an advanced filtration material, Qiang's group assembled a robust POSS-based hydrophobic cotton fabric from the hydrophobic-oleophilic POSS via a one-step dip-coating strategy. The novel POSS derivate was synthesized by functionalization of the commercial agent, octavinyl-POSS (VPOSS) with 3-mercaptopropyltrimethoxysilane (MPTMS) via thiolene-click chemistry. The POSS layer endowed hydrophobicity to the modified cotton fabric membrane with WCAs above 142°. Notably, the POSS-modified cotton membrane withstood unfavorable conditions such as UV light exposure, chemical corrosion, cycles of ultrasonic washing as well as repetitive and long-lasting mechanical abrasions. The modified cotton membrane potentially separated the oil/water mixture by portraying a high permeation flux of 114,744 L m^{-1} h^{-1}.

Additionally, this activity is maintained even in the presence of harsh and highly concentrated solutions of acid, alkali, and saturated salt solutions [106].

Alkylamines with long chains have as well been effectively applied as treatment agents of cotton fabrics for imparting superhydrophobicity. For instance, Yu's group synthesized polydopamine nanocapsules of octadecanethiol and octadecylamine (ODA), as the encapsulated superhydrophobic agents, and then coated onto surfaces of cotton and polyester textiles using the dip-coating technique. The coated cotton textiles possessed incredibly high WCA of 152°. The coated cotton also demonstrated self-healing mechanism on exposure to mechanical forces, including friction, stretch out, compression, and also mechanical washing, by allowing the water repellent molecules to be released and then recovered to regain hydrophobicity [112]. In a related report, Xu's group assembled tannic acid (TA) and Fe(III) metal-organic hybrid via coordination chemistry, to create micro-rough groove depositions on cotton fabric surfaces, before treatment with ODA [113]. On pre-treatment with TA: Fe (III) (4:1 ratio), the ODA modified cotton fabrics achieved hydrophobicity with WCA of 145°. The functionalized fabric demonstrated selective absorption of oil from the oil-water mixture, high stability under strong acids and bases, and long-standing washing.

Alkyl-acrylates, just like long-chain silanes, have created water repellency when applied on cotton fabric surfaces, depending on the chain length of their alkyl segment [17]. The acrylate coated fabrics have demonstrated extreme durability and selective separation of oil from mixtures. Attia's group developed smart superhydrophobic layers using MTP-acrylate commercial binder and nanoparticles of TiO_2 and ZnO for coating on surfaces of textile fabrics, including 35% cotton in polyester and 20% polyester in cotton [122]. The modified textiles achieved WCAs of up 160°. Nevertheless, the nanoparticles supplemented improved protection from UV and mechanical abrasions, and antibacterial action onto the fabrics. Recently, Xiangdong's group synthesized a durable and self-healable superhydrophobic layer of poly[(methyl methacrylate)-*b*-(trifluoroethyl methacrylate)] (PMMA-*b*-PTFMA) diblock copolymer via RAFT polymerization, for coating on cotton surfaces using the mist-treatment method (Fig. 18.2A–C) [124]. The modified cotton fabric (Fig. 18.2b, d) possessed WCA above 160° and excellent stability, whereby WCA remained higher than 140° after 2000 abrasion cycles or 60 laundering cycles. Moreover, this superhydrophobicity was ably 99% renewed by applying perchloroethylene (Fig. 18.3A) [124]. The coating on the cotton fabric imposed a 100% separation efficiency of oil/water mixtures (Fig. 18.2D, E) [124]. The mist-modification approach also proved to be an efficient method for the preservation of the desired cotton properties such as flexibility, tensile strength, and vapor permeability (Fig. 18.3(1–4)).

Nevertheless, Li's group used various functional alkyl methacrylate monomers to show that the lengths of the alkyl chain moieties determine the surface hydrophobicity, graft density, and the degree of grafting polymers [17]. For example, cotton fabrics modified with short alkyl chains required higher grafting density to occupy the entire fabric surface area, whereas a lower critical grafting density was required for those with long alkyl chains.

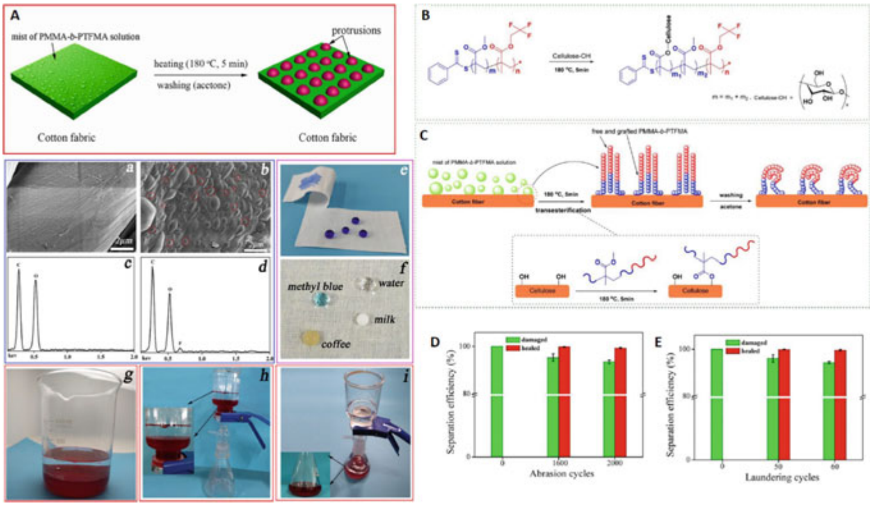

Fig. 18.2 **A** Schematic illustration for the preparation method and conditions, **B** surface modification process of cotton via transesterification of PMMA-b-PTFMA copolymer with cellulose, and **C** self-assembly of PMMA-b-PTFMA chains on the surface. SEM images and EDS spectra of **a**, **c** unmodified side, **b**, **d** modified side, and **e**, **f** optical images of the Cotton-1 fabric sample. **g** Water-$CHCl_3$ mixture, **h** before, and **i** after the separating experiment. The oil-water separation efficiency of Cotton-1 fabric during the **D** abrasion, and **E** laundering processes, reprinted from Ref. [124], copyright 2020, with permission from Chemical Engineering Journal

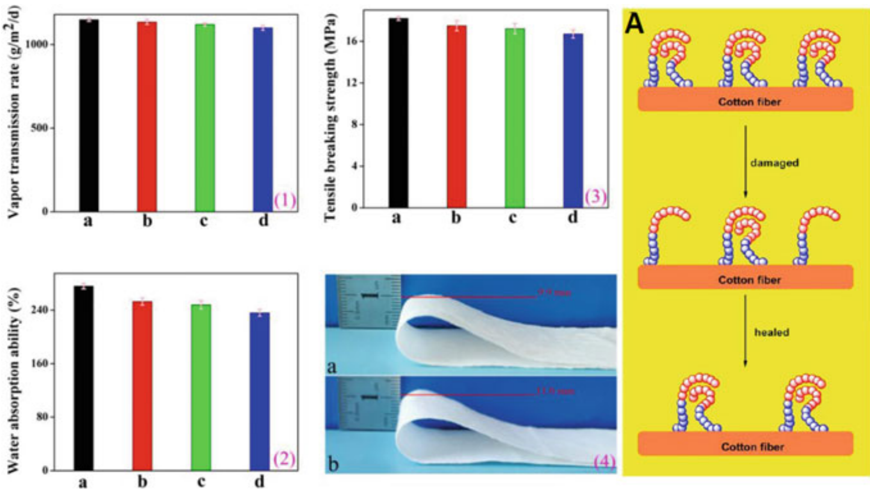

Fig. 18.3 Effect of surface modification on different physical properties of cotton; (**1**) water vapor transmissibility, (**2**) water absorbability, (**3**) tensile strength, and (**4**) flexibility. (a) Original cotton, (b) Cotton-1, (c) Cotton-2, and (d) Cotton-3 fabric samples. **A** The schematic diagram of the self-healing mechanism after mechanical abrasion, reprinted from Ref. [124], copyright 2020, with permission from Chemical Engineering Journal

Among the silicone/fluorine-free treatments, Bisque's group reported robust and efficient water repellent textiles, functionalized with several derivatives of catechol having linear alkyl chain groups of various lengths and in different numbers [125]. The WCA of the functionalized cotton fabrics were higher with longer polymer chain coatings, for instance, cotton fabric coated with 1% w/v solution concentration of poly-4-undecylcatechol (poly-C11) presented a low WCA of 140°. The authors also verified that double-long alkyl chain (3,5-diheptadecylcatechol) substituted catechol-based coatings on the textile materials do not provide a substantial enhancement in the water repellency performance. In addition to the hydrophobic polymeric agents, cotton fabrics have also been hydrophobized through treatment with graphene oxide [126], nanoparticles with or without binding polymers [43, 46, 127, 144, 145] and water repellency via plasma-induced surface roughness [129].

Naturally, bio-based materials have also been recently exploited to prepare environmentally benign biodegradable hydrophobic cotton and other cellulosic fabrics [15, 133, 146, 147]. For instance, stearic acid was utilized to insert hydrophobicity onto cellulose [134]. Nevertheless, natural polymers, unlike synthetic, have hindrances such as low thermal stability, moisture-prone, and poor chemical properties that do not favor the attainment of superhydrophobicity threshold (WCA ≥ 150°). In order to achieve renewable, biodegradable and non-toxic traditional superhydrophobic cotton fabrics, Jian-Bing's group prepared robust nanoparticle and fluorine-free cotton fabrics, through acid-etching followed by coating the surface of cotton fabrics with epoxidized soybean oil resin (CESO) and subsequent addition of stearic acid (STA) for low surface energy modification (Fig. 18.4A) [132]. The modified fabrics portrayed immense resistance against acidic and alkaline water droplets

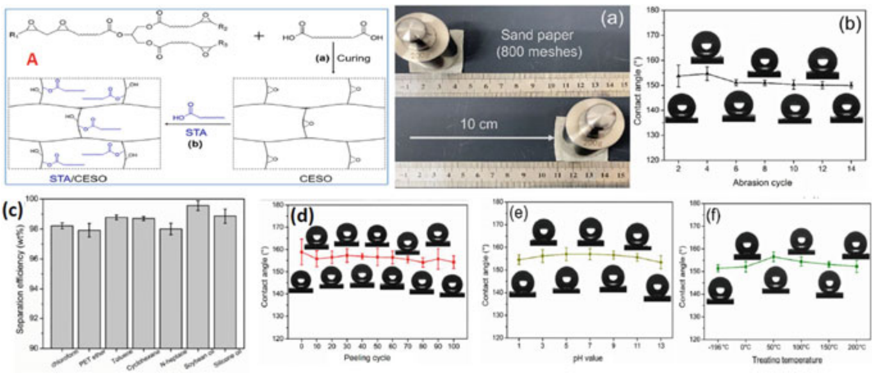

Fig. 18.4 **A** Schematic illustration for curing epoxidized soybean oil with sebacic acid to form CESO (a) and reaction of STA with residual epoxy groups of CESO (b). **a** Photograph of the abrasion process. **c** The separation efficiency of different oil/water mixtures. Variation of water contact angle of treated cotton fabric with **b** abrasion cycles, **d** peeling cycles, **e** different pH water droplets and **f** at different temperatures for 5 h. Insets are optical images of 5 μL static water droplets on corresponding treated fabric surfaces, reprinted from Ref. [132], copyright 2019, with permission from the International Journal of Biological Macromolecules

with WCA over 150° (Fig. 18.4e) [132]. Moreover, the treated fabric effectively separated oil/water mixtures by registering above 97.9% efficiency, while sustaining the repellence property even after 10 times reuse. With exceptional mechanical, chemical, and environmental stability (Fig. 18.4a, b, d–f) [132], the biologically-modified cotton fabrics are environmentally benign substitutes to traditional superhydrophobic textiles, with efficient oil/water separation potential (Fig. 18.4c) [132].

18.3 Flame Retardancy

Fires cause colossal property loss, loss of lives, and world-wide damages every year. Accordingly, property loss worthy multimillions of dollars and above 70,000 victims are reported annually around the globe. Therefore, it is essential to counteract fire risks by adopting flame-retardant management of ignitable materials, to suspend combustion and impede the spread of flames [148, 149]. Textile materials such as cotton fabrics take most applications of industrial products consumer needs, and therefore, their flammability is a vital issue. Cotton is a natural cellulosic fiber, highly susceptible to fire due to its low LOI of 18% and combustive temperature of 350 °C [150]. That is, when cotton is ignited, it burns very fast to form a dangerous flame in less than 15 s [151], causing human mortalities and property loss higher than those due to natural tragedies. This restricts their applications. However, there has been a progressive study of fire retardancy for cellulosic materials, which has dramatically developed the technology of flame resistance for cotton fabrics [152].

Flame-resistant agents potentially lessen fire threats by delaying the combustion time, hence deterring flames to propagate [148, 153], and formation of a layer of char to protect the modified cotton fabric from heat conduction and emission of burnable volatiles, thus boosting cotton's extinguishing ability [154]. Flame-resistant cotton fabrics have been created from agents with chemical compounds such as halogens, which have been commonly used due to their high efficiency. But these generate poisonous and caustic HCl and HBr gases during thermal degradation [155]. Therefore, numerous eco-friendly cotton retardant agents containing phosphorus, nitrogen, silicon, boron, zinc, and aluminum, were investigated to replace the halogenated agents. Though, agents containing phosphorus showed the most significant potential because they can be burnt into phosphorus-based acids with low smog, which accelerates char formation from the cotton fabrics [156–159]. Cotton fiber and cotton-endowed fiber materials have two characteristic flame retardants of organophosphorus developed for them, that is, Pyrovatex CP® (Ciba) and Proban® (Rhodia). Pyrovatex CP®, in particular, links tightly with cellulosic materials via C-O-C covalent bonds, granting the functionalized samples with hard-wearing flame-retardancy. Inversely, phosphorous treated cotton fabrics, emit carcinogenic formaldehyde when used [160]. Therefore, research has targeted efficient non-formaldehyde fire-resistant materials. As a solution, innovative, long-lasting, and eco-friendly intumescent flame-retardant molecules have been treated on cotton fabrics. Intumescent flame

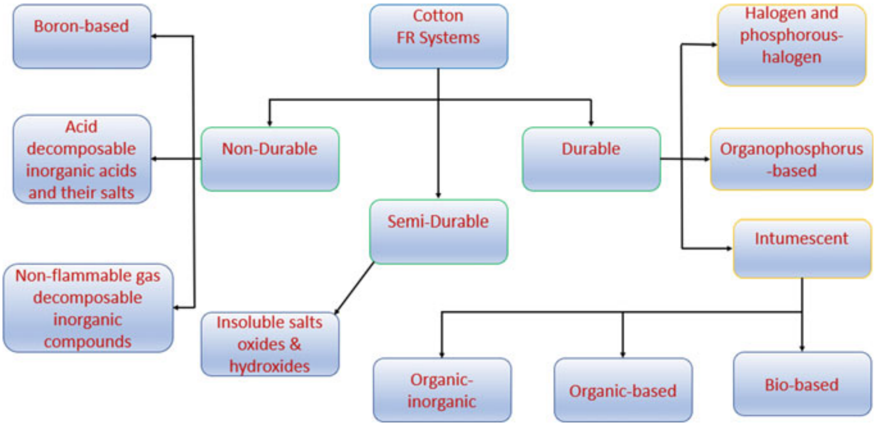

Fig. 18.5 A summarized description of the FR-systems of cotton fibers and fabrics

retardants contain both phosphorus and nitrogen elements linked with a P-N covalent bond, thus impose synergistic effects in the fabric [161, 162]. They include natural agents like proteins, phytic acid, and deoxyribonucleic acid (DNA) [163, 164] and synthetic agents. Nevertheless, flame retardant agents with P-O-C covalent bonds, have also imparted excellent fire resistance and durability properties on treated cotton fabrics [165–167]. Figure 18.5 briefly describes the categorization of the different flame resistant/retardant (FR) agents that have been utilized on cotton textiles.

For instance, Zhang's group functionalized cotton fabrics with tetra-ethylene pentaamine heptamethyl phosphonate ammonium salt (ATEPAHA), via P-O-C covalent bonds. The LOI value of modified cotton fabrics with 18% and 26% ATEPAHA contents, attained 37.0% and 40.5% values, and these decreased slightly to 28.2% and 31.8%, respectively, over 50 washing cycles. The maximum heat release rate of modified cotton (14.64 kW/m^2) was significantly below that of pure cotton (186.55 kW/m^2). Therefore, ATEPAHA endowed cellulosic cotton with high grafting, excellent sturdiness, and effective fire resistance, without compromising its tensile strength and soft hand [168]. Meanwhile, Guangxian's group had previously grafted phosphorus ammonium phytate (APA), a plant-derived formaldehyde-free flame retardant, onto cotton fabrics via P-O-C covalent linkages. The grafted cotton fabric recorded a reduced char length by 269 mm, a high LOI of 43.2%, which persisted above 30.5% even after 30 laundering cycles, thus suggesting its sufficient semi-durable flame retardancy. It also registered a reduced heat release rate and thermal oxidation stability [169]. In order to attain high whiteness in a piece of durable modified cotton fabric, Guangxian's group synthesized a self-buffering flame-retardant ammonium amino trimethylene phosphate (AATMP), using a single-step water-solvent technique, and crosslinked onto cotton fabric via the dip-dry-cure process (Fig. 18.6A) [170]. The 15% AATMP functionalized cotton presented LOI values of up to 43.9% (Fig. 18.6c) [170], and these were maintained above 34.8%

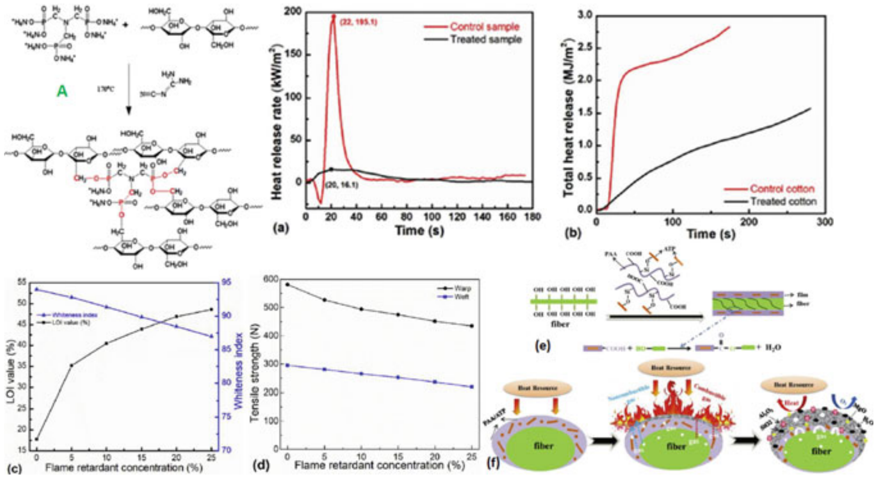

Fig. 18.6 **A** Grafting reaction of AATMP and cotton fibers. **a** Heat release rate and **b** total heat release curves of fabrics. Effect of AATMP flame retardant concentrations on **c** LOI values and whiteness indices and **d** tensile strength of cotton samples. Based on reported data [170]. Copyright 2019, Polymer Degradation, and Stability. **e** Schematic illustrations of PAA/ATP nanocomposite on the cotton fiber surface and **f** its flame-retardant mechanism, reprinted from Ref. [171], copyright 2019, with permission from Carbohydrate Polymers

and 29.7%, after 30 and 50 laundering cycles, respectively. For comparison, no after-flame was expressed during the vertical flammability test, thus suggesting the durability of AATMP as a flame retardant. The total and peak heat release of functionalized cotton were 1.6 MJ/m^2 and 16.1 kW/m^2 less, compared to pure cotton (2.8 MJ/m^2 and 195.1 kW/m^2), respectively (Fig. 18.6a, b) [170], which strongly authenticated the efficient fire resistance of AATMP. The treated material also had a sustained tensile strength (Fig. 18.6d).

For natural and environmentally friendly non-P-O-C flame retardants, Dangge's group applied free radical polymerization to synthesize attapulgite-poly (acrylic acid) (ATP-PAA) nanocomposite from 3-methacryloxypropyltrimethoxysilane-modified attapulgite and acrylic acid, and after that coated cotton surfaces with the nanocomposites, using dip-pad-dry process (Fig. 18.6e) [171]. The nanocomposite-modified cotton fabric displayed improved mechanical, thermal, and flammability properties, with the LOI value and breaking strength of up to 22.7% and 420.9 N, respectively, though the whiteness decreased slightly. These were attributed to the presence of attapulgite in the nanocomposite (Fig. 18.6f) [171]. This research portrayed the effectiveness of the hazardous-free natural compounds, PAA and ATP, upon flame retardancy.

For intumescent flame-retardant materials, Xue's group applied the pad-dry-cure technique to deposit phosphorus-nitrogen (P-N) enriched ammonium polyphosphate, branched poly(ethylenimine) for flame retardancy, and polyacrylate soap-free latex to add superhydrophobic properties onto cotton fabrics [95].

The modified textile presented durability and flammability potential with LOI value reaching 24.86%. Furthermore, Przybylak's group synthesized Hexakis(3-(triethoxysilyl)propyloxy)cyclotriphosphazene (P-N/L) using hydrosilylation for the first time, and directly bonded to the cotton fiber surface. The renovated cotton textiles portrayed flame retardation, which became more reliable with both increasing concentration of a layer in a single step and after modification. In particular, the 5% (P-N/L) mercerized and silanized cotton fabric exhibited an over 80% decrease in Qmax compared to neat fabric and a 27.7% oxygen index. This was attributed to the existence of synergism between P-N-enriched compound and tetraethoxysilane, for additional protection of fibers against the fire sources. More considerably, the modified fabrics were wash-resistant [172].

Dendritic structures have numerous ends with functional groups, molecular symmetry, and unique physical and chemical properties that favor their application as flame retardant agents. Malek's group [173] enhanced the fire resistance, dye adsorption, and antimicrobial potential of cotton fabrics after grafting on poly(propyleneimine) dendrimer with terminating amino groups using crosslinking agents of polycarboxylic acids. Mahdi's group [174] also functionalized cotton fabrics with second and fourth generation poly(amidoamine) (PAMAM) dendrimers with aminated end groups, as novel flame retardant agents, using citric acid (CA) as a cross-linker. The modified cotton fabrics presented excellent flame-retardant behavior with LOI values of over 25% and 0.16 mm/s decrease in burning speed, for the vertical flame test. Additionally, the modified cotton fabrics not only left more residue of 2 mm char length but also had good durability after repeated washing cycles and rubbing fastness. This confirmed a protective role of PAMAM and CA on the degradation of cotton fabric [174].

In another vie to eradicate fluorinated flame-retardant agents, nanoscale particles such as inorganic metallic ions like silica, alumina, zinc oxide, and zirconia have been applied for functionalization. These nanoparticles are not only more stable than organic metallic substances but are also incorporated easily in cellulosic materials [175]. For instance, Xu's group uniformly incorporated NPs of SiO_2 and ZnO onto cotton and cotton-polyester fabrics via the sol-gel process for the formation of durable flame retardant fabrics [176]. The $SiO_{2,}$ for example, are endowed with large amounts of water, which facilitated the reduction of burning kinetics and production of smoke [177] while photocatalytic ZnO promoted char formation, thus enhancing flame retardancy [178].

18.4 Conclusion Remarks, Challenges, and Prospects

The arena of modification of cotton textiles for physical applications such as superhydrophobicity and flame retardancy is endlessly undergoing evolution, as portrayed in this chapter, owing to the numerous driving forces. These have caused innumerable effort towards designing novel products with high effectiveness, scalability to industrial use, and certainly with appreciable durability. However, some research products have been affected by the low environmental impact, which poses a threat to their effectiveness. This discrepancy is very important to pose new challenges for further research in the future.

As elaborated in this chapter, after the exclusion of certain agents such as C8 fluoropolymers for superhydrophobicity and halogenated compounds for flame retardancy from practical use, other novel agents have been executed in various studies. Also, cotton textile treatments such as layer-by-layer construction, dip-coating, solution immersion, spray coating, and sol-gel have been applied along with various mechanisms of chemical modification. However, most of these procedures involve the dissolution of the agents using various solvents to enable impregnation onto cotton surfaces. Most chemical agents are soluble in organic solvents such as tetrahydrofuran, cyclic hydrocarbons, chlorinated hydrocarbons, alcohols, and ketones. These are expensive, not easily recyclable, and apart from some alcohols and water, most of them are detrimental to the environment. Equally, some of these reported coating techniques such as layer-by-layer deposition, require multiple steps which appear complicated, require much time and high production costs. Therefore, simple procedures and novel alternative approaches should be emphasized. Also, some modifying agents are expensive, unavailable, none-waterborne dispersions, have low rates of bio-clearance, and highly toxic. Therefore, the use of natural or bio-based materials should be put into more consideration to create modified cotton materials for frequent future use. However, durability against various conditions and their allergic potential effects onto human skin should be the other issues to consider during the research studies. This chapter also shows more need for research investigation into transforming these modified cotton materials into water-borne versions. Finally, with the incorporation of green science to reduce the release of water wastes and nanotechnology to improve the compatibility of the agents, the manufacture of precise advanced cotton textiles for future application in an eco-friendly environment is achievable.

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Chapter 19
Advanced Biological Applications of Modified Cotton

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Abstract Microbes, such as bacteria and fungi that attach or enter into human bodies through either wounds or natural openings, and disease-spreading insects such as mosquitoes, usually are present in our living environment. These can be hazardous to our health if the human environment, especially those comprising of textile materials, is kept unhygienic. With the current public awareness of environmental sanitation for good health, there has been an increasing demand for disinfected, hygienic, clean, easy-care, comfortable, and protective cotton textiles. These have been studied through the incorporation of synthetic and natural agents onto cotton materials, to provide advanced biological functions such as antimicrobial activity, wound healing, insecticidal potential. This chapter, therefore, reports the current state-of-art for modification of cotton fabrics for advanced biological applications. It also highlights the developments in the biocidal agents, incorporation mechanisms and imparting techniques, the treated bugs, quality, and effectiveness of the obtained products. Finally, the chapter is wrapped up with concluding remarks, including research gaps and future opportunities.

Keywords Treated cotton · Antimicrobe · Medical · Insecticide · Bioactive agents

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Abbreviations

Ag NPs	Silver nanoparticles
BA	Butyl acrylate
BR	Bacterial reduction rate
DD	Degree of deacetylation
HPLC	High Performance Liquid Chromatography
LODs	Limits of detection
MOFs	Metal–organic frameworks
NPs	Nanoparticles
NSAIDs	Non-steroidal anti-inflammatory drugs
PDMS	Polydimethylsiloxane
PEG	Polyethylene glycol
RSDs	Relative standard deviations
SERS	Surface-enhanced Raman spectroscopy/scattering
SP	Solid phase
UV	Ultra-violet
WCA	Water contact angle
WSA	Water shedding angle

19.1 Antimicrobial

Due to their high surface area for the habitation of microorganisms, textile materials, especially those used as hospital fabrics, baby wears, sports outfits, bras, and underwear, are remarkable mediums for microbial growth [1, 2]. Being natural cellulosic textiles, cotton fabrics, in particular, especially those for medical and home use, are prone to growth and transmission of pathogenic microorganisms such as bacteria, fungi, and molds [3, 4]. This is attributed to their porous structure that allows a high surface area for the retention of moisture, thus providing appropriate conditions for microbial contaminations [1, 2, 5, 6], such as dirt odors, skin allergies, discoloration, mold and fungal straining, cross-infection in hospitals, and even degradation. Therefore, with the increasing awareness about hygiene and personal health, scientific research has recently received great demand for the advancement of antimicrobial properties among textile materials [7]. These surface modification advancements have not only allowed antimicrobial action but also added novel characteristics, for example, biocompatibility, water repellency, and self-cleaning to the materials while sustaining their stability and mechanical strength [8]. Thus, as well as finding use in the food processing industry [9, 10].

Antimicrobial agents function by preventing the growth of odor-creating bugs, reducing potential settling of microbes on textile surfaces, and allowing the ability to minimize the risks of health complications [11]. Selection of antimicrobial agents for modification demands standards such as their activity, toxicity, effectiveness, cost, laundry durability, and stability during release [12, 13]. The stability of antimicrobial finishing agents is classified into two groups, permanent/durable and impermanent [13]. Permanent finishing agents are normally characterized by a slow-release system of chemicals from treated fabrics to neutralize microbes [14]. While impermanent finishing agents not only easily attain treatment onto fabric surfaces, but they are also easily washed away [15]. Therefore, the various antimicrobial agents applied on cotton surfaces for effective resistance against bacteria, fungal bugs, and molds [16], include synthetic agents such as nitro-based compounds, oxidizing agents, metallic complexes, phenolics and dyes, onium and quaternary ammonium salts [17–22], triclosan, imidazolium salts, Nanoparticles (NPs) of Ag, TiO_2, CuS and natural agents such as the most commonly used chitosan. Table 19.1 summarizes the different agents for antimicrobial cotton textiles.

Chitosan is an amino polysaccharide [61], existing as a natural antibacterial agent. Its antimicrobial activity is owed to its polycationic structure [61, 62] and influenced by structural factors including its molecular mass (Mw), degree of deacetylation, nature of the microbial organism, and physical factors such as pH and ionic strength [63]. Unlike chemical biocides, chitosan furthermore has a very strong activity against microbes, a high rate of execution, a wide activity range, and low cytotoxicity to human cells [29]. Chitosan's mechanism of antimicrobial activity involves electrostatic interaction of its positively charged NH_3^+ groups with the negatively charged membrane of bacterial cells and hence transforming the membrane permeability. This results in the discharge of the intracellular matrix, amino components, vitamins, among others, thereby obstructing the normal metabolic activity and hence complete cell demise [64, 65]. With such potential activity, several investigations on the incorporation of chitosan particles onto cotton textile surfaces have been charted. For instance, Ivanova and Philipchenko [66] used a simple procedure involving spraying chitosan NP dispersions onto textile surfaces, to design superhydrophobic antibacterial cotton fabrics. But previously, Li's group had made core–shell nano-particles with an approximate diameter of 300 nm, using poly-BA as core and chitosan NPs as shell, and applied the pad-dry-cure process to coat the synthesized particles onto cotton. The modified cotton had an exceptional antibacterial action against *S. aureus,* with a 99% biocidal rate [19]. In 2011, Joshi's group [22] reported antimicrobial cotton fabric acquired using the layer-by-layer method for the first time, by self-assembly of chitosan and poly(sodium-4-styrene sulfonate) coating. They noted an enhancement of the durability of antibacterial action for up to several cycles of laundering involving ultra-sonication.

On this note, several approaches, such as grafting, have been examined to impart antibacterial activity onto cotton fabrics using chitosan. This consists of using cross-linking agents such as glyoxal, glutaraldehyde, or citric acid to fix chitosan onto cellulose fabrics [67]. For instance, Liu's group [24] engineered antibacterial cotton after grafting on chitosan–gelatin microcapsules via a cross-linker of dimethylol dihydroxy ethylene urea. Their modified cotton had excellent durability with anti-biocidal action against *S. aureus* and *E. coli* of approximately 65% even after 25 laundry cycles. However, Shirai's group had previously functionalized UV-irradiated cotton fibers with chitosan via citric acid bridging link, in the presence of NaH_2PO_4

Table 19.1 Summary of chemical agents, imparting techniques, and properties of antimicrobial cotton textiles

Chemical agents and imparting techniques	Treated microbes	Highlights	Ref
Unmodified chitosan			
Poly (n-butyl acrylate); chitosan core–shell NPs *By pad-dry-cure*	*S. aureus*	99% BR rate	[19]
Chitosan NPs; poly (sodium-4-styrene sulfonate) *By layer-by-layer self-assembly*	*S. aureus*	98.7% BR rate; Hydrophobicity with 89.8° WCA; Retained handle and breathability; Durable for a laundering cycle	[22]
Fungal chitosan *By pad-dry-cure*	*E. coli; C. albicans*	100% toxicity; Durability to 10 launderings	[21]
Chitosan *By pad-dry and UV curing*	*E. coli*	100% reduction	[23]
Grafted chitosan			
Chitosan–gelatin microcapsules; dimethyloldihydroxyethylene urea cross-linker *By solution-immersion*	*S. aureus* *E. coli*	65% inhibition rate for 25 laundry cycles	[24]
Chitosan; citric acid linker *By dip-dry-cure*	*E. coli; P. chrysogenum*	100% toxicity for 43 h of inoculation	[25]
Chitosan-derived microcapsules with grapefruit seed oil *By dip-dry-cure*	*E. coli; S. epidermidis*	100% toxicity for 48 h of incubation	[26]
Chitosan-N-PEG graft copolymer; citric acid bridge *By pad dry-cure*	*S. aureus; E. coli*	Antibacterial activity for 20 laundry cycles	[27]
Chitosan; glutaric dialdehyde cross-linker *By pad-dry-cure*	*E. coli; Hay bacillus*	92.52% inhibition	[28]

(continued)

Table 19.1 (continued)

Chemical agents and imparting techniques	Treated microbes	Highlights	Ref
Chitosan; Butane tetracarboxylic acid and ArcofixNEC cross-linkers *By pad-dry-cure*	*B. subtilis; B. cereus; E. coli; P. aeruginosa; S. aureus; C. albicans*	Antibacterial activity for 20 laundering cycles	[29]
Chitosan-dendrimer PPI hybrid *Using pad-dry-cure*	*E. coli* *S. aureus*	100% toxicity Improved fabric elongation, force, and rupture. Durable for 12 washing times	[30]
Chitosan derivatives			
O-acrylamidomethyl-N-[(2-hydroxy-3-trimethylammonium) propyl]chitosan chloride *By Pad-dry-cure and cold pad-batch*	*S. aureus*	100% BR Durable for 50 washing cycles	[31]
N-(2-hydroxy)propyl-3-trimethylammonium chitosan chloride Citric acid, butane tetracarboxylic acid, and dimethyloldihydroxyethylene urea cross-linkers *By Pad-dry-cure*	*S. aureus* *K. pneumoniae* *E. coli*	Durable for 20 washing cycles	[32]
Carboxymethyl chitosan *By Pad-dry-cure*	*E. coli;* *S. aureus*	Wash fastness; Dye exhaustion; 85% BR rate; Durable for five laundering cycles	[33]
Ag NPs *By dip-dry*	*E. coli;* *B. subtilis;* *S. aureus;* *C. albicans*	1.2 cm bacterial inhibition zone for three laundering cycles	[34]
Carboxymethyl chitosan with hard-wearing Ag NPs *By mist modification and solution-immersion*	*S. aureus* *E. coli*	Water absorbability 95% bacterial inhibition for 50 washing cycles	[35]

(continued)

Table 19.1 (continued)

Chemical agents and imparting techniques	Treated microbes	Highlights	Ref
Carboxymethyl chitosan binder; Ag NPs *By pad-dry-cure*	*S. aureus; E. coli*	100% bacterial inhibition; 94% BR rate for 50 laundering cycles	[36]
Carboxymethyl chitosan and L-cysteine (Cys) binders; Ag NPs *By pad-dry-cure*	*E. coli; S. aureus*	97% BR rate for 180 washing cycles; Non-toxic to human cells	[37]
α-ketoglutaric acid modified chitosan binder; Ag NPs *By pad-dry-cure*	*E. coli;* *S. aureus*	95% BR rate for 30 washing cycles	[38]
Poly- (imidazolium vanillyl)-grafted oligochitosan Schiff bases; Ag nano-biocomposites *By pad-dry-cure*	*E. coli* *S. aureus*	92% BR rate for 30 washing cycles	[39]
1-Phenyl pyrazole-3, 5-diamine, 4-[2-(4-methylphenyl) diazenyl] and 1H- pyrazole-3, 5-diamine, 4-[2-(4-methylphenyl) diazenyl] encapsulations; liposomal chitosan *By pad-dry-cure*	*E. coli* *S. aureus*	Retained tensile strength Limited toxicity for skin fibroblast cell line	[40]
Chitosan phosphate and 1,2,3,4-butanetetracarboxylic acid; TiO_2 NPs *By pad-dry-cure*	*S. aureus; E. coli* *A. flavus; C. albicans*	Flame retardancy and thermal stability	[41]
Other Chemical Compounds			
4-(2-N, N-dimethyl amino) ethyl amino-N-(2-hydroxyethyl)-1,8-naphthalimide; chloroacetyl chloride *By solution- immersion*	*B. cereus;* *A. johnsonii;* *P. aeruginosa;* *C. lipolytica*	Zn(II) and Cu(II) detection	[42]
1-aminoanthraquinone, 2-aminoanthraquinone, and 1-amino-4-hydroxy anthraquinone *By solution- immersion*	*E. coli*	99.9% BR rate under visible light irradiation; Thermal stability; Self-cleaning; Phototoxicity	[43]

(continued)

Table 19.1 (continued)

Chemical agents and imparting techniques	Treated microbes	Highlights	Ref
2-anthraquinone carboxylic acid (2-AQC) *By solution- immersion*	*E. coli* *S. aureus*	99% photo-induced BR rate; Photo-induced self-cleaning; Thermal stability; Maintained surface morphology and tensile strength	[44]
Gentamicin and octadecyl amine; tert-butyl acetoacetate *By dip-dry*	*S. aureus;* *E. coli*	99.99% BR rate; Hydrophobic with 145° WCA for ten standard washing cycles	[45]
Poly (diallyldimethyl ammonium chloride-allyl glycidyl ether) P(DMDAAC-AGE)/Ag/ZnO composite *By pad-dry-cure*	*S. aureus;* *E. coli* *A. flavus*	99.70% BR rate; Preserved cotton's originality; The durability of 99.00% BR rate for 11 washing cycles and anti-mildew for seven days	[46]
ZnO nano-particles grafted by poly (methacrylic acid); nalidixic acid *By dip-dry*	*S. epidermidis;* *E. coli*	100% BR rate; Drug loading and release ability	[47]
Au NPs *By solution- immersion*	*E. coli*	Catalysis; UV protection; Coloration; SERS	[48]
Ag NPs of *Curcuma longa* leaf extricate *By dip-dry*	*S. pyogenes;* *C. albicans* *S. aureus;* *P. aeruginosa*	Maximum BR Wound healing potential and less cytotoxicity to fibroblast (L929) cells	[49]

(continued)

Table 19.1 (continued)

Chemical agents and imparting techniques	Treated microbes	Highlights	Ref
Ag NPs; poly-dopamine; $N_3P_3[NH(CH_2)_3Si(OC_2H_5)_3]_6$ *By dip-dry*	*E. coli;* *S. aureus*	99.99% BR rate; Flame retardancy; Durability for 30 soap washing cycles	[50]
CuO-NPs; Sodium dodecyl sulfate and $C_{18}H_{40}NOCl$ surfactants *By dip-dry*	*S. aureus;* *E. coli*	95% BR rate; Durable for ten washing cycles	[51]
Cu NPs; Succinic, citric, and 1,2,3,4-butane tetracarboxylic acid modifiers *By dip-dry-cure*	*E. coli* *S. aureus*	99.9% BR rate Controlled Cu^{2+} ions release	[52]
CuS; stearic acid *By dip-dry*	*S. aureus* *P. aeruginosa*	High BR rate; Superhydrophobic (151° WCA) and super-oleophilic character; Photocatalysis; Oil–water partition for ten cycles	[53]
Cu_2O/TiO_2 NP composites *By dip-dry*	*E. coli;* *K. pneumoniae;* *Saccharomyces sp.*; *S. aureus*	25 mm zonal BR UV protection; Catalytic photodegradation; Self-cleaning	[54]
CuO NPs; PDMS, Aminoethylaminopropyltrimethoxysilane, Amino-propyltriethoxysilane, and Methacryloyloxypropyltrimethoxysilane cross-linkers *By dip-cure*	*E. coli* *S. aureus*	99% BR rate; Superhydrophobic with 153° WCA and 5° WSA; Retained air permeability and flexibility; Durable against 500 abrasion cycles, one ultrasonic laundry, and chemical solutions	[55]

(continued)

Table 19.1 (continued)

Chemical agents and imparting techniques	Treated microbes	Highlights	Ref
N-halamine polymers; Household bleach *By flat-screen printing dry-cure*	*S. aureus;* *E. coli*	100% BR rate; Wound healing ability; Retained bioactivity	[56]
Ag NPs; 3-chloro-2-hydroxypropyl trimethyl ammonium chloride cat-ionizing agent; oxytetracycline hydrochloride drug *By solution-immersion*	*E. coli;* *S. aureus* *C. albican*	98% BR rate and 83% antifungal; Drug delivery; 80% of human cell viability	[57]
Trimetallic nano-particles of Ag/ZnO/Cu *By dip-dry-cure*	*E. coli* *S. aureus*	98% BR rate; durable for 20 washing cycles; UV protection; electrical conductivity; hydrophobicity with 126.7° WCA	[58]
Au NPs *By pad-dry-cure method*	*S. aureus; E. coli*	UV-blocking	[59]
Zeolitic imidazolate framework-8 (ZIF-8) nanocrystals; PDMS *By dip-dry-cure*	*S. aureus* *E. coli*	100% BR rate; Superhydrophobic with 151.36° WCA and 3.6° WSA; Oil/water separation; Self-cleaning Durable for 300 abrasion cycles and five laundry cycles	[60]

BR—Bacterial Reduction rate

catalyst [25]. The proposed mechanism between the reacting components during UV irradiation treatment showed less cellulose entanglement, thus confirming high chitosan addition, compared to raw cellulose. Significant antimicrobial activity of the chitosan-coated cellulose against *E. coli* and *P. chrysogenum* pathogens were thereby demonstrated. The same group later [26] examined the durability and antibacterial action of the same UV irradiated cotton fabric while grafted with chitosan-derived microcapsules, comprising of an essential oil extract of grapefruit seed oil. Fascinatingly, these microcapsule-cellulosic fabrics demonstrated 100% toxicity against *E. coli* and *S. aureus*. Later on, Abdel-Mohsen's group [27] showed the cross-linking of water-soluble chitosan-N-PEG graft copolymer onto the fabric surface via a citric acid bridge, using the pad dry-cure method to obtain antimicrobial cotton. The modified cotton reserved antibacterial activity even after 20 laundry cycles, with treatment against *S. aureus* and *E. coli*. In 2003, Zhang's group [28] elaborated on the effect of factors such as concentration, molecular weight, and DD of chitosan, cross-linked via glutaric dialdehyde, to prepare antibacterial fabrics. The as-treated cotton successfully displayed antimicrobial activity after investigation with *E. coli* and *Hay bacillus* concentrations below 0.5 g/l. Hudson's group [29] studied the influence of cross-linking agents such as butane tetracarboxylic acid and ArcofixNEC with low formaldehyde content, for linkage of cotton with or without chitosan. They noted that cotton fabrics treated with chitosan of 1.5–5 kDa molecular weight, 0.5–0.75% concentration and cured at 160 °C for 2–3 min, produced the highest antibacterial activity.

As a further study, Tayel's group [21] used biowaste of fungi *Aspergillus niger* to extract chitosan. The cotton fabrics functionalized with this chitosan having 89.6% DD, and 25,000 Da Molecular weight, presented excellent antimicrobial properties against pathogens like *E. coli* and *Candida albicans*. In contrast, Monica [23] applied a green method involving the use of UV curing techniques to introduce antibacterial potential onto several fabrics, including cotton, for resistance against *E. coli*.

Chitosan has free amino and hydroxyl groups that enable chemical modification by cross-linking and graft polymerization through carboxylation, sulfation, and phosphorylation, to form water-soluble bioactive derivatives, that are reactive with cotton. For instance, Lim and Hudson [68] reported the dyeing and antibacterial potential of a fiber reactive derivative, O-acrylamidomethyl-N-[(2-hydroxy-3-trimethylammonium) propyl]chitosan chloride (NMA-HTCC/O-HTCC), with/without direct and reactive dyes. This derivative had improved wash fastness and good antibacterial action against *Staphylococcus aureus*. However, the O-HTCC derivative dyed with CI Direct Red 80 and Blue 78 dyes presented 3.86 and 6.76% bacterial drop, respectively, while as the one dyed with CI Reactive Orange 107 and Blue 21 exhibited 41.71 and 62.56% bacterial drop, respectively. The authors attributed this decline in antibacterial activity with dyeing, to the strong ionic bonds formed between the anionic dye molecules and O-HTCC, thus blocking the cationic group responsible for its antibacterial effects. The authors [31] further imparted the (NMA-HTCC/O-HTCC) derivative onto cotton fabrics to obtain a durable textile material with excellent antibacterial activity against *S. aureus*, of more than 99% even after 30 successive washing cycles, when they applied a pad cold-batch technique.

Earlier, Kim's group [32] had demonstrated the antibacterial activity of cotton functionalized via covalent bonding with N-(2-hydroxy)propyl-3-trimethylammonium chitosan chloride (HTCC) derivative, with or without cross-linking agents such as citric acid (CA), butane tetracarboxylic acid (BTCA), and dimethylol dihydroxy ethylene urea (DMDHEU). The cotton treated with the inclusion of polycarboxylic acid as the cross-linking agents imparted durable antimicrobial properties, that is, 0.1% HTCC in BTCA solutions preserved antimicrobial potential for more than 20 washing cycles. The authors also noticed that DMDHEU was ineffective in bridging HTCC with cotton. Gupta and Haile [33] explained the fastness, dyeing, and antibacterial effect of a water-soluble carboxymethyl chitosan derivative on cotton. The functionalized cotton possessed outstanding fastness and dye exhaustion, and also exhibited durable antibacterial efficiency.

Furthermore, chitosan NPs have been combined with other nanoparticle-based antibacterial vehicles such as Ag to induce total antibacterial proficiency. For instance, Liu's group covalently linked carboxymethyl chitosan with hard-wearing silver nano-particles tightly adhered by coordination bonds, onto the surface of cotton fabric via an esterification reaction, using a basic mist-treatment procedure (Fig. 19.1A & B) [35]. This modified fabric displayed excellent antibacterial activity and washing durability, with over 95% bacterial inhibition rate of *S. aureus* and *E. coli* after 50 consecutive laundry cycles. Markedly, the mist modification

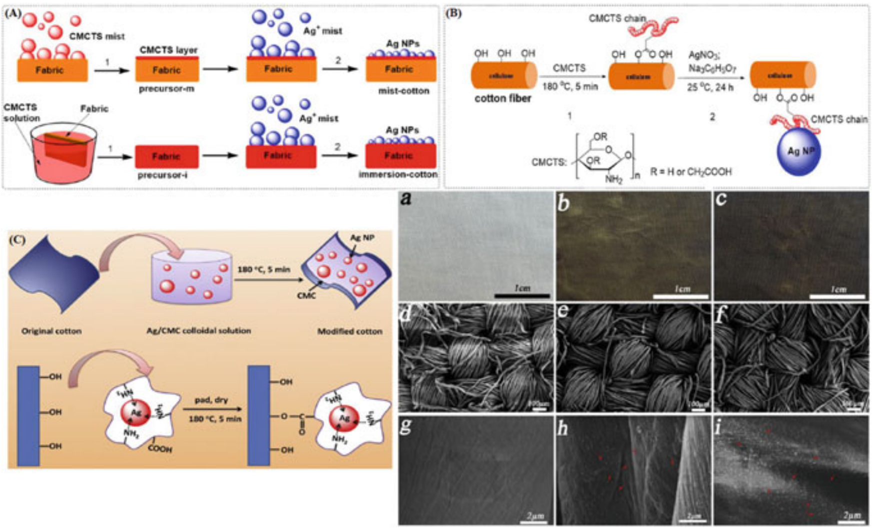

Fig. 19.1 **A** Schematic illustrations of the preparation processes of mist-cotton and immersion-cotton, and **B** reactions for linkage of Ag NPs onto cotton, reprinted from ref. [35], copyright 2017, with permission from Carbohydrate Polymers. **C** Schematic illustration of the preparation procedure of treated cotton. Optical and SEM images of (**a**, **d**, **g**) original cotton, (**b**, **e**, **h**) Cotton-1, and (**c**, **f**, **i**) Cotton-2 fabric samples, reprinted from ref. [36], copyright 2019, with permission from Carbohydrate Polymers

showed more adhesiveness of the small-sized silver nano-particles on the surface of mist-cotton than the immersion method, with a slight effect on the fundamental properties of cotton.

The same group also applied carboxymethyl chitosan as a binder and stabilizer for cotton fiber and Ag NPs via ester and amine coordination bonds, respectively (Fig. 19.1C) [36]. The as-modified cotton fabric was characterized by a uniform dispersion of tightly immobilized small-sized Ag NPs, from 10 to 80 nm, adhered to the cotton surface (Fig. 19.1h & i) [36]. This enabled the as-modified cotton fabric to have extraordinary and durable antibacterial action against both *E. coli* and *S. aureus*, with over 94% sustained reduction rate after 50 laundering cycles (Fig. 19.2a-c) [36]. The as-modified fabric also displayed no toxicity for Hacat cells, thus showing safety for the human skin (Fig. 19.2d) [36]. The same authors further expounded on the same research while using L-cysteine (Cys), as the second binder for immobilization of silver nano-particles onto carboxymethyl chitosan via an amidation reaction [37]. The grafted cotton fabric presented much better sustained bacterial reduction rates of more than 97% for both *S. aureus* and *E. coli*, for up to 180 laundry cycles. The authors ascribed the excellent observations to the formation of a stable SP dispersion on the modified surfaces of cotton by the two binders, leading to preservation of over 89% silver coated layer after 180 laundry series.

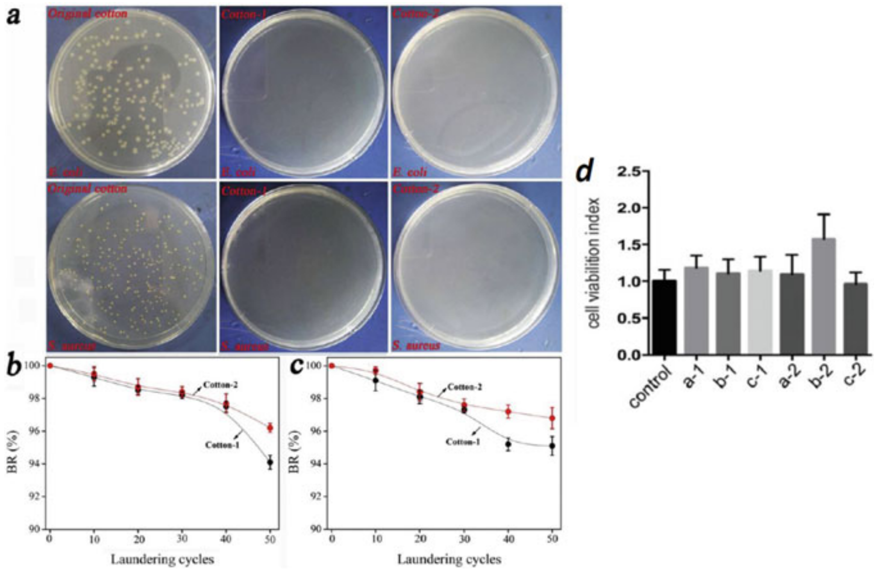

Fig. 19.2 **a** Antibacterial effect of the cotton fabric samples, optical images of the antibacterial tests, and the durability results of the antibacterial properties against **b** *E. coli* and **c** S. aureus. And **d** In vitro cytotoxicity (CCK-8) of the fabrics' leachate solutions. Data are presented as the mean ± SD (n = 5), (The leachate was obtained by incubating the original cotton fabric for 24 h (**a**), the Cotton-1 fabric for 12 h (**b**), and the Cotton-1 fabric for 24 h (**c**) in physiological saline solution), reprinted from ref. [36], copyright 2019, with permission from Carbohydrate Polymers

Furthermore, the modified cotton staged trivial cytotoxicity towards human immortalized keratinocyte (Hacat) cells, thus indicating its wearable safety against the human skin [37]. However, the same group [38] had previously modified the reactive functional moieties in chitosan using α-ketoglutaric acid, forming a chitosan binder for cotton fabrics and Ag NPs via covalent and coordinate bonds, respectively. The modified cotton fabrics possessed the sustainable antibacterial potential for the resistance of *E. coli* and *S. aureus* for over 30 washing cycles.

Imidazolium salts also proved to be effective biocidal agents [69]. Specifically, long alkyl (with 15–18 methylene groups) chained imidazolium salts cause microbial cell death by limiting their penetrability, hence affording durable antibacterial features with mere contact to cell membranes of germs [70]. For instance, poly-(imidazolium vanillyl)-grafted oligo-chitosan bases were applied with Ag NPs to prepare antibacterial cotton fabrics [39].

Multifunctionally appealing macromolecules such as cyclodextrin, crown ether, sugars, and dendrimers have also been attached to chitosan, leading to change in its structure. This inoculation offers a strong linkage of cotton fabrics onto chitosan, thus enriching chitosan with efficient and durable properties on the textiles like chelation, guest molecule carriers, and, most importantly, antibacterial action [71]. For instance, Sadeghi-Kiakhani's group successfully initiated the functionalization of cotton with chitosan-dendrimer hybrid using the padding technique, to prepare antibacterial textiles [30].

In other studies of non-chitosan agents, purely nanoparticle-based agents have transformed the antimicrobial potential of cotton textiles. For example, Ag and Ag-enriched materials have properties such as biocompatibility and non-toxicity to human cells at effective biocidal concentrations, in well-dispersed and non-agglomerated NP form [72–77]. Also, being a non-toxic and resilient inorganic metallic agent, Ag can exterminate almost 650 infectious microbes [78, 79]. Antimicrobial activity of Ag-derived agents is characterized by slow and sustainable release from cotton fabrics to the target area to intoxicate microbes since they are not strongly bonded to the fabrics. It is alleged that Ag NPs bind with the protein molecules of the microbial cells and inhibit their metabolic rate and hence finally exterminate the organism [76, 77]. Unlike the use of synthetic reducing agents, the production of Ag NPs from natural materials such as *Curcuma longa* leaf extricate is environmentally benign and, thus, the most recommendable process [49]. Dangge's group utilized Ag NPs to synthesize a durable antibacterial organic–inorganic P(DMDAAC-AGE)/Ag/ZnO composite via free radical polymerization and linked it to cotton fabrics through covalent bonds. The composite-functionalized cotton fabrics registered a bacteriostatic inhibition rate above 99.70% for *S. aureus* and *E. coli*, and this persisted over 99.00% even after 11 augmented washing cycles (equal to 55 home washing cycles). Besides, the coated fabric had an outstanding anti-mildew performance above seven days and preserved cotton's originality [46]. Titanium dioxide (TiO_2) are the other nano-particles (NPs) which have been extensively used to impart numerous properties onto cotton fabrics, owed to their peculiar properties like non-toxicity and inexpensiveness [80]. Considerably, Memon's group suspended TiO_2 NPs into silica nanosol for coating of a polyester-cotton blend, to produce antibacterial curtains via the plasma treatment process [81]. Au NPs are the other explored agents for the production of antibacterial cotton fabrics [48].

Chlorinated phenolic compounds such as triclosan (2,4,4′ trichloro 2′ hydroxy diphenyl ether), are as well applied as antimicrobial and protective fabric drugs [82–85]. For example, Ibrahim's group imparted antibacterial properties onto cotton/polyester fabrics using triclosan derivatives [83]. Other chemical cationic surfactants of quaternary-ammonium salts [84], especially those with long-chained alkyl groups (12–18 carbon atoms), have also been used primarily as biocidal fabric finishes [85].

In other studies, cotton fabric was covalently linked to three aminoanthraquinone (ANQs) dyes acting as photosensitizers, to form an antimicrobial material [43]. The fabricated cotton fabrics presented high bactericidal activity with inhibition of up to 99.9% against *Escherichia coli* under visible light irradiation (400–800 nm). The high thermal stability and self-cleaning phototoxic activity of the fabricated cotton occurred even in concentrations as low as 9 $\mu molg^{-1}$. This was ascribed to the highly reactive singlet oxygen ($^1O_2$), as detected at 1270 nm [43].

19.2 Medical

Cotton fiber has been treated with anti-inflammatory, antimicrobial, antioxidant and analgesic medical agents to extend its values for example, in the pharmaceutical industry, as wound and antimicrobial dressings in hospitals or cosmetic field as health nursing products, proficient in delivering bioactive components that can treat skin ailments at the cutaneous/subcutaneous strata, or even in the field of food technology as active foodstuff packages to prolong shelf life and food safety qualities.

For wound treatment applications, for instance, Mao's group prepared a hybrid hemostatic material by first carboxymethylation of cotton fabric via the exhaustion technique, and after that, using sodium carboxymethyl cellulose to bind chitosan, by the flat-screen printing method. The hybrid hemostatic and carboxymethylated cotton fabrics portrayed excellent swelling and water absorption potentials. Whereby the hybrid material, in particular, had a blood clotting index of 3.15-fold below that of the carboxymethylated fabric. Also, lower hemostasis time and blood loss were obtained with the hybrid material when using the rat with wounded liver and femoral artery. Thus, indicating future application in trauma therapy [86]. In another study, Meléndez-Ortiz's group prepared drug-eluting wound dressings with antimicrobial activity, by grafting poly(methacrylic acid) (PMAA) onto medical cotton gauze via free radical polymerization (Fig. 19.3A & b) [47], and after that loaded with antibacterial ZnO nano-particles. The ZnO-treated samples (Fig. 19.3c) with almost 90% grafting percentage exhibited better loading and release performance for the antimicrobial agent, nalidixic acid (Fig. 19.3C & D) [47]. The PMAA-g-gauze (Fig. 19.3b) also displayed a high anti-biocidal effect by inhibiting the growth of *S. epidermidis* and *E. coli*, thus suggesting their usage in the biomedical area [47]. Maghimaa and Alharbi exploited *Curcuma longa* leaf extricate to extract metallic Ag NPs, for

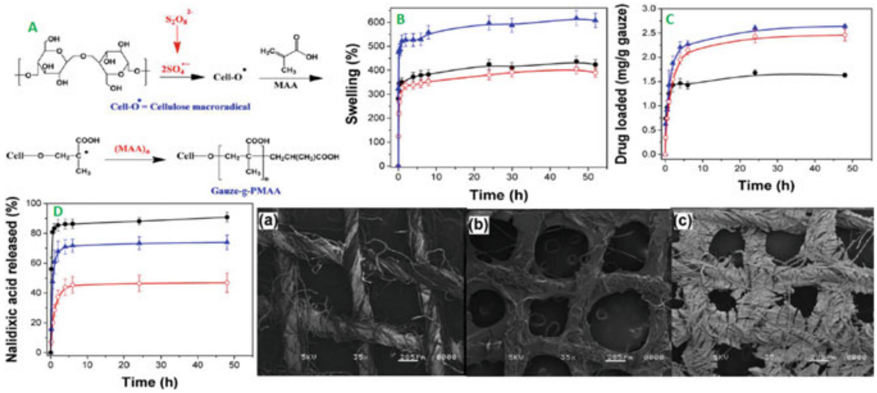

Fig. 19.3 **A** Reaction scheme for modification of cotton gauzes with PMAA by free radical polymerization. **B** Swelling in water as a function of time at 25 °C, **C** nalidixic acid loading and **D** release profiles in phosphate buffer pH 7.4 and 37 °C for PMAA-modified gauzes with different grafting percentage: 30 (full black circles), 87 (full blue triangles), and 180% (empty red circles). SEM images of (**a**) pristine cotton gauze, (**b**) gauze-g-PMAA 87%, and (**c**) ZnO-loaded gauze-g-PMAA, reprinted from ref. [47], copyright 2019, with permission from Carbohydrate Polymers

preparation of Ag NPs-coated cotton fabric, with antimicrobial and wound healing ability.

The crude extract and silver-loaded cotton fabric presented a noticeable decrease in the growth of the skin infection-causing pathogens such as *S. pyogenes*, *C. albicans*, *S. aureus*, and *P. aeruginosa.* The silver-loaded cotton fabric also presented wound healing potential in the fibroblast (L929) cells [49]. To prepare a delivery system, a new eco-friendly polymeric hydrogel was formed between β-cyclodextrin (β-CD) and carrageenan (κ–CAR), encapsulated with the natural honey bee propolis (HBP) extract, and after that, fitted into cationized cotton fabrics via a cross-linking agent, glyoxal. On testing the hydrogels at the same conditions, the 4% HBP/1.5% glyoxal hydrogel system achieved the highest water retention, with high mechanical properties at natural medium and maximum value (13%) at acidic medium.

The in-vitro release profile tests of HBP from the hydrogel system showed that the higher the HBP concentration, the higher the swelling ratio and the faster the HBP release. Nevertheless, this was controllably sustained at higher concentrations of HBP. The treated cationized cotton fabric produced high inhibition zone for antimicrobial activity of the fungal and bacterial species at lower concentrations of HBP. Hence, the treated cationized cotton has a high potential in wound healing [87].

UiO-66 is a zirconium carboxylate-based MOFs material obtained from a reaction mixture of zirconium tetrachloride and pyromellitic acids in an aqueous solvent, under solvothermal conditions. UiO-66 [88] has exceptional chemical stability, good pH tolerance and hydrothermal stability, high porosity, and large specific surface area [89]. It also depicts non-toxicity and stability in physiological conditions, with exclusive nano-sized conduits, for microextraction of compounds with small molecular weights, such as phenols [90], domoic acid [91] and NSAIDs. For instance, Abdelhameed's group, for the first time, constructed a filter-like MOF based on a composite of zirconium/cotton fabric for kidney dialysis, using a straightforward and low-cost strategy. The fabric composite had a maximum adsorption capacity of 192.3–212.8 mg/g of creatinine from mimic blood, while pristine fabric portrayed a maximum of 113.6 mg/g. Furthermore, 82% adsorption capacity of creatinine was achievable by the composite, even after three cycles of regeneration [92].

In another report involving studying the selective microextraction of NSAIDs, such as ketoprofen, naproxen, and flurbiprofen, Zilin's group formulated a novel MOF-modified cotton by immobilizing UiO-66 onto the cotton surface, using a polydopamine (PDA) functionalized method (Fig. 19.4a) [93]. Using the optimized conditions for SP microextraction, the functionalized cotton presented good stability and outstanding extraction efficiency for ketoprofen, naproxen, and flurbiprofen (Fig. 19.4b) [93]. This was mainly credited to the strong pi-pi and electrostatic interactions between UiO-66 and the extracts. The applied method exhibited high reproducibility, wide linear range, outstanding linearity, and adequate sensitivity. Also, extraction tests of NSAIDs in swine muscle samples using the same process showed good recoveries from 88.54 to 95.7% with RSDs less than 3.77% (Fig. 19.4c & A–D) [93]. This, therefore, showed cotton as an ideal carrier material of SP microextraction and UiO-66 as a promising adsorbent material for the treatment of NSAIDs in solutions.

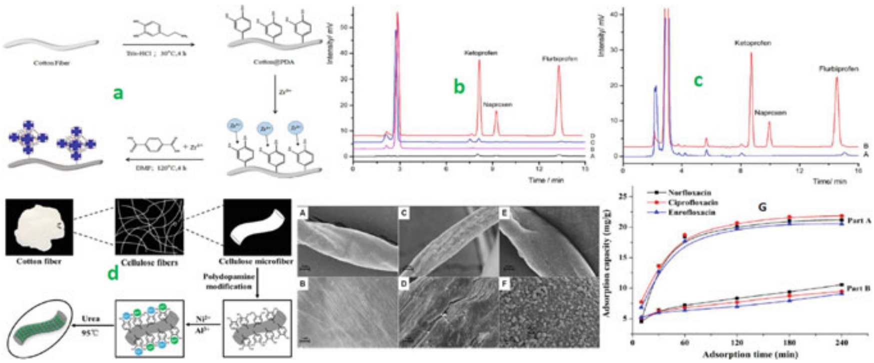

Fig. 19.4 **a** Schematic illustration of the preparation of cotton@PDA@UiO-66. **b** Chromatograms of ketoprofen, flurbiprofen, and naproxen solution before extraction (**A**), after extraction with cotton (**B**), cotton@PDA (**C**), and cotton@PDA@UiO-66 (**D**). **c** Chromatograms of none-spiked swine muscle samples (**A**) and swine muscle samples (spiked with 10 μg/g of three NSAIDs) after extraction by cotton@PDA@UiO-66 (**B**). SEM images of (**A** and **B**) bare cotton, (**C** and **D**) cotton@PDA, (**E** and **F**) cotton@PDA@UiO-66. A, C and E were at 2000 folds magnification; B, D, and F were at 10,000 folds magnification, reprinted from ref. [93], copyright 2018, with permission from Journal of Chromatography A. (**d**) Schematic diagram of LDHs modification of cotton fiber. (**G**) Adsorption kinetics of the three fluoroquinolones over LDHs modified cotton fiber (Part A) and freestanding LDHs (Part B), reprinted from ref. [94], copyright 2018, with permission from Talanta

Properties such as large specific area, the hygroscopic and alterable shape, present cotton fiber as a biodegradable support material for SP extraction. Thus, Chen's group demonstrated in situ immobilization of layered double hydroxides (LDHs) onto the surface of cotton via polydopamine cross-linker, as the stationary phase, to prepare inorganic LDHs/cotton fiber for SP extraction (Fig. 19.4d) [94]. The cotton fiber not only increased specific area and rate of mass transfer but also prevented clumping and blockage of detached LDHs crystals. Under the optimized abstraction parameters, the LDHs/cotton disclosed excellent extraction efficiency with 37–47 enrichment factors and selectivity for fluoroquinolone drugs such as enrofloxacin, ciprofloxacin, and norfloxacin. This was ascribed to the features on LDHs that enable anion exchange and electrostatic interaction with the drugs. Besides, the adsorption capacity of LDHs/cotton was 20.54, 21.85, and 21.18 mgg^{-1} for enrofloxacin, ciprofloxacin, and norfloxacin, (Fig. 19.4G) respectively, which was two times that of detached LDHs crystals. Notably, the applied HPLC-fluorescent detector technique was very efficient even in real samples of chicken eggs and pork liver [94]. For broad examination of protein glycosylation via SP extraction, cotton was treated with boric acid-functionalized titania nanomaterial and then packed into pipette tips.

The treated cotton wool tips detected 26 glycopeptides from digests of trypsin and horseradish peroxidase, and permitted removal of most nonglycosylated peptides, with the human immunoglobulin G inclusive. The LODs for glycopeptide was below 5 mol [95].

Fernández-Ponce's group demonstrated the efficiency of supercritical solvent impregnation on the production of functional cotton fabric, loaded with mango polyphenols from various families such as gallic acid, iriflophenones, mangiferin, and quercetin glycosides. These polyphenols showed high loads when coated on cotton fibers using $CO_2 + 6\%$ ethanol, under the pressure of 300 bar, and temperature of 45 °C. This was attributed to their high affinity with polar groups of the cotton fiber. The functional cotton fabrics exhibited successful antioxidant capacity with 2,2-diphenyl-1-picrylhydrazyl radical [96].

19.3 Insecticide

In order to avert disease infections as a result of insect bites, World Health Organization (WHO) emphasizes the use of prevailing methods such as spraying of inner remainings with bug killers, using insecticidal-treated clothes, and lasting insecticidal nets, or preventive measures when one is away from home or if not under protective nets, and in places where insect vectors are positioned [97]. As a substitute and inventive way of providing lifelong safety, insect repellent chemicals have been incorporated in textile materials [98, 99]. This is as a result of their principal function of effectively shielding people from arthropod vectors, unlike other approaches [100]. Mainly in tropical zones of Africa and Asia, these insect repellent textiles can ensure the safety of humans from the most severe public health troubles of mosquito-spread illnesses, including malaria, filariasis, dengue hemorrhagic fever, dengue fever, and

Nile fever, through protection from bites due to mosquitoes [101]. Insecticides are part of personal care products capable of controlling arthropod reproductive cycles and, accordingly, limit the transmission of infections on clothes, human-skin, or other faces [102]. They can be extracted naturally or synthetically [102]. Insect repellent textile agents used on cotton surfaces include natural materials such as pyrethrum and essential oils and synthetic chemicals, i.e., N, N-diethyl-m-toluamide, bioallethrin, permethrin, cypermethrin, citriodiol, and picaridin.

For instance, Abdel-Mohdy's group incorporated limonene onto cotton fabrics using conventional impregnation and surface coating methods and also grafted monochlorotriazinyl-b-cyclodextrin onto pre-modified cotton fabrics via innovative technology. The treated fabrics demonstrated toxicity against mosquitoes, with durability after washing [103]. The same group later developed durable bioallethrin coated cotton fabric using the same conventional methods, and these also demonstrated toxicity against mosquitoes [104]. In another study, the same authors functionalized cotton fabrics with cypermethrin polymer via a cross-linker and formed mosquito toxic treated fabrics with durability against wash and 18 months storage [105].

To prepare a durable insecticide fabric via the sol–gel technique, Borja's group incorporated permethrin (tetraethyl orthosilicate (TEOS)) onto a cotton fabric by a silicon (IV) oxide nanocoating, using padding followed by curing. The nano-sol coated cotton fabric demonstrated high anti-mosquito potential while maintaining its softness and flexibility. Whereby, the nano-sol coated cotton fabric with 500 mg/m^2 permethrin loading, sustained 100% insecticide activity in 120 min, even after 50 washing cycles [106]. Also, intending to create an efficient and durable system**,** Hermida's group prepared microcapsules comprising of citronella essential oil and citriodiol® biopesticides and incorporated them on the surface of cotton fabrics using various treatments. Eventually, Citriodiol-treated cotton exhibited prolonged durability and 100% repellency of *A. aegypti* mosquitoes, for more than 30 days after treatment with cotton fabrics [107].

Via the acrylate cross-linker as well as a thickener, Naik's group grafted cotton fabrics with gel-like chitosan nanocapsules of oil from lemongrass (*Cymbopogon citratus*). The acrylate-treated fabric had 75% bio-efficacy against mosquitoes post-fifteen washing cycles, while the fabric without acrylate achieved only 51% repellency. This confirms the enhanced launder durability and retention of nanocapsules on cotton. Moreover, the nanogel fabric showed no dermal toxicity even after 36 days of repetitive treatment on Swiss albino mice. The formulation was, therefore, suitable for impregnation on uniforms of military and on-field duty personnel with higher risks of mosquito bites [108].

19.3.1 Conclusion and Prospects

Microbes and disease-spreading insects form a substantial part of our ecosystem. With their endless disease-causing effect, especially to human lives, they have prompted the public to demand more protective means, including textiles such as protective cotton. As expounded in this chapter, treated cotton textiles can ably provide advanced biological applications such as antimicrobial activity, wound healing, drug delivery, insecticidal potential, thus providing good health to beings. These treated cotton materials can, therefore, be applied in fields such as home textiles, bed nets, camping gear and tents, military uniforms, and pharmaceutical industry, as wound and antimicrobial dressings.

To enable these biological applications, cotton materials have been treated with several synthetic and natural antimicrobial, medical and insecticidal agents, with the use of cross-linking agents and nanocapsules for increased compatibility. However, natural functional agents such as pyrethrum, essential oils, and most especially chitosan have proved more appealing to use since they are skin and environment-friendly, but they have low durability and solubility on cotton surfaces. Nevertheless, more research involving chemical modification of cotton textiles with the agents, and the use of nanotechnology is underway to improve compatibility, as discussed above. The synthetic agents are more effective and durable biocides and insecticides, but they present slight toxicity to humans and the environment. Besides environmental effects, there is sometimes the emergence of resistant strains to these drugs. Therefore, the development of cotton materials with novel alternate chemical group-based agents that are skin-friendly, biocompatible, and robust is essential to overcome these issues, and thus an aid to humanity.

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Chapter 20
Advanced Chemical Applications of Modified Cotton

Ishaq Lugoloobi, Mike Tebyetekerwa, Hafeezullah Memon, and Chao Sun

Abstract Lightweight and flexible electronics are gaining popularity, especially in wearable technologies, because they allow a safe, healthy, and comfortable life. Cotton materials are among the most attractive substrates, given that they are inexpensive, environmentally benign, light, accessible, and processable. Incorporation of conductive materials onto cotton textiles modifies their surface chemistry by allowing free movement of electrons and other atomic species like radicals in metallic and non-metallic nanoparticles, delocalization of π-electrons with high mobility owed to the continuous overlap of π-orbitals along the backbone of conductive polymers, and free transfer of charges. On the addition to a large surface area and enhanced mechanical strength of the substrate, the conductive cotton textiles can provide chemical applications such as electrical and thermal conductivity, energy storage, sensitivity, EMI shielding, catalysis, and redox detoxification of certain pollutant chemicals in the environment. This chapter, therefore, discusses the various chemical and multi-advanced applications of modified cotton textiles, highlighting the research advancements, the active materials, and imparting techniques used.

Keywords Modified cotton · Conductivity · Sensitivity · Catalysis · Multi-advanced applications

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Abbreviations

Ag NPs	Silver nanoparticles
ATRP	Atomic transfer radical polymerization
BA	Butyl acrylate
BR	Bacterial reduction rate
CNTs	Carbon nanotubes
CVP	Chemical Vapor Deposition
EMI	Electromagnetic interference
DMAEMA	2-(Dimethylamino)ethyl methacrylate
DD	Degree of deacetylation
DMSO	Dimethyl sulfoxide
DCM	Dichloromethane
FAS	Fluoroalkyl silane
GMA	Glycidyl methacrylate
GO	Graphene oxide
HEMA	Hydroxyethyl methacrylate
HFBA	Hexafluoro butyl acrylate
HMDSO	(Hexamethyldisiloxane)
HPLC	High Performance Liquid Chromatography
LbL	Layer-by-layer
LODs	Limits of detection
LOI	Limiting oxygen index
MMA	Methyl methacrylate
MOFs	Metal-organic frameworks
NPs	Nanoparticles
NSAIDs	Non-steroidal anti-inflammatory drugs
NWs	Nanowires
OCA	Oil contact angle
PDMS	Polydimethylsiloxane
PDTS	1H,1H,2H,2H-perfluorodecyltriethoxysilane
PEDOT	Poly(3,4-ethylenedioxythiophene)
PEG	Polyethylene glycol
PEI	Polyethyleneimine
PMMA	Poly(methyl methacrylate)
POSS	Polyhedral oligomeric silsesquioxane
POTS	1H, 1H, 2H, 2H-perfluorooctyltriethoxysilane
PP	Polypropylene
PSS	Poly (styrene sulfonate)
PTFMA	Poly (trifluoro ethyl methacrylate)
PVDF	Poly (vinylidene fluoride-co-hexafluoropropylene)
PVD	Physical Vapor Deposition
SA	Stearyl acrylate
RhB	Rhodamine B

rGO	Reduced graphene oxide
RSDs	Relative standard deviations
SERS	Surface-enhanced Raman spectroscopy/scattering
SDS	Sodium dodecyl sulfate
SP	Solid phase
UV	Ultra-violet
UPF	UV protection factor
WCA	Water contact angle
WSA	Water-shedding angle

20.1 Electrical Conductivity, Sensitivity, and EMI Shielding

Conductivity in textiles involves the transfer of an electric current to/from materials. Electrically conductive fabric materials are termed electronic-textiles (e-textiles). These e-textiles can also serve functions as solar cells [1], EMI shielding, and organic photovoltaic (OPV) materials. Their specific applications are, therefore, usage as fiber field-effect transistors; fiber sensors [2, 3] such as capacitive [4, 5], piezoelectric [6, 7], triboelectric and resistive; wearable electronics such as transparent and flexible strain sensor [8], wearable antennas [9], wearable solar textiles, wearable activity monitors [10], wearable lithium-ion batteries [11, 12], wearable solid-state supercapacitor [13–15], electronic skins [16–20]. These different applications of conductive cotton are summarized in Fig. 20.1.

E-textiles possess essential features, including flexibility, lightweight, stretchability, availability, wearer comfort, wearable power sources, and, most importantly, are cheap [21]. Besides, the capability of e-textiles in EMI shielding is the protection of the public from pollution attributable to EMI pollutants such as electromagnetic waves that harm human healthiness with illnesses, including Parkinson's, Alzheimer's, tumors, and cancer [22–24]. These electromagnetic waves also endanger electrical gadgets and communications that depend on electromagnetism.

The cotton fabric is an excellent electrical insulator, and this curtails its conductivity applications. However, researchers have utilized specific methods to integrate conductivity potential to cotton fabrics. Generally, two ways of fabricating conductive cotton fabrics exist, firstly the incorporation of conductive filler materials into cotton yarns via polymeric functionalization. These filler materials include metal nanoparticles (such as Ag, Cu, gold, Zn, Ti, and Al-coatings on textiles) [5, 25, 26], metal oxides, composites, CNTs, graphite, GO, rGO and PEDOT, owed to possession of very high conductivity [27, 28]. Secondly, conductive cotton can be designed using conductive polymers having very little or no metals [29], to form composites comprising of natural and/or synthetic micro and macro fibers [30, 31]. For instance, a drop-casting method was utilized to prepare non-metallic cotton fabric

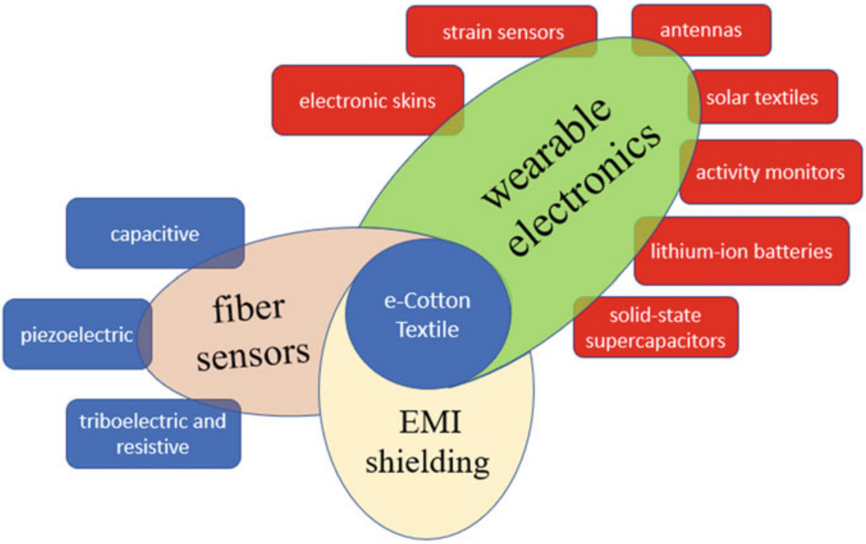

Fig. 20.1 Illustration of the different applications of conductive cotton textiles

conductors using DMSO as a secondary dopant, to disperse the commercial conductive PEDOT:PSS film. The resistance of fabric conductors containing 21.7 wt% PEDOT:PSS was 1.58 U/sq. Such fabrics were applicable as electrodes, conducting wires, and wearable electronics, thus wholly replacing ITO and copper [32].

Furthermore, Mao's group demonstrated in-situ polymerization of pyrrole via micro-dissolution onto the surface of pre-treated cotton fabrics. Initial chemical treatment of the fabrics created surface roughness by the addition of more adsorption sites for firm attachment of polypyrrole. The e-textiles portrayed a resistance of 1.98 Ω/sq, which persisted for 10 laundry cycles, EMI shielding of 15.4–62.9 dB for 1 to 3000 MHz frequency range, and admirable UV protection. The flexibility of the treated fabrics was maintained after exposure to mechanical forces, thus a theoretical confirmatory for application as a wearable electrode textile [33]. Meanwhile, Zhang's group prepared a paper-based lithium-ion battery separator from grafted-modified PP and cotton fiber via the wet nonwoven papermaking method. The PP/Cotton fiber composite displayed improved performance, for example, 180% electrolyte uptake, ionic conductivity of 1.76 $mScm^{-1}$, thermal stability, tensile strength of 1.6529 kNm^{-1}, unchanged size at 170 °C, discharge capacity of 169.9 $mAh{\cdot}g^{-1}$ and 92% activity after 100 cycles. Thus, revealing the fiber composites as efficient future lithium-ion battery separators [34].

Graphene is a two-dimensional carbon material with the conductivity of approximately 6000 Scm^{-1} [35], of which 10^{-3} Scm^{-1} is required for EMI shielding. This proves the potential application of its derivatives as conductive materials in e-textiles. For instance, Kowalczyk's group prepared rGO-cotton fabric using commercial rGO particles dispersed in organosilicon sol via the sol–gel process, but obtained high surface electrical resistance in orders of 10^5–10^{10} Ω, due to poor dispersion and agglomerate formation of rGO [36]. But a lower surface resistance of 1.43 × 10^3 Ωcm^{-1} had been previously reported on the reduction of GO-coated cotton fabric to rGO-cotton fabric using $Na_2S_2O_4$, after seven coating cycles [37]. Later on, Sarma's group fabricated conductive fabrics by treating grey cotton fabrics with glow discharge oxygen plasma for enhanced adhesion of GO and then cationization with Bovine Serum Albumin (BSA). The plasma-treated fabrics were then coated with GO solution via the dip-dry-cure process, before chemical reduction to rGO using hydrazine hydrate via a vapor reduction technique. The plasma-treated cotton fabrics showed not only an increase in the oxygen functional groups but also an increase in the surface roughness, thus improving the adhesion of GO (Fig. 20.2A) [38]. Plasma treatment reinstated a high electrical conductivity at the surface of rGO cotton fabrics with the resistance of 1.07 × 10^6 Ω, from 1.65 × 10^{10} Ω and 7.51 × 10^6 Ω for cotton fabrics and rGO plasma-untreated cotton fabrics, respectively, as derived from their I-V curves using Ohm's law (Fig. 20.2B). This research proved the development of wearable electronics for biomedical applications [38].

Fu's group obtained higher electrical conductivity of 2.3 × 10^{-1} S/cm^{-1} (Fig. 20.2a), when they prepared rGO dyed cotton fabric, by microwave-aided reduction of GO-coated cotton fabric at 100 °C, utilizing a green reducing agent of L-ascorbic acid. This improved the adhesion, loading and as well, uniform distribution of rGO on the fiber surface. The authors also reported EMI shielding effectiveness within the range of 30–1530 MHz in X-band as −26 to −35 dB (Fig. 20.2b), and

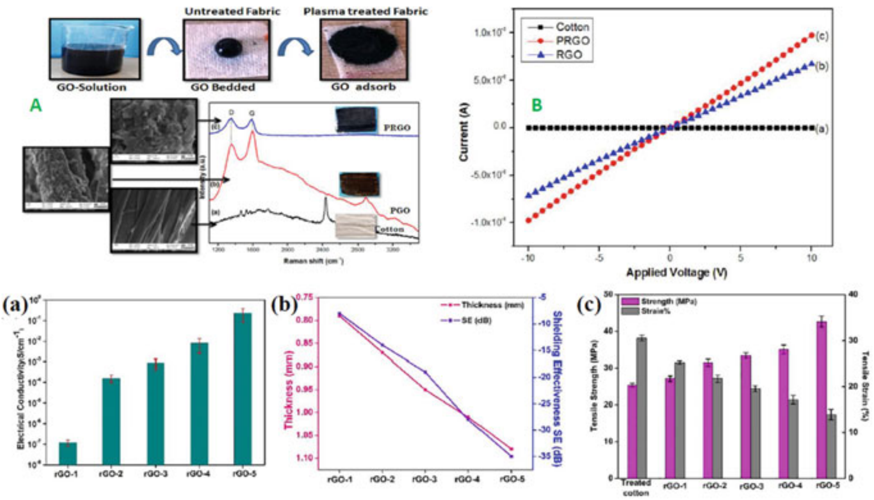

Fig. 20.2 **A** Schematic illustration summarizing the characterization process of fabrics. **B** I-V plots of (**a**) original cotton (**b**) no plasma RGO and (**c**) plasma-treated RGO fabrics, reprinted from ref.[38], copyright 2018, with permission from Diamond & Related Materials. **a** Electrical conductivity, **b** Thickness on maximum shielding effectiveness, and **c** Tensile strength and strain of rGO dyed cotton fabrics, reprinted from ref. [39], copyright 2019, with permission from Applied Surface Science

improved tensile properties of the material (Fig. 20.2c) [39]. They attributed these results to the many rGO layers formed in the coated fabric. However, a hot solution of ascorbic acid was previously used to reduce Graphene oxide deposited on cotton via a dip-pad-dry process [40]. The graphene-cotton fabric had electrical resistivity of 91.8 kΩ/sq, and this raised to 112.5 kΩ/sq on the addition of polymethyl siloxane nanofilament for superhydrophobic functionalization.

Nevertheless, graphene can be incorporated into other organic conductors and metallic nanoparticles for effective conductivity. For instance, Peng's group prepared graphene/CNT composite fibers with high tensile strength, electrocatalytic activity, and electrical conductivity of 450 ± 20 S/cm, and interweaved them with cotton fibers to form a conductive fabric [41]. Unfortunately, they had low flexibility, high density, and quickly decayed. While Wang's group coated cotton fiber with Ag NW-doped rGO, using the hydrothermal process. This stretchy and wearable piezoresistive sensor was constructed with the face-to-face alignment of rGO on the lower part and Ag NW on the other side, for increased conduction, thus enhancing sensitivity to ~4.23 kPa^{-1}. The Ag NWs also allowed fast response and recovery properties with ~0.22 and ~0.42 s, respectively. Notably, the Ag NWs were well protected by rGO from oxidation, hence excellent stability for applications in flexible and wearable pressure sensors of human activities [42].

In a study related to using inorganic materials, Goldthorpe's group utilized the dip-coating technique to deposit networks of Ag NWs onto cotton fibers, and acquired conductive threads with 11 Ω/cm resistance [43]. The threads, however, had poor mechanical properties due to the brittleness of the silver film. Since Ag NWs have been used as biosensors [44, 45] and antimicrobials [46], owing to theirs low cellular toxicities[47], these modified cotton threads can, therefore, be applicable as e-textile sensors, antiseptic wound dressings, and clothes.

With a resolve to prepare flexible wearable supercapacitors that can be integrated into energy storage electronic systems, Ge's group directly converted cotton fabrics into carbon fabric electrodes via a mercerizing and carbonizing process, for the first time [48]. The self-supporting electrodes exhibited a high specific capacitance of 1087.9 mF/cm^{-2}, good rate performance, and cycling lifespan above 91.12% for 3000 cycles. When 23.08 mW/cm^3 power density was applied between two electrodes, they displayed an excellent volumetric energy density of 1.57 mWh/cm^3. Moreover, the tensile strength of the prepared electrode was enhanced from 2.67 to 4.20 N. In another study; the same group deposited polypyrrole (PPy) onto the surface of carbonized cotton fabric (CCF) substrate by in-situ electrodeposition to form a flexible bind-free composite electrode (Fig. 20.3a) [49]. The electrode demonstrated a higher specific capacitance of 3596 $mFcm^{-2}$ (Fig. 20.3b) at the same current density of 2 $mAcm^{-2}$, a good rate capability, and high cycling stability with above 96.5% capacitance retention for 4000 cycles (Fig. 20.3c) [49]. The authors attributed this observation to the hierarchical 3D porous substrate that provided conductive pathways for the fast transfer of electrons and a large surface area for the loading of polypyrrole. In comparison, polypyrrole shortens ion diffusion paths to ensure perfect contact between the electrode and the electrolyte. This lightweight and flexible supercapacitor (FSC) (Fig. 20.4a & b) also possessed a high volumetric energy

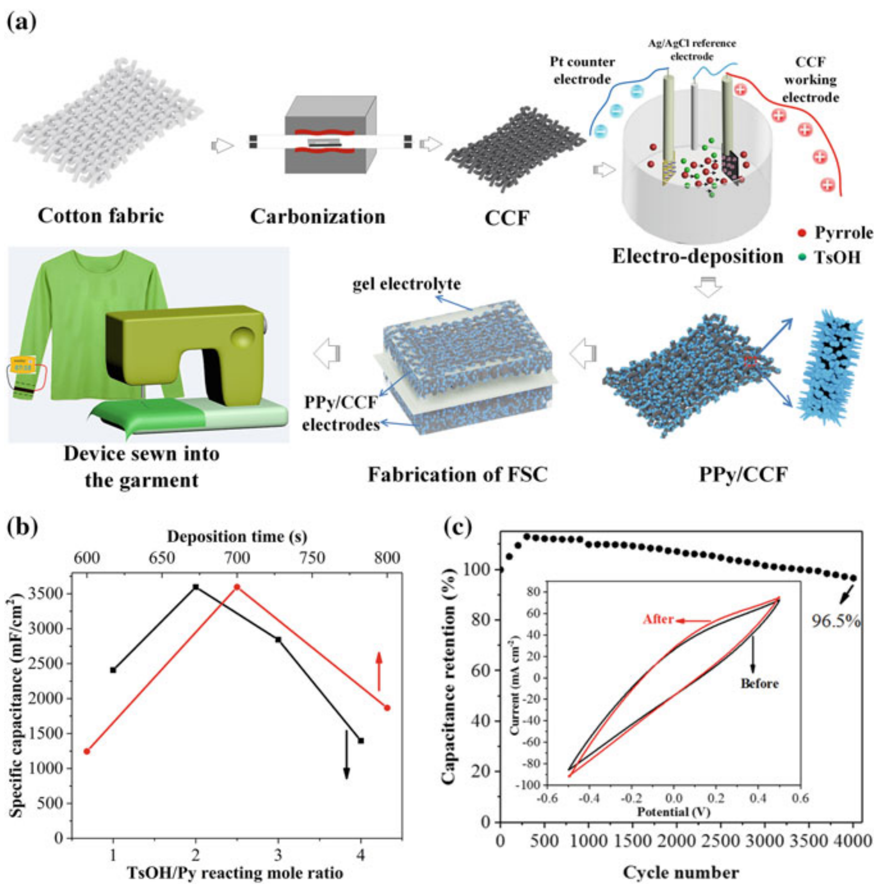

Fig. 20.3 **a** The flow diagram for the fabrication of electrode materials and all-solid-state supercapacitors. **b** The specific capacitances of different PPy/CCF electrodes. **c** The percentages of capacitance retention of PPy/CCF-1:2, inset: CV curves of initial and after 4000 cycles, reprinted from ref. [49], copyright 2019, with permission from Electrochimica Acta

density of 1.18 mWh/cm^3 at a power density of 17 mW/cm^3. The same group also applied the carbonization method to prepare flexible oxygen and nitrogen co-doped carbonized cotton electrodes with high electrochemical ability [50]. The 10 wt% carbonized cotton showed a good specific capacitance of 1836 $\pm$ 20 mF/cm^2 at 2 mA/cm^2, superb stability of 99.1% capacitance retention for 5000 cycles. The exceptional performance was attributed to both the double-layer capacitance and the pseudo-capacitance of N and O heteroatoms. Therefore, these lightweight and easily fabricated supercapacitors are future candidates for application as wearable energy storage devices, for providing power to other devices such as light-emitting diodes and electronic watches (Fig. 20.4c & d) at a low-cost.

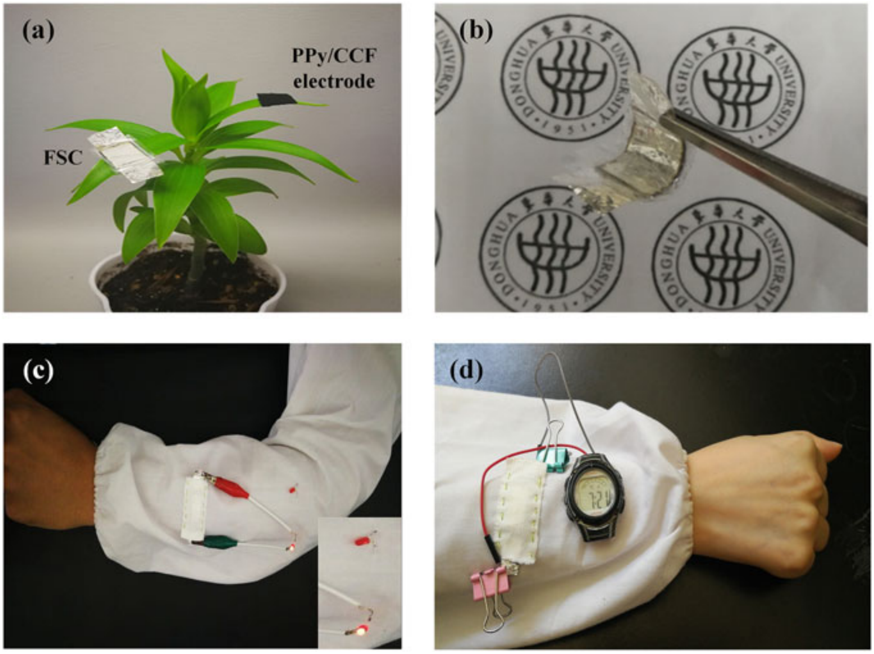

Fig. 20.4 Digital images of **a** the lightweight feature of PPy/CCF electrode and FSC, **b** bending state of FSC, and the two connected FSCs sewed into a garment for powering **c** a light-emitting diode and **d** an electronic watch, reprinted from ref. [49], copyright 2019, with permission from Electrochimica Acta

20.2 Chemical Detoxification and Photocatalysis

Various perilous chemicals including halogenated chemical stains and oils [51], pigments, unsafe water-soluble/insoluble finishing and dyeing chemicals, formaldehyde-derived softening and cross-linking agents from textile industries, acids and alkalis, dispersants and those from other fields/industries such as medical, are usually released as water wastes. These cause pollution to the environment and hence pose severe jeopardy to public health and the ecological system, owed to their effects arising from toxicity, teratogenicity, carcinogenicity, or mutagenicity [52–55]. These wastes also increase the biological and chemical oxygen demand, and the total of dissolved solid levels in water-bodies, thus inflicting detrimental effects on nature [56].

However, cotton fabrics can be utilized to alleviate these limitations due to chemical wastes by functionalization with agents for the detection of dangerous chemicals using a powerful technique based on SERS activity and their decomposition through a photocatalytic process that uses cheap and available UV light. Photocatalytic species such as Fe(III) facilitate photodecomposition by improving UV absorption, delaying the reassociation of photogenerated carriers, and increasing the conduction rate of electrons [57]. SERS active agents are usually metal NPs attached to solid substrates, including copper [58], silicon [59], Au [60], glass [61] or quartz [62] while Photocatalytic compounds applied in textile include TiO_2 or ZnO, CuS [63] and other conductive chemical substances.

Notably, Ugur's group reported the coating of multi-nanocomposite layers of anatase TiO_2 NPs onto cationized cotton fabric surfaces, via a molecular layer-by-layer self-assembly method [64]. The modified fabrics presented photocatalytic degradation of red wine pollutants, protection from UV radiations, self-cleaning ability, and exceptional durability. In a similar study involving the use of the same self-assembly method, Zhang's group designed easily recyclable titanium (IV)oxide/potassium alginate-CNTs photocatalyst coatings on surfaces of cotton fabrics, for photodegradation of gas and liquid pollutants, under simulated sunlight irradiation. The nanocoating displayed a high photocatalytic capacity with a 1.676 h^{-1} degradation rate constant for formaldehyde and degradation of 92.7% RhB within 50 min [65]. Furthermore, photocatalytic and semiconducting TiO_2 still in the anatase phase, together with BiOCl NPs, were successfully deposited onto cotton fibers by in situ approach [66]. The functionalized cotton fibers demonstrated photocatalytic degradation of naphthol blue-black di-azo and distinct oxidant species such as terephthalic acid and benzoquinone. The BiOCl modified cotton fiber displayed more facile synthesis at room temperature, stability, and extended light absorption up to the visible range with light irradiation, as compared to TiO_2 modified cotton fiber, which, more importantly, showed extended reusability of up to six cycles. Thus, the novel BiOCl modified cotton fiber showed a potential application for photocatalytic degradation of pollutants and self-cleaning ability [66]. In another study, cotton fabric was effectively functionalized with the photocatalytic TiO_2/Ag/AgBr nanocomposite layer via the sol–gel process. This new immobilized heterostructure layer imparted intense photocatalytic action under visible light that was strongly absorbed by the Ag crystals at the AgBr surface. This led to the decomposition of Remazol brilliant blue dye solution and dimethyl methyl phosphonate, a nerve agent simulant. Thus, toxic chemical protection by these self-detoxifying fabrics, when applied in clothing for chemical protection [67]. Previously, Ag/AgCl-TiO_2 nanolayer complex had been imparted onto cotton for the preparation of catalytically photoactive fabrics for degradation of an aqueous solution of methyl orange [68]. The catalysis process demonstrated in the above studies was attributed to photoexcitation of Ag NPs electrons under UV light, due to surface plasmon resonance. These excited electrons are after that injected into the TiO_2 conduction band and transferred to the AgCl particle surfaces, where radicals such as •OH, Cl^0, $O_2{\bullet}^-$ and H_2O_2 are produced to cause catalytic photodegradation of the organic pollutants. Baojiang's group also prepared photo-catalytically active cotton fabrics of Fe(III)/BiVO4-cotton, with extraordinary recyclability under visible-light irradiation, via thiolene-click reaction (Fig. 20.5 Experiment Process). Fe(III)/BiVO4-cotton presented outstanding photocatalysis by the degradation of over 90% of both Cr(VI) and C.I. reactive blue 19 in 90 and 30 min (Fig. 20.5 a–d), respectively, within five cycles. This was accredited to the synergistic impact of $BiVO_4$ and Fe(III) species (Fig. 20.5 Possible mechanism) [57].

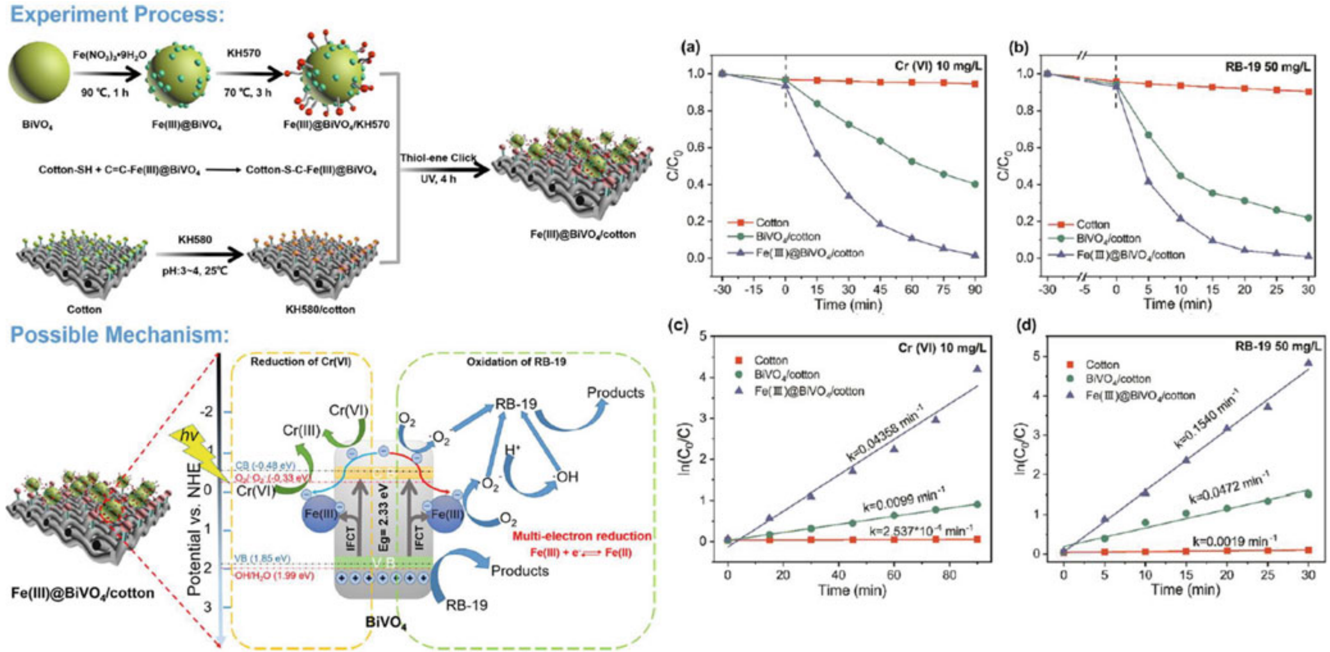

Fig. 20.5 Illustrations for the experimental preparation process of Fe(III)@BiVO4/cotton photocatalytic fabric, and the proposed mechanism of its reduction of Cr(VI) and oxidation of RB-19 under visible light irradiation (k > 420 nm) (**LEFT**). Degradation and kinetic fitting graphs of **a**, **c** Cr(VI) and **b**, **d** RB-19 of the as-prepared samples, reprinted from ref. [57], copyright 2019, with permission from Advanced Powder Technology

Graphite-identical nanosheets of carbon nitride were anchored onto poly (diallyl dimethylammonium chloride) (PDDA) modified cotton fabrics via electrostatic interaction, and tested for catalytic photodegradation under replicated UV irradiation. These modified fabrics exhibited catalytic photodegradation of 90.2% RhB within 80 min and superior UV light-driven self-cleaning performance for coffee and wine stain elimination. The modified fabrics were as well reusable in catalysis reactions with extreme durability [69].

Traditional cotton fabrics were dyed with CNT ink to prepare low-cost and washable solar-driven photothermal membranes for desalination of seawater. The prepared CNT-cotton fabrics demonstrated strong optical absorption of 95.7% efficiency within the range of 250–2500 nm. On using the CNT-cotton fabrics with a thermo-insulator of polystyrene foam, they exhibited a high seawater evaporation rate of 1.59 $Kgm^{-2}\ h^{-1}$ under irradiation of sunlight (1.0 KWm^{-2}), accompanied by solid salt accumulation. Prominently, the fabric was easily cleaned and recycled by hand-washing to remove the salts [70].

Inorganic chemicals such as bismuth oxyhalides (BiOX; X = I, Cl, Br, and F) have been utilized for the preparation of photocatalytic cotton fabrics. BiOI and BiOBr, for example, are characterized by non-toxicity, high reflectance of near-infrared, absorption of visible light at wavelengths lower than 630 nm, and thus the capability of photodegradation of organic stains, given that they release photocatalytic active radical species such as h^+, •OH, or $•O^{2-}$. For instance, Mao's group utilized the method to immobilize bismuth oxyiodide (BiOI) nanosheets onto the cotton fabric surface. The functionalized textile was characterized by self-cleaning, UV shielding of 50 + UPF, and 99% photocatalytic degradation rate of RhB. The fabric was also superhydrophobic, with WCA of about 140° [71]. The same group later on first carboxymethylated pure cotton to ease the growth of $Bi_2O_2{}^{2+}$ crystal nuclei during the anchorage of ($BiOBr_xI_{1-x}$ ($0 \leq x \leq 1$)) nanosheets on the fabric surface [72]. The obtained textile expressed properties such as UV-blocking, self-cleaning, the reflection of near-infrared, and hydrophobicity due to the presence of fluorine groups.

SERS is regarded to be sensitive, accurate, repeatable, and hence, a powerful trustable analytical method used to detect and identify molecules, primarily through enhancement of signals on adsorption of molecules onto plasmonic surfaces [73]. Qu's group designed SERS-active cotton swabs after assembling Ag NPs and detected Rhodamine 6G at a limit of 8.1×10^{-13} M [74]. Also, Wang's group prepared substrates for SERS detection via a dip-coating procedure of negatively charged Ag NPs onto cationized cotton fabrics. The Ag NPs-coated fabrics exhibited sensitive SERS signals for 10^{-8} M p-amino thiophenol (PATP) and 10^{-5} M carbaryl pesticides on fruits, with excellent reproducibility and stability, thus a practical detection [75]. Pakkanen's group utilized the hydraulic pressing technique to prepare low-cost and active silver nanowire-decorated cotton fiber substrates (Fig. 20.6A) that allow urine bacteria to be filtered and detected (Fig. 20.6B). These composite materials exhibited efficiency as SERS platforms with a 1×10^6 M enhancement factor and 1×10^{-9} M detection limit towards 4-aminothiophenol (Fig. 20.7a). These sieve-like compressed cotton fibers (Fig. 20.6b & c) also effectively filtered *E. coli* from urine

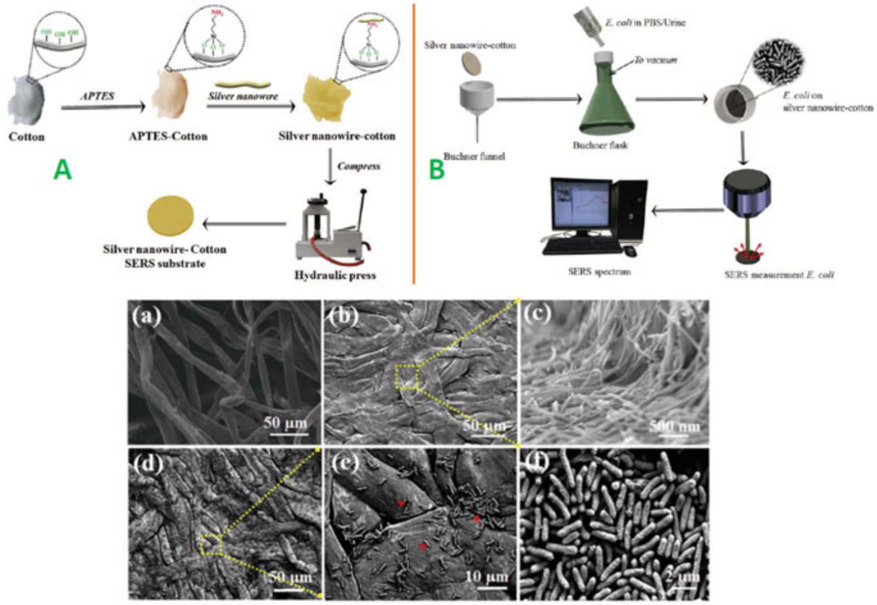

Fig. 20.6 **A** A schematic illustration for the fabrication process of the silver nanowire-decorated cotton SERS substrate, and **B** their application for trapping of E. coli bacteria from a PBS solution or urine for SERS measurement. FE-SEM images of **a** pristine silver nanowire-cotton, **b**, and **c** silver nanowire-cotton fibers after compression. **d**–**f** HD|VP SEM images of E. coli bacteria trapped on silver nanowire-cotton fibers. Red arrows highlight selected E. coli bacteria in **e**, reprinted from ref. [76], copyright 2019, with permission from Applied Surface Science

and buffered phosphate solution (Fig. 20.6d–f, 20.7c & d). With the presence of highly sensitive silver nanowire SERS materials, these porous fibers can effectively detect biomolecules [76].

Having facile reducer glucose units for silver mirror reaction, Jia's group employed natural cotton as a self-sacrificial template in an *in-situ* reduction process, to synthesize hollow silver microtubes for both catalysis and SERS activity. The Ag fibers effectively catalyzed the reduction of 4-nitrophenol to 4-aminophenol, using $NaBH_4$. Moreover, they displayed appreciably high SERS sensitivity towards dye molecules like methylene blue (MB), with the detectability of 10^{-8} M. The superior SERS and catalytic activity of Ag fibers proved its potential future applications in catalysis during wastewater treatment, biomedical, and environmental determination [77]. In an indirectly related study, Rayappan's group prepared gas-sensing cotton fabrics for organic vapors such as ammonia, ethanol, and acetaldehyde by coating ZnO NPs via a sol–gel process. These wearable gas sensors also portrayed UV-blocking properties with 378 UPF, hence protection against skin ailments such as cancer [78].

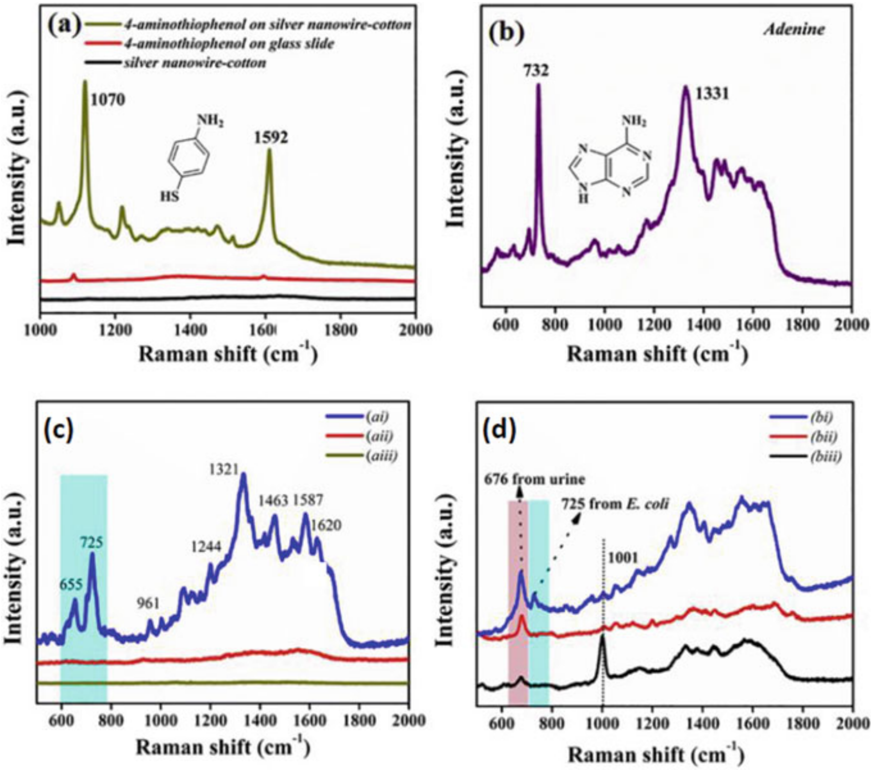

Fig. 20.7 **a** SERS measurement of 4-aminothiophenol (1 μM) measured on silver nanowire-cotton and 4-aminothiophenol (0.01 M) measured on a glass slide. **b** SERS measurement of adenine (100 μM) measured on silver nanowire-cotton substrate. **c** SERS spectra of (*ai*) E. coli bacteria trapped from PBS with a silver nanowire-cotton substrate and measured after rinsing, (*aii*) E. coli bacteria dropped on a glass slide and measured after rinsing, (*aiii*) silver nanowire-cotton without E. coli. **d** SERS spectra of (*bi*) E. coli bacteria trapped from 100% urine with a silver nanowire-cotton substrate and measured after rinsing with water, (*bii*) a urine sample on silver nanowire-cotton measured after rinsing, (*biii*) the urine sample on silver nanowire-cotton measured before rinsing, reprinted from ref. [76], copyright 2019, with permission from Applied Surface Science

20.3 Multi-advanced Applications

Cotton fibers and fabrics, as the skeletal biomass materials, have been treated with a special functional agent or agents, to construct suitable surface chemistry and tested for their final potential activity in various advanced applications (Fig. 18.1 Chap. 18). This arose with the demand to multiply the advanced applications of single cotton textiles. That is, a study on expanded functions of cotton fabric such as electrical conductivity, photocatalytic, and anti-UV potential can be considered. Wei's group used doped acids of sodium dodecylbenzene sulfonate and sulfosalicylic to prepare PANI-TiO_2-cotton fabric in one-step in-situ polymerization. The conductivity of

PANI-TiO_2-cotton textile was 14.2 S/cm, but with an increase in amounts of TiO_2, it slightly decreased to 8.8 S/cm at 4 g/L. The composites attained an up to 87.67% absorption and degradation efficiency of RhB, and durable UV protection even after ten washing cycles [79].

Wang's group fabricated conductive, EMI shielding, and flame-retardant cotton fabrics from polyethyleneimine/phytic acid (PEI/PA) layers, with a network of Ag NWs on top, via layer-by-layer assembly and dip coating techniques (Fig. 20.8A and C) [80]. The 7.5 wt% Ag NWs fabric displayed an efficient self-extinguishing ability with a peak heat release rate lowered by 41.41% (Fig. 20.8a) [80]. Also, a superior conductivity of 2416.46 Sm^{-1} (Fig. 20.8d), and an effective EMI shielding of more than 99.9% efficiency, were attained in the X-band frequency range (Fig. 20.8e) [80]. This was ascribed to the well-coated PEI/PA intumescent flame-retardants and the external interlocked conductive network. Nevertheless, the modified fabric presented a significantly improved elongation at break of about 71.6% (Fig. 20.8f) [80] and durability with bending forces, laundry, and sandpaper abrasion tests. Thus, with this inspiration, multifunctional eco-friendly textiles with additional functions can be prepared.

Furthermore, Trimetallic nanoparticles of Ag/ZnO/Cu were prepared concomitantly from their metal salts, and after that, coated on cotton fabrics. The functionalized cotton fabric expressed good antibacterial potential even after 20 washing cycles, as well as excellent UV protection and high electrical conductivity [81].

Kowalczyk's group modified polyester/cotton woven fabric with carbon nanotubes and obtained hydrophobic and conductive hybrids with the lowest resistance and shielding effectiveness of 1.03×10^3 Ω and 0.991 S, respectively. Unfortunately, with the decrease of the SDS dispersant after rinsing, conductivity decreased though hydrophobicity increased [82]. In another study, Sun's group imparted conductivity and healable super-amphiphobicity onto cotton fabrics via the solution-dipping technique by depositing Cu and, consequently, a dispersion of fluorinated-decyl POSS and POTS onto cotton. On adding to the super-amphiphobic character of 166° WCA and 155° OCA for liquids of different surface tension, the resulting fabrics were durable, self-cleaning, and outstandingly resistant to 100 washing cycles and corrosives like acids and alkalis. The functionalized cotton displayed ~0.33 $\Omega \cdot sq^{-1}$ sheet resistance, superb EMI shielding, and electrothermal heating capacity. More importantly, the super-amphiphobicity was easily healable by treating the fabrics with either heat or 1.0 V [83]. Mizerska's group recently applied the sol–gel technique to coat a dispersion of organosilicon sol and GO particles onto cotton fabrics, and after that, heated to 220 °C to reduce GO to rGO and to also complete the cross-linking reactions. The coating imparted surface resistance of 2.7 $M\Omega sq^{-1}$ and hydrophobicity of ~150° WCA to the fabric. These properties were sustained even after intense sonication in SDS, owed to enhanced bonding and stabilization of the organosilicon matrix. Though resistivity of coated fabrics portrayed sensitivity to strain, the initial value was restored after strain release [84]. Also, Correlo's group fashioned wearable semi-conductive cotton fabrics using polyaniline and polypyrrole polymers for conductive biomedical applications in stimuli quantification. With maintained flexibility and durability upon polymerization, the modified textiles showed optimal

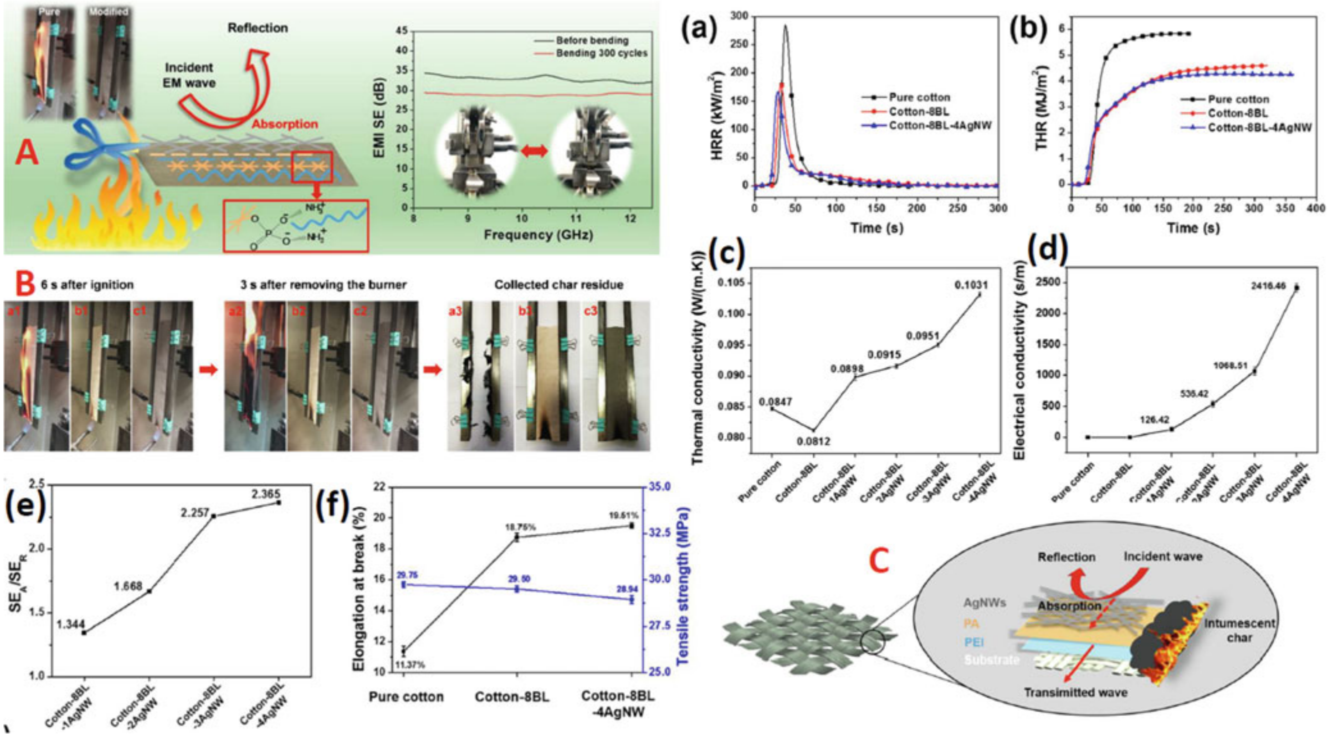

Fig. 20.8 **A** Schematic summary of preparation, applications, and mechanical resistance of modified cotton. **B** Real-time images of vertical flame tests for pure cotton (a1, a2, a3), Cotton-8BL (b1, b2, b3) and Cotton-8BL-4Ag NW (c1, c2, c3). BL-complete layer. **C** The scheme for the possible flame retardant and EMI shielding mechanism. **a** HRR **b** and THR curves, and **f** mechanical properties of pure cotton, Cotton-8BL, and Cotton-8BL-4AgNW. **c** Thermal conductivity and **d** electrical conductivity of all samples. **e** The ratios of SER/SEA reprinted from ref. [80], copyright 2019, with permission from Chemical Engineering Journal

conductivity ($10^{-6} < \sigma < 10^{-4}$) and hydrophobicity with WCA > 90°. The conductivity was unaffected even after laundry and friction tests. The conductive fabrics also showed higher than 70% cell viabilities of L929 cells [85]. Xingrong's group generated conductive cotton fabrics via layer-by-layer assembly of aminated and carboxylated multiwalled CNTs and further modification with polydimethylsiloxane. The modified cotton fabric achieved a superior hydrophobic character with a WCA of 162°, high separation efficiency and great recyclability. Owed to the excellent water repellency and conduction, the cotton-derived pressure sensors demonstrated steady response to detection of human motion in different conditions. Thus, broadening the field of high-performance electric sensors [86].

A flame retardant and antibacterial finishing agent for cellulose fabric (cotton 100%) using TiO_2 nanoparticles obtained by sol–gel method, and chitosan phosphate, was successfully cross-linked through a conservative pad-dry-cure technique. The addition of sodium hypophosphite and 1,2,3,4-butane tetracarboxylic acid to cotton fabrics during the preparation increased the thermal stability and portrayed antibacterial action against two pathogens, *S. aureus* and *E. coli* [87]. In 2018 however, Mao's group prepared durable fire-resistant and antibacterial cotton by simultaneously polymerizing dopamine and hydrolytically condensing $N_3P_3[NH(CH_2)_3Si(OC_2H_5)_3]_6$, followed by incorporation of silver nanoparticles after that. An improved flame retardancy, with a little hybrid coating (7.2%) and superior antibacterial activity (99.99%) against Gram-positive bacteria *S. aureus* and Gram-negative bacteria *E. coli,* was exhibited by the modified cotton fabrics. These properties remained largely intact after 30 soap washing cycles [88].

Ren's group prepared intumescent flame-retardants via LbL assembling of an organic/inorganic hybrid mixture of PEI-wrapped nanosilica and polyphosphoric acid onto cotton fabrics, followed by deposition of hydrophobic REPELLAN FF agent using the dip-pad-cure procedure. The as-modified cotton fabrics exhibited sufficient flame retardancy of 28.2% LOI value, high thermal stability with 41% char yield, and hydrophobicity of 142° ± 1° WCA [89]. Furthermore, Guo's group coated chitosan and phytic acid as the intumescent flame-retardants, and SiO_2 modified with hexamethyl disilyl amine as the hydrophobic layer, onto cotton fabrics to acquire superhydrophobic and fire-resistant textiles. The functionalized fabrics presented outstanding water repellence with 150° WCA and about 5° WSA, thermal and mechanical stability, significant anti-fouling, and self-cleaning characteristics for more than 50 cycles of abrasion [90]. Dai's group prepared polymer networks by cross-linking poly(methyl methacrylate glycidyl ester-co-dodecylheptafluoroethyl methacrylate) and octa(aminophenyl)silsesquioxane, and via the dip-cure-dry process, were coated onto cotton surface pre-treated with 9, 10-dihydro-9-oxa-10-phosphaphenanthrene 10-oxide. The functionalized cotton fabrics exhibited characteristic superhydrophobicity of 154° WCA, improved flame retardancy, chemical resistance, and heat resistance. With hydrophobic-lipophilic attributes, the modified cotton fabric showed promising self-cleaning performance and efficient separation of oil/water mixtures and emulsions, whereby 94% of chloroform could be quickly extracted from chloroform/water solution even for 100 cycles [91].

Nevertheless, Xingrong's group utilized a one-pot sol–gel process for the generation of waterproof and flame-retardant fabrics using intumescent flame-retardant ammonium polyphosphate, tetraethoxysilane, and hydroxyl-terminated PDMS (HPDMS) to form PDMS-silica-APP micro-nanocoated cotton fabric [92]. The modified cotton fabrics presented exceptional durability, self-cleaning potential, and superhydrophobicity of more than 160° WCA. This cotton composite also quickly charred with fire exposure due to the physical fire-barrier of PDMS-silica and APP. These approaches were simple, cost-effective and timesaving, for production of superhydrophobic and flame-retardant textiles for usage in fields, such as indoor decorations, outdoor clothing, tents, and automotive interiors. In another study, for the fabrication of multi-applicable photocatalytic and superhydrophobic textiles, Weiqu's group generated robust and self-cleaning non-fluorine cotton fabrics using anatase TiO_2 sol and PDMS via a facile, low-cost, and green dip-coating technique [93]. The as-prepared cotton unveiled appealing superhydrophobicity of 153° WCA and catalytic photodecomposition of oil red O. Prominently, the as-prepared fabrics expressed satisfiable resistance against acids, alkalis, organic corrosives, lasting UV light exposure and washing. The above properties were attributable to the synergetic effect of anatase TiO_2 microparticles and PDMS [93]. Therefore, this simple strategy can be utilized to prepare multifunctional materials applicable to various practical conditions. Nevertheless, multifunctional cotton fabrics were prepared by a simple technique involving the coating of CuS onto cotton and subsequently modifying with biobased stearic acid (STA) (Fig. 20.9A) [94]. The coated fabrics with super-

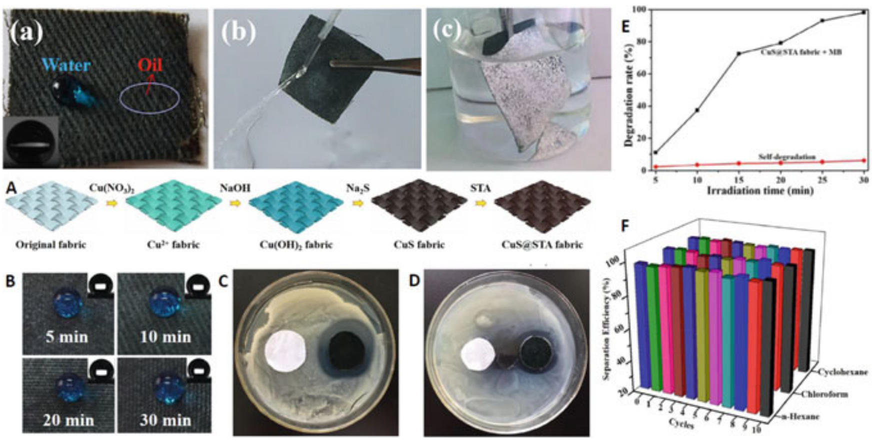

Fig. 20.9 **A** Scheme of fabrication, **a** wetting performance, with water contact angle (inset), **b** water repellency, and **c** a silver mirror-like phenomenon of the CuS@STA coated fabric. **B** Wetting performance of the fabric after different degradation time, with corresponding water contact angles (inset). Antibacterial action of pristine fabrics (on the left) and CuS@STA coated fabrics (on the right) against **C** *P. aeruginosa* and **D** *S. aureus*. **E** The degradation rate of MB solutions. **F** The separation efficiency of the CuS@STA coated fabric for recycled experiments, reprinted from ref. [94], copyright 2019, with permission from Materials Letters

hydrophobic (WCA 151°) and super-oleophilic character (Fig. 20.9a), portrayed efficient oil–water partition, by separating over 97% of the mixture after reasonable recycling (Fig. 20.9F) [94]. Additionally, the fabrics demonstrated superior photocatalytic activity with the degradation of methylene blue solution under visible light irradiation (Fig. 20.9E) and outstanding antibacterial action against *S. aureus* and *P. aeruginosa* (Fig. 20.9C & D) [94].

In order to comprehend a synergistic effect of separating oil–water mixtures and photocatalytic degradation of the filtered water-soluble pollutants such as RhB and methylene blue, Wang's group assembled self-cleaning and superhydrophobic silanized TiO_2 cotton fabric composites via combined immersion and spraying processes. During the separation of oil–water mixtures, the as-prepared cotton realized photodegradation of 93.74% RhB solution in 45 min. More importantly, after more than 10 test cycles, these functional filtration-membrane materials maintained an outstanding performance for separating oil–water mixtures, above 89% photodegradation rate, and a slight decline of WCA from 150 to 147° [95]. Photocatalytic self-cleaning, UV, and heat shielding textiles were prepared by electrostatically coating Cs_xWO_3 nanosheets onto Poly (diallyl dimethylammonium chloride) modified cotton fabrics. These treated materials were capable of degrading the methyl orange solution in 10 h [96]. Furthermore, Wenzhi's group fabricated UV light receptive water-repellent BiOBr cotton fabrics via an immersion process, to serve similar functions. The as-prepared material portrayed a close to 100% separation efficiency of DCM/water mixture and a superior photodegradation efficiency of 98% and 97% for water-soluble methylene blue and RhB, respectively. The authors attributed this to the $^{\bullet}O_2^-$ and h^+ ionic species. More importantly, the modified fabric sustained high stability after 2400 friction test cycles, ultrasonic tests in ethanol, and acid–base exposures. Also, 94% degradation performance of RhB was maintained after cycling six photodegradation tests [97]. Therefore, the modified fabrics possessed sustainable stability, which showed their high potential for application in microbial and oil-polluted water treatments, and environmental refurbishment for good human health.

Weiqu's group constructed robust superhydrophobic cotton fabrics with decent UV stability and shielding qualities, stupendous self-cleaning, and oil/water separation potentials, with the use of ZnO sol and 3-Mercaptopyltrimethoxysilane through an economical and straightforward dip-coating route, and after that introduction of dodecafluoroheptyl methacrylate (DFMA) using a thiolene-click reaction. The functionalized cotton fabrics exhibited outstanding superhydrophobicity with WCA of 156° and WSA of 6° when the DFMA concentration was 10%. Laundering and abrasion tests in solutions of acid, alkali salt, and organic solvents, revealed a pleasing resistance, thus excellent mechanical stability of the coating for industrial applications [98]. An easy modified solvothermal process was utilized for the synthesis of incredibly thermal stable Cu_2O-doped TiO_2 NP composites and coated onto cotton fibers to impart UV protection, catalytic photodegradation, and biocidal properties. The Cu_2O/TiO_2-modified cotton fibers portrayed self-cleaning properties by completely removing the MB stained dye in 5.5 h under sunlight, compared to the TiO_2-fiber, which needed more than 12 h. The Cu_2O/TiO_2 modified cotton fiber also revealed high toxicity against Gram-negative (*E. coli*, *K. pneumoniae*, *Saccharomyces sp.*) and Gram-positive (*S. aureus*) bacteria. The auspicious photodegradation and antibacterial effects were credited to the reactive species of O_2 produced by the Z-scheme mechanism in the presence of sunlight [99].

In other studies, involving the assembly of antibacterial and superhydrophobic cotton fabrics, PDMS with antibacterial CuO nanoparticles directly attached through fluorine-free silane cross-linkers, was incorporated into cotton textiles. The modified cotton exhibited reasonable superhydrophobic character with WCA > 153° and WSA < 5°, and bactericidal potential of up to 99%. Due to the presence of silane coupling agents, the modified cotton presented high durability against mechanical abrasions, ultrasonic laundry, and chemical solutions. The coating allowed the fabric to remain air-permeable and flexible [100]. A straightforward method for the construction of non-fluorinated cotton was utilized by in situ growing of nano-zeolitic imidazolate framework-8 crystals onto cotton fibers at room temperatures, and afterward treating with PDMS. The prepared cotton fabric displayed superhydrophobic potential with WCA of 151° and WSA of 3.6°, and 100% biocidal action against *S. aureus* and *E. coli*. The prepared fabrics preserved their outstanding bactericidal potential and superhydrophobic character after 300 abrasion cycles and five laundry cycles [101]. Also, Xiaofeng's group applied the heterogeneous transesterification reaction to graft the acetoacetyl group onto the cotton fabric surface, followed by post-modification with gentamicin and octadecyl amine molecules for advanced multifunctionality. The functionalized cotton fabric exhibited great hydrophobic and bactericidal activity against *S. aureus* and *E. coli*, with over 99.99% bactericidal rates and 145° WCA, even after ten standard washing cycles [102]. These robust cotton fabrics, therefore, have potential usage in biomedicine as bandages or clothes for protection that are functional in sanitary and moist surroundings.

20.4 Conclusion

Functional agents are applied to cotton fabrics, mostly as finishing chemicals that can impart advanced functionalities. With the growing public mindfulness and mounting demand for fabrics that serve functions beyond clothing, advanced research on the cotton fabric was vital. To add these functions, cotton has been treated with different synthetic and natural chemicals using various techniques either via cross-linking or not, in the presence of particular conditions as elaborated in this part. 4 of the book review serie. As a result, multifunctional cotton products can be obtained and utilized in different fields. Though the current products are facing challenges as discussed in the preceding chapters of part. 4, large-scale manufacturing of some of these advanced cotton fabrics is experiential. However, intensive research is still underway to acquire highly durable and efficient cotton fabrics with advanced applications, using simple, economical, and eco-friendly functional agents and methods. Also, the originality of the textile in terms of mechanical properties, appearance, texture, weight change, flexibility, comfort, and cytotoxicity should not be suppressed in the finally modified cotton. Nevertheless, green technology should also be embraced to lower the environmental impact of the applied agents and hence the final product. Though an all-green technology is difficult to anticipate for complete replacement of the existing ones, more innovations, determination, and commitment in the textile industry can lead to the formation of quality multifunctional cotton textiles in a cleaner environment.

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Chapter 21
Recycled Cotton Fibers for Melange Yarn Manufacturing

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Abstract The textile industry delivers two types of wastes during production, namely hard waste and soft waste. These are used as a raw material in Blow Room mixing with virgin cotton with limited volume. Besides, the sector also releases a large amount of used garment/cloth and remnants (solid waste), which causes landfill and pollution. Recycling of used clothes and remnants was started in the late 1980s to reduce such an impact on the environment. Recycling also helps to reduce raw material costs in mélange yarn manufacturing. The used clothes, as well as the garment wastes, are collected and supplied to the factories. Before the processing, they are sorted depending on their color and fabric type. These fabrics are converted into fibers called "reclaimed/regenerated fibers" by a serious of machines, i.e., cleaning, cutting, conditioning, shoddying/tearing, and baling. The reclaimed fibers are mixed with virgin cotton in preset volume according to the desired end product. Mainly mixing/blending in factories is practical at Blow Room and Draw Frame. Sometimes it is done at Speed Frame. The conventional spinning types of machinery with different settings are used to process reclaimed fibers. But there are also supplementary processes. In this chapter, the fiber preparation methods, mixing types, spinning are discussed. Also, the advantages, disadvantages, and application areas of mélange yarn are discussed.

Keywords Mélange yarn · Recycling · Reclaimed fiber · Spinning · Virgin cotton

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21.1 Introduction

The story of yarn processing gets focus in early times of the nineteenth century during the ring-spinning enabled this practically achievable. After this, various technical advances were made, and optional process techniques were adopted for the best effective and suitable system of yarn processing. Yarn is an extended continuous span of twisted fibers, appropriate intended for application in the making of textiles, knitting, sewing, crocheting, weaving, embroidery, or rope making. Based on their manufacturing techniques, there are several yarns, for example, spun yarn, fancy yarn, twist less yarn, slub yarn, mélange or dyed yarn, and so on.

Technological innovation has helped the textile sector to manufacture different types of fancy yarns. Any intentional ornamental discontinuity or interruption is introduced in fancy yarns either in color or yarn structure, or both. Mélange yarns are renowned by their eye-catching shade and manifestation amongst the fancy yarns [1].

Initially made in the 1980s, Indians were the founders of making the mélange yarn. It can be characterized by merging more than two fibers. The name mélange is conventionally applied to those yarns that are generated by the mixture of two natural or synthetic fibers, regardless of whether a similar variety. However, unlike in color or type of fiber used is different. Cotton mélange yarns are spun using Ring Frame or Rotor spinning machines from a variety of different color cotton fibers. A popular technique of producing a variety of fancy yarns is the combination of dyed and undyed fibers of varying degrees [2].

In the context of cotton mélange yarn, "a mélange yarn is the yarn that is made with various mixtures of raw white and dyed cotton or dyed fiber." For instance, if 70% virgin white cotton and 30% dyed cotton of any color combined, subsequently, it is said to be mélange yarn [3]. The cotton fibers are mainly blended with either polyester fibers or viscose fibers to produce mixed yarns [4]. Moreover, mélange yarn may be divided into two of its most common categories:

Blended Mélange Yarn: this category of yarn where fibers of different origin natural or synthetic are mixed/blended collectively in a specified percentage, for example, PC (Polyester Cotton blend) 50:50, PC 60:40, PV 70:30, and CVC 50:50. Non-Blended Mélange Yarn: in this case, fibers of the same variety or origin having different colors as well as proportion is used to produce the yarn, e.g., 100% cotton dyed yarn, 100% jute [5].

Mélange yarn follows exclusive dyeing practice, and it is great technical regarding fiber dyes, color matching, and mixed textile of multiple fibers. Dyeing of fiber before spinning enables to maintain of power-saving, emission cut, and ecological security. Mélange yarn is capable of showing several colors on one yarn, giving it rich colors, slenderness, and tenderness. Textiles produced from such yarns have some unclear cyclic effects [3].

Mélange yarns are universal because of their distinguishing and a fantastic look in the cloth. The wavy like look as a result of the mixing of various fibers and the number of color tones because of the blending of different fibers makes it familiar and attractive. The smooth cloth is very more durable. Mélange yarn is capable of displaying several colors in one yarn, making it stuffed in colors and tenderness. Fabrics manufactured from such yarn appeared to have some vague cyclic effect. Mélange yarn is an art of fashion design and production of interest and has no artistic limitations. The use of slub, chain, and stretch attachments just opens up a wide variety of products only possible in mélange yarns [6].

Mélange yarn's market share over conventional yarn is growing day by day [7]. Mélange yarn is commonly applied at weft knitting machines as well as warp knitting machines, a range of V-bed knitting machines, and cone winding machines. Mélange yarn is pertinent to underwear textiles, casual wear, sportswear, shirts, business suits, socks, and all sports clothing items, as well as bed sheets, towels, decorative fabrics, and other goods for home fabrics [3].

21.2 Fiber Preparation Methods

21.2.1 Dyeing of Virgin Cotton

Mélange yarn production is comparable to the best known conventional gray yarn. However, it includes additional supplementary processes that require explanation. At the start, the virgin cotton incoming from the ginning factories is stock up in the form of bales inside go downs. This raw cotton, after a definite period of acclimatization, is delivered to the manufacturing section for coloration operation. In the processing section, fibers are opened to flock form using conventional opening machines and, disperse dyes, reactive dyes, and VAT dyes are used for fiber coloration.

The recipe of the appropriate goal or standard colors offered by the buyer or selected from a catalog should be forecasted in the actual manufacture first. This recipe is a compilation of dyed fiber percentages. Simply stated, the prediction of the formula is an estimate of the components and percentages for a yarn or cloth. First, the colorists check the factory's warehouse for identical dyed samples, subsequently change the recipe concerning their expertise, and lastly spin a little sample (mostly 50 g), as well known as a 'hand sample', and evaluate the sample color with the required color change expressed as CIELAB or CMC (2:1). The entire cycle is repeated several times until the shade of the hand sample matches the desired color criteria [8].

Mélange yarns have a special coloration method through a low liquor-to-fiber ratio (typically below 10:1) that be able to minimize input consumption in terms of dyestuffs, chemicals, auxiliaries, and water consumption compared to yarn dyeing or fabric dyeing [9].

Following fiber coloration, they are pressed and come back to the spinning section; the fibers packed in the form of bales are once more opened, gently mixed, and stored in a ventilated room for 24 h for conditioning. Then after the flock of fibers are pressed together and assigned with a lot number. This number possibly will vary from mill to mill for detection reasons. However, it is necessary to explain since we are not confident whether we get identical types of dyed fibers (in terms of dye-ability, dye affinity, rubbing & washing fastness) of the fibers every time or not. This could rely upon the dyeing situations, dye quality, recipe, process conditions, fiber used (mature/immature/ dead fiber content). These factors are crucial to recognizing as these are few unknown variables that trigger quite basic problems in mélange yarn, i.e., shade rejection. It is necessary to make the lots so we can easily trace where the mistake occurred [5].

This identification leads us to the proper issue of bales for particular order to overcome the shade variations. However, another method that is called "sampling" can be used. A specimen must be conducted and cross-checked with the customer's sample for each new lot or a new mix of the running order. In this way, it is possible to reduce the likelihood of defect, and shade variance can be restricted and expected in advance, so required corrective action can be taken.

21.2.2 Recycled Fibers as a Raw Material for Mélange Yarn

Among the various industrial sectors, the textile and garment industries are deemed among the significant pollutant around the whole world. Textile wastes and byproducts are growing to astonishing levels at superior rates because of the look, recognition, and obsolescence of fast fashion [10]. Some are recycled to reduce those wastes which are responsible for polluting the environment. Waste recycling is one of the best options for the yarn spinners to produce profitable products as well.

In addition to virgin fibers, recycled fibers are also used as raw material for mélange yarn manufacturing. The rags incoming from garment and textile factories are recycled and mixed with polyester and virgin cotton to produce mélange yarn. The processes steps in recycling the rags are explained in the paragraphs below.

21.2.2.1 Sorting and Cleaning

The rags/remnants are supplied from textile and garment factories. Besides, the factory, which is manufacturing mélange yarn, releases such wastes. The rags are sorted based on their color and fabric type. The rags are mostly knitted fabrics. In addition to segregation, unnecessary materials like foreign fibers, metal pieces, plastics, and trashes are also removed at this stage (Fig. 21.1).

21.2.2.2 Cutting

In this stage, the fabric is cut into pieces by the fabric cutter. The size of remnant fabrics reduced to make them suitable for the shoddying process. Besides, water and

Fig. 21.1 **a** Rag or remnant supplied from textile and garment factories **b** cleaning and manual segregation of remnants depending on their color [Picture was taken from ETUR Textile PLC, Adama, Ethiopia]

Fig. 21.2 Rag cutting machine [Picture was taken from ETUR Textile PLC, Adama, Ethiopia]

oil are sprayed on to the fabric to overcome the action of beaters during the shoddying process (Fig. 21.2).

21.2.2.3 Material Conditioning

A large conditioning box is used at this stage. Besides, it is used for temporary storage. The cut pieces are transported from cutting machines to the conditioning box via transport pipes. Conditioning is done for 24 h at standard temperature and

Fig. 21.3 Conditioning box [Picture was taken from ETUR Textile PLC, Adama, Ethiopia]

relative humidity. Absorbing water helps the cut pieces to withstand the action of beaters and rollers (Fig. 21.3).

21.2.2.4 Shoddying or Tearing

The main step in recycled/regenerated fiber processing is shoddying. In this machine, the conditioned rag is changed in to fiber. The machine has openers which convert the cut pieces of fabric into fibers. Tearing is accomplished stepwise. There are six stages of the opening where the density of the tooth increases stepwise (Fig. 21.4).

21.2.2.5 Baling

The final stage in recycling is baling. The reclaimed fibers are compressed into bales, which must then be covered to protect them from contamination during transportation and storage. Bales can be produced into three forms, i.e., modified flat, compress universal density, and gin universal density. These bales are packaged at densities of 14 and 28 lb/ft^3 for the modified flat and universal density bales, respectively (Fig. 21.5).

Fig. 21.4 Shoddying machine [Picture was taken from ETUR Textile PLC, Adama, Ethiopia]

21.2.2.6 Regenerated Fiber Storage

The regenerated fibers which are sorted based on their color are stored for further processing. The store should be well ventilated and a vast room which can hold a stock for several months. The bales must be stored in a segregated manner according to their lot number. Bales are recommended to be laid down on their smaller side to minimize contact with the floor to reduce contamination. Enough space must be left for conditioning of bales before introducing for production (Fig. 21.6).

21.3 Fiber Mixing and Blending

The various categories of blending or mixing yield different aesthetic appearances of the end yarn and, therefore, different final appearance of the fabric [10]. The types of blending or mixing systems affect the quality as well as the consistency of melange yarn produced either in Ring spinning or rotor spinning. The main objectives of mixing are to get the required characteristics of the end product, to give variations in

Fig. 21.5 Bale press machine [Picture was taken from ETUR Textile PLC, Adama, Ethiopia]

Fig. 21.6 Regenerated fibers [Picture was taken from ETUR Textile PLC, Adama, Ethiopia]

the characteristics of the raw material, to minimize raw material cost, to attain effects by altering color, fiber characteristics. For better processing, blended fibers must be compatible in respect of length, fineness, strength, and elongation. Usually, the types of blends depend upon the proportion of shade or colored fibers in the mixing recipe or yarn. Accordingly, the following categorization is principally based upon the Shade proportion. Cotton mélange yarn quality and consistency are significantly impacted by the mixing process (cotton for Nonwovens). The draw frame blending techniques accomplish enhanced mélange yarn quality than blow room blending technique [11].

21.3.1 Blend Shade in Blow Room

Mixings that are performed in successive blow room opening, mixing, and cleaning machines are called "Blow Room blends". In general, darker shades and shades components range of colored fibers are manufactured as blow room blend shades. Typically, shades which have a proportion more significant than 15% are processed as blow room blends. It enables us to attain the highest blending and consistency in the shade. It must be noted that by the name "shade" at this point, it means the whole proportion of colored fibers in the yarn structure. Different mixing systems are used to achieve the desired shade in Blow Room. Compared with other techniques, Blow room blending is more useful, considering the shade uniformity point of view [12].

Before Mélange Yarn spinning, the mixing of various shades is going to be done mainly manually. Specific weights of different colored fibers are measured, then mixed manually. The manual mixture of the fibers results in better-finished product properties as the cotton fibers after dyeing lose their strength, and Short Fiber Index is increased if they are mixed automatically [13].

Stack Mixing

This system of mixing is often called 'sand witch mixing'. It is the most convenient way to blend different kinds of fibers. In this system, fibers are to spread in a bin in horizontal layers and cut in vertical slices. This process is carried out two times to attain homogeneity.

Bale Mixing

This is carried out at the beginning of the blow room process. Depending on the fiber type, about 40 to 80 bales are laid out for simultaneous flock pulling out. With cautious utilization, this enables the yarn quality to be maintained almost regularly. This type of mixing is very complimentary if all bales have the same mean values for length, fineness, strength, and trash. This type of blend is inappropriate for strongly differing fibers, for example, cotton and synthetic fibers.

Flock Blending

Flock blending is carried out at the blow room itself. Flocks are very small tufts of fiber. It is also carried out for synthetic fiber mixing after opening out the fiber by bale opener. It generally occurs in an uncontrolled manner. It can be made in a controlled manner if weighing pan and mixing blenders are used. It has the same kinds of advantages and disadvantages as bale mixing has.

Lap Blending

This is barely used this day. But it was previously used occasionally for the blending of cotton and synthetic fiber. For this, a doubling scutcher is needed, on which 4–6 laps could be laid. The laps are processed using the beater. Then a pair of cages are used to re-condense and form a lap sheet. Lap blending provides perfect transverse mixing and also the longitudinal blending. This is an uneconomical process as it essentially requires an additional machine and process.

Web Blending

Its major objective is to achieve better uniformity at the stage of comber lap as well as to obtain fiber blend in comber lap. Besides, this technique is also used for nonwovens. Now a day, the method is hardly used in the industry. Now despite web doubling, sliver doubling is used at the draw frame stage. However, web blending provides better longitudinal as well as transverse blend comparing to that of sliver blending.

21.3.2 Sliver Blending

These shades that are mixed on the drawing frame in the form of duplicate alterations are called "Drawing Blends." Predominantly, lighter colors are merged onto the draw frame, because they are trouble-free to blend as well as promote the process's balance. We can mix in drawing blends with shades of 15% each. This technique is used for the blending of natural fibers and synthetic fibers. It is carried out in the draw frame stage. For this, each material is to be processed separately up to the stage of the draw frame. The desired blend ratio can be obtained by selecting the suitable number of slivers of the fibers to be blended. This provides a high degree of homogeneity of blends in a longitudinal direction. Draw frame blending can be used in special cases for the production of fancy mélange yarn [12].

21.4 Mélange Yarn Spinning

The fiber of dyed mélange yarn is becoming an emerging product in the field of textiles. Cotton mixed yarns are spun from a variety of different colored cotton fibers. Mélange yarn is manufactured by combining some pre-colored fibers. The steps involved are dyeing, mixing (opening, carding), combing, drawing, roving, spinning, and knitting [8]. Colored spun yarn is spun usually by conventional ring spinner with a limited manufacturing capacity [1]. A common method of producing a variety of fancy yarns is combining dyed and undyed fibers of varying degrees.

First, the fibers are dyed and then mixed to spin mélange yarn with other gray fibers, thus reversing the conventional yarn forming cycle [7].

Mixing of fibers with various colors could be achieved either at the beginning of the spinning preparation in the blow room section or by providing/input various colored fibers into the draw frames. Studies have found that the scoring and dyeing phase of cotton fibers results in higher entanglement and cohesion between them, reducing the strength of fibers and eliminating a portion of the wax present on the cotton fibers surface. Yet more mechanical operations on these fibers cause fiber damage and their length to decrease. These irregularities in fibers not only affect spinning process performance, yet also the final yarn and fabric's mechanical and physical properties [2] (Fig. 21.7).

The processing of colored cotton fibers and they are blended with grey cotton fibers in the rotor spinning system isn't quite so common compared to the ring-spinning method, possibly due to an issue of premature fiber breakage due to roller opening and deposition of trash and dye particles in the rotor groove. Fiber damage in rotor mélange yarn is more than ring mélange yarn because of the additional opening by opening roller [2]. The key advantage of dyed cotton fibers manufactured using open-end spinning is that even when mixed at draw frame, random and homogeneous mixing of dyed and grey fibers is possible.

Fig. 21.7 Mélange yarn [Picture was taken form ETUR Textile PLC, Adama, Ethiopia]

21.5 Factors Affecting Spinning Mélange Yarn

The very first and paramount concern in the spinning of mélange yarns is to align the shade according to the specific specimen given by the product customer and get agreement and manage the same throughout the whole manufacture of the mass amount. It needs expertise in mixing department preparation and tracking. The knitting efficiency issue is also another influential factor to bear in mind. Thus it is mandatory to give attention to the entire process flow, including card clothing, output capacity, draw frame roller settings and machine speed, roving frame job efficiency. The third important consideration is the question of color fiber contamination that typically happens because of the use of various colored fibers in the factory, making mixed products. Conscious attention must be made to reduce fiber contamination. Besides the usual measures followed to make knitting yarns, the aspects mentioned above are the main critical to take care of without mistake, or else the fabric created would be downgraded because of noticeable problems.

Fiber Selection: while processing a variety of fibers in the same process flow/machines, the length of fiber variation must be minimized as much as possible.

Blending: The blending systems must guarantee that at the last phase, the desired shade composition should be fulfilled as much as possible.

Processing: The machines should be fixed with the process of the utmost fiber amount if there is blending 10% colored viscose in 90% cotton fiber. A considerable quantity of virgin cotton fibers (which is not colored) are typically applied in the making of mélange yarn to minimize the use of dyes [8]. The machine parameter may be close to cotton; however, at each step allowance to be prearranged considering colored viscose, relative humidity percentage in the department must as well be set, taking consideration both fibers. There is higher fiber damage in rotor mélange yarn due to the rotation of opening roller comparing rotor mélange yarn and ring mélange yarn [2]. The saw tooth coverings on the opening roller further break the individual fibers before twisting operation at the rotor groove.

Critical things to remember in traveler use, when spinning mixed yarn

(1) Because dyed fibers are in mélange yarn, one must pick the travelers with considerable bow height to have adequate yarn clearance.
(2) Because of decreased strength in mélange yarn, lighter travelers should be used, and spindle speed should also be held lower than the conventional yarn.
(3) Periodic cleaning of the ring should be done to avoid the deposition of dye on rings.

21.6 Classification of Mélange Yarn

One may classify mélange yarn into two of its most essential categories:

- Blended
- Non-blended

21.6.1 Blended

Mixed type of mélange yarn wherein various fibers are mixed/blended jointly at a known proportion, for example, PC (Polyester Cotton blend) 60:40, PC 50:50, PV 70:30, and CVC 50:50.

21.6.2 Non-Blended

In this category of mélange yarn, there is only one type of fiber use, but different colored fibers of the same origin are used to manufacture the yarn, e.g., 100% cotton dyed yarn, 100% jute yarn. Besides, any other natural or synthetic fiber could be used to produce non-blended mélange yarn.

21.7 Pros and Cons of Mélange Yarn

21.7.1 Advantages of Mélange Yarn

Mélange yarn is famous for all good reasons. It can provide a wide range of shades, some shades maybe just 0.5%, and some can even be one hundred percent [13]. It also makes the fiber dyeing, color matching, and fiber blending processes easy. It's the yarn of the modern textile industry. It's an environment-friendly yarn made of organic elements. It is dyed before the spinning process, which ultimately preserves the energy and adds to the environmental safety.

Different proportions of colored fibers of various colors and textures can spin into mélange yarns. Through the benefits of power-saving, conserving water, as well as reducing pollution in their processing, mélange yarns are becoming increasingly common in manufacturers [9].

Mélange yarns also trend in the fashion industry. Now a day, there is an extensive market possibility for fancy yarns compared to conventional yarns that stay more eye-catching [14]. At a reasonable cost, a buyer gets a blend of various colors on the same fabric and high tensile strength and a great color holding capacity. An enduring brightness and opulence in the fabric color can be achieved through mélange yarns.

These fancy yarns have fabric beauty advantages and could be applied in informal wear, sportswear ties business suits, socks, and all kinds of textile items, as well as bed sheets, towels, ornamental fabrics, and other home-made fabrics [1].

21.7.2 *Significant Problems in Manufacturing Mélange Yarn*

Almost all wet treatments in all steps of the textile processing alter the fiber morphology and physical properties of the fibers significantly [13]. The coloration process of cotton fibers leads to increased interference and cohesion between them, and subsequent mechanical means contribute to fiber rapture that makes the process of manufacturing yarn more difficult [1]. Before coloration, there are fiber pretreatment processes, including bleaching and scouring. These processes remove natural wax present on the fiber surface. Depending on temperature and time, there can be a decrease in fiber strength after dyeing. Even if mélange yarn presents a vast diversity of shades, however, its strength is lesser than usual conventional yarn, and the loss in strength rises with an increase in the volume of colored fiber. There could be several problems happening in the manufacturing process, but the topic just emphasizes those issues that are especially relevant to the mélange yarn. Any of these problems will result in the output being rejected and eventually experiencing a significant loss. And, to get rid of this, we need to find certain significant defects and concentrate on their remedies. Those situations are:

(1) Shade variation
(2) Variation in proportion (esp. in PC/PV/CVC) yarns
(3) Unnecessary spots at the fabric surface

(1) **Shade Variation**

- Twist variation in the yarn produced either by ring frame (T.M/T.P.I variation) or rotor spinning
- Foreign fiber blended/percentage of fiber is not the same
- The moisture content of the yarn
- Count variation
- Colored fiber

Selected quality parameter tests, which include yarn count, tenacity, evenness, elongation at break, shade matching, variation, and the visual appearance of end products, are accomplished before shipment to eliminate the cancelation of orders. In the late 90 s, shade matching and variation were among the main causes of the cancelation of orders [14].

Twist Variation

The variations are spotted in the shade, whereas identical shades are being spun on two machines but with differences in TPI. This represents like more the TPI may result in the deep shade as evaluated to the lower TPI. TPI checks must be firmly enforced to prevent the occurrence of such kind of problem.

Foreign Fiber Blended (Improper Mixing)

Among the problems, the one and significant fault found is the addition of inappropriate fiber/inadequate fiber proportion of foreign fiber that contributes to changes in the knitted fabric's tone and depth. So, to avoid this significant flaw, it is important for proper selection, and the exact proportion is a fundamental requirement. The tint is coloring that makes a substantial pale shade. A tint mainly reflects the least volume of color, which may deliver a detectable form of dyeing. In yarn manufacturing, fugitive tints are applied for detection and then removed in the finishing section.

Moisture Content

It is mostly known that Cotton fibers are naturally hydrophilic and absorb or adsorb the water vapor from the environment depending upon their percentage regain. Cotton, as well as other cellulosic fibers, exhibit such unique property. Yarn conditioning enables the cotton fiber to swell water hence improvement in tensile strength. Also, fiber will gain additional weight. As a result, if the yarn is manufactured from the mixture of conditioned and unconditioned yarn cones, a form of shade appears in the knitted fabric.

Count Variation

An inside shade sort, noticeable while the fabric is exposed to the sunlight in the tilted situation, is observed on the fabric if there is found a minute variation in a count of the two cross-matched yarns. So wrapping should be performed regularly to eliminate the differences in sliver hanks, roving hank, and yarn count.

Dyed Fiber

Fiber dyeing is among the factors which are not given much attention. Manufacturers are not confident regarding the dye rubbing and washing fastness. Therefore due to this, most mélange yarn producers are facing many limitations in fabrication. Thus, to overcome this issue, manufacturers required conducting washing as well as rubbing fastness tests of fiber used and must allocate the "LOT NUMBERS" as explained in the previous topics.

(2) **Variation in Proportion**

In Blended mélange yarn, i.e., mainly in PC/PV/ Heather Grey yarn, this fault is observed. This may help the shade either dark or lighter. This is attributed to the percentage change in each of the yarn components. This can be eliminated once more by periodic wrapping and sliver hank checking at the draw frames and the Speed frames. The proportion may also be verified as well as validated whether the measurements have been made as required or not.

(3) **Unnecessary spots at the fabric surface**

While the colors of two "LOTs" in the identical running product fluctuate, it is called "Shade Variation". The color of the yarn or knitted fabric will vary overall, which should be omitted to prevent the elimination of LOT. There are several explanations for the deviation in the shade. Among them, some are described below:

Such a problem has to do with fabric quality parameters. Unnecessary spots at the surface give a clue about the last fabric/yarn quality. It is always vital to recognize that the surface of dark shades must not include any of the white spots (neps). Similarly, at lighter shades, there should be no dark neps. And to prevent these problems, the raw material used should be considered beforehand. Any darker shade, for example, like 70%, is shade, and 30% is virgin cotton. Thus it is better to use combed sliver in mixing in place of cotton bales, which could result in neps in the final fabric.

21.8 Application of Mélange Yarn

Such fancy yarns are commonly manufactured in the textile sector, and their application is predominantly in the hosiery clothing segment. Mélange yarns are common because of their distinctive and exclusive fabric look. The wavy like outcome due to various fibers mixing and several color tones due to different fibers blending makes it very common and abundant in appearance. A fabric made of mélange yarn has much better smoothness compared to that of conventional. The use of slub, chain, and stretch attachments just opens up a wide variety of products only possible in mélange yarns [4].

Mélange yarn is usually used in warp and weft knitting machines, in different V-bed knitting machines, as well as winding machines. It is also used to manufacture men's and women's underwear, casual wear, sportswear, shirts, business suits, socks, as well as bed sheets, towels, decorative fabrics, and other home fabrics items [3]. With continual developments in production technology in recent years, mélange yarns are extensively used in denim, upholstery, and even luxurious fashion fabrics in the garment industry [9].

21.9 Conclusion

Among the various industrial sectors, the textile and garment industries are deemed among the significant pollutant around the whole world. Textile wastes and byproducts are growing to astonishing levels at superior rates because of the look, recognition, and obsolescence of fast fashion. For example, more than 16 million tons of used textile waste is generated each year in the United States, according to the Environmental Protection Agency. Among this amount, most of it sent to landfill.

Second, to oil, the clothing and textile industry is the world's biggest polluter. Recycling of textiles and clothing is a potentially beneficial practice from environmental, social, and economic aspects, as opposed to landfilling or energy use. The key advantage of textile recycling operations is the prospect of reusing clothing. It is possible to minimize pollution and the energy-intensive development of new garments by the recycling of clothes and textiles.

Mélange yarns are renowned by their eye-catching shade and manifestation amongst the fancy yarns. Mélange yarn follows exclusive dyeing practice, and it is excellent technical regarding fiber dyes, color matching, and mixed textile of multiple fibers. Dyeing of fiber before spinning enables to maintain of power-saving, emission cut, and ecological security. Mélange yarn's market share over conventional yarn is growing day by day. Therefore, using textile garment wastes for mélange yarn manufacturing has an opportunity to minimize landfilling. Besides, recycling spinning section soft wastes, as well as used clothes, significantly reduce the production cost.

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Chapter 22
Cotton Melange Yarn and Image Processing

Hua Wang, Habiba Halepoto, Muhammad Ather Iqbal Hussain, and Saleha Noor

Abstract Over the last decade, considerable progress has been made in the image processing of textile materials. First, this dissertation provides a detailed discussion of the present, past, and future of image processing for the melange yarn industry. Second, this dissertation covers the brief introduction of various aspects being analyzed in the twenty-first century, where the research methodology is booming day and night. The critics on the other researchers are omitted, and everyone's research related to image processing of textiles is warmly welcomed. Moreover, the conventional and advanced yarn inspection done by the manual vision and computerized vision and their respective disadvantages and advantages have also been discussed in detail. Next, it presents the macropixel analysis in particular.

Keywords Image processing · Mélange yarn · Computerized inspection · System architecture

22.1 Introduction

The different types of blending yield different aesthetic appearances of the final yarn and, thus, different final aesthetics of the fabric [1]. The effects and aesthetic of the final product might even be changed just by changing small production parameters,

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i.e., twist multiplier [2]. Due to this, there is a large variety in Melange yarn not only in terms of colors but also according to the texture of the yarn. Correspondingly, Memon et al. [3] have maintained that the changing dyeing parameters cause changes in the final yarn quality.

The final feel, hand, and aesthetic of each class is different, which opens up the room for designers to choose fibers and yarn types selectively, what they require but also suggests the researchers researching in the field of image processing to develop computational models for the assessment and inspection of the quality of the final products. Among various Melange yarns, Snowy, Neppy, Heather, Marl, and Siro are some standard classes of Melange yarn. One of the major classes of these Melange yarn is neppy Melange yarn, in which a certain number of neps are introduced to achieve unique aesthetics. It should be noted that for this class of yarn, the neps are not the fault; preferably, they have been deliberately introduced into the Melange yarn. However, the size, color, and dispensability of the neps are essential for the production of this class of yarn. Since a little change in any of the parameters would cause the final product to look different.

The image processing technology is a subject that combines the theory, the primary method of image processing, and its application in intelligent detection [4]. It first extracts the relevant image information by unique methods, then processes the image, and finally uses computer programming and related digital image technology for practical analysis, to obtain the expected results. One of the critical fields of artificial intelligence and machine learning is data mining, which has been reviewed recently [5]. Their matrix is shown in Fig. 22.1.

Digital image processing is a method and technology to remove noise, enhance, restore, segment, and extract features. The emergence and rapid development of digital image processing are mainly affected by three factors.

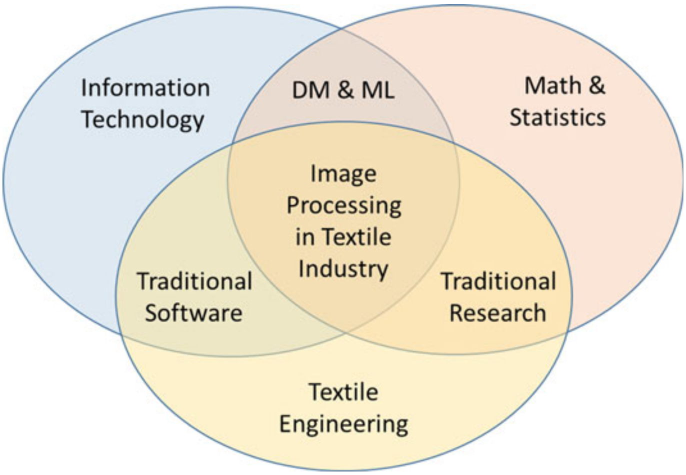

Fig. 22.1 Relation matrix for image processing in textile industry

1. The development of the computer;
2. The development of mathematics;
3. The growth of the application demand of a wide range of agriculture, animal husbandry, forestry, environment, military, industry, and medicine.

Image processing technology has been applied to the testing field of textile materials since the late 1980s. With the development of computer technology, the application space of this technology in the field of textile testing has become broader. Mainly, the application of this technology has replaced part of the manual testing in textile testing, overcoming some faults in the traditional manual testing process [6]. It plays an essential role in the development of automation, quantification, and objectification of fiber material testing.

22.2 Importance of This Technology

Image processing technology refers to the process in which image signals are transformed into digital signals and processed by computers. Collecting digital image, image segmentation, image enhancement, image restoration, image analysis, and image compression coding are the main contents of image processing technology.

The image processing technology is divided into analog image processing and digital image processing technology. Since it is done directly by computers or real-time hardware processing, govern by computers, so it is also called computer image processing. Digital image processing is a subject about using a computer to process images. The digital image processing technology is to transform the image signal into the digital signal and use the computer or some digital processing hardware to process or to improve the usability of the image.

Since the technology is growing at a faster pace, there is some well-developed software for shade matching Melange yarn, as a window of MatchColor software shown in Fig. 22.2. However, these type of software only discusses shade matching, since they have been designed to predict the mixing recipe and to predict the dye concentration or the amount of the dyed fiber to be used.

Due to rapid development in the technology, there are the yarns with structural effects like waves, lines, neps, slubs, and so on, optical effects like color, luster, dull, bright, fluorescent, feel effects, like soft, ultra-soft, harsh, and so one. Therefore, it is essential to study each class of yarn separately. Hence, neppy Melange yarns are worth to be studied for their homogeneity using advanced software tools.

In recent years, with the influence of the continuous progress of science and technology, more and more advanced technologies are applied in the textile industry, and image processing technology is also one of them, which has the advantages of stability, simplicity, and accuracy, promotes the testing efficiency of textiles, and has a positive impact on optimizing the testing level of textiles.

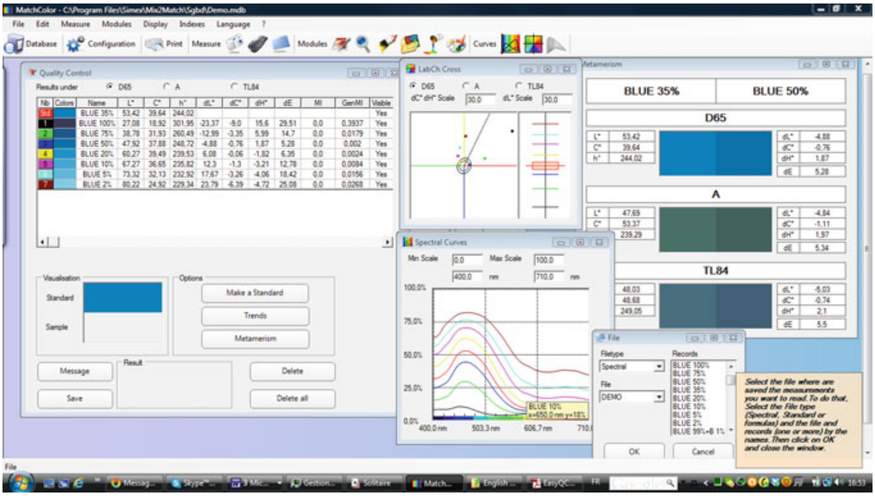

Fig. 22.2 The window of MatchColor software

Even though these algorithms attain functional consequences, they are computationally too complicated, and mostly these are not appropriate for real-time applications. The best filter design method is about the choice of a filter that delivers the exact judgment concerning two textures. Mostly these methods use the gray level co-occurrence matrices (GLCM).

This method delivers statistical evidence over an area, and the values are utilized for the segmentation of the image. If there will be bigger windows for the data collection, it is better for the sample collection statistically. However, these methods are affected by non-uniform lighting environments in the image that causes wrong segmentation. Therefore, such methods generally require the pre-processing step for the improvement and betterment of lighting inequalities in the image. Moreover, the main benefit of the statistically-based procedures is their computational easiness.

As the complication of an algorithm develops, it becomes too challenging to implement the image inspection in real-time. Thus, an algorithm for real-time yarn quality control ought to be mainly aimed at the root of fast computational approaches.

22.3 Development in Fiber and Yarn Image Processing During the Last Century

In the 1920s, image processing was used for the first time to improve the image quality of the submarine cable between London and New York. In the 1950s, when the digital computer developed to a certain level, digital image processing attracted people's interest. In 1964, the U.S. jet propulsion laboratory used computers to process a large number of pictures of the moon sent back by the spaceship, which has achieved remarkable results. At the end of the 1960s, digital image processing had a relatively complete system and formed a new discipline.

In the 1970s, digital image processing technology developed rapidly, the theory and method were further improved, and the application scope was extensive. In this period, image processing is mainly related to the research of pattern recognition and image understanding system, such as character recognition, medical image processing, and remote sensing image processing. From the late 1970s to now, various application fields put forward higher and higher requirements for digital image processing, which promoted the development of this subject to a higher level. Especially in the field of scene understanding and computer vision, image processing has developed from two-dimensional processing to three-dimensional understanding or interpretation. In recent years, with the rapid development of computers and other related fields, such as the development of image representation, visualization of scientific computing, and multimedia computing technology. Digital image processing has changed from a specialized research field to a universal tool in scientific research and human–computer interface.

Image Processing Toolbox provides a full range of reference standard algorithms and graphics tools for image processing, visualization, investigation, and development of the algorithm. It can be used to denoise or restore noisy or degraded images, enhance images for higher definition, analyze outlines, extract features, and textures, and matching two pictures.

Most of the functions in the toolbox are written in MATLAB. Thus, one can check the algorithm, amend the foundation code, and make custom functions. Image Processing Toolbox in the MATLAB provides support for engineers and experts in all the fields of science.

22.4 Possible and Practical Software Approaches in the Melange Yarn Industry

There are many items included in dyed fiber inspection, among which evenness, cleanliness, cleanness, deviation, and a maximum deviation of size are all inspection indexes for dyed fiber grade judgment. Among various indexes, evenness and cleanness are the main indexes in the classification of dyed fiber. Image processing technology for human visual ability has the effect of substitution and expansion and has a decisive role in solving the problems in the past measurement methods.

Automatic cleaning tests based on the shape of the rough faults described by standard classification and statistical cleaning can be performed using image processing. The detailed information, such as center gray, area, perimeter, width, and length, can be measured using an image processing technique. In essence, the evenness test by image processing technique will distinguish the gray difference. The two-dimensional gray function based on the gray value of the image can be processed to obtain the discrete image so that the image can be easily measured by computer, and then the evenness of dyed fiber can be distinguished by the method of pattern recognition.

Recognition of dyed fiber will be one of the long-standing problems in the textile industry. In the past, testing dyed fibers were often tested by colorimeters and spectrophotometers, and inspectors need to identify according to experience. There is no objective and unified standard in the evaluation standard. Therefore, image processing technology is an effective method to solve this problem. Image processing technology with artificial neural network technology would be worth studying. Compared with the traditional method of observing dyed fibers with a spectrophotometer first, and then distinguishing them with the experience of inspectors, the evaluation using image would be beneficial.

Image processing can analyze the change of Melange yarn tension in the process of Melange yarn post-processing, especially in the process of winding, by processing the digital image of the Melange yarn air loop. So it will improve the timeliness of Melange yarn tension online monitoring. To a certain extent, the system would be more in-line with the requirements of textile automatic production and monitoring and thus will provide a way for the research and development of a non-contact tension detection system for Melange yarn.

The number of hairiness with different lengths can be obtained by judging and analyzing the feather segmentation points by image processing. Image processing technology will play a more critical role in the future textile testing field. However, in the later development process, because the test method is not specific to a specific test object, so in the later image analysis process, it is necessary to strengthen the programming and software research for different tests of textiles. At the same time, the accuracy and speed of image processing are improved continuously to meet the needs of a large amount of data for later image analysis. With the progress of science and computer technology, image processing technology conforms to the development trend in the field of textile testing, and its application range is bound to be more comprehensive.

Shen et al. [7] revealed that the conversion of overlapping spectral data into linear separable spectral data in high dimensional space and then identifying and determining by trained support vector machine classifiers. Shen et al. [8] also suggested a back-propagation neural network-based spectrophotometric color matching algorithm and its process using a back-propagation neural network to predict the extended average spectrum and then using the constrained least-squares method to predict the incremental average spectrum.

Yang et al. [9] suggested a new idea of predicting the coloring of Melange yarns from the reflection spectrum by using the idea of modular artificial neural networks and decomposing the entire data set into different units with dyed fibers as modular units. Compared with artificial neural networks, modular artificial neural networks has apparent advantages in correlation coefficient, training execution time, and formula root mean square error. The average color change of the forecast spectrum got by the modular artificial neural networks model is 1.26, which is much lower than that. The average CMC obtained by artificial neural networks.

From the above discussion, it can be said that the Melange yarn is less studied by computer scientists. This is somehow due to the involvement of complex models. Moreover, it is important to mention here that the digital image processing is being used in the Melange yarn industry for the following purposes,

1. Improve the visual sensory quality of images of shade cards to produce images more suitable for human visual observation and recognition, For example, the brightness and color of the image of shade cards are transformed, the image is enhanced, and the image is geometrically transformed to improve the quality of the image of shade cards.
2. Extract some features or private information contained in the image of shade cards to facilitate the computer analysis of the image the extracted features can comprise many aspects, such as gray/color, boundary/region, texture, and shape/topology.
3. Transform, code and compress the image data to improve the efficiency of information transmission and reduce the storage capacity of image information The amount of image and video information is tremendous, so it is often necessary to compress this kind of data effectively.
4. To help people comprehend and investigate data, that is information visualization by using the technology and methods of graphics and images of the final product as well as processing.

The yarn quality in real-time can be watched and recognized by digital image processing technology.

22.5 Melange Yarn Inspection

For every industry, it is essential to inspect the quality of their product before the shipment. It is essential to meet the customer's requirements, and the final product must not much deviate from a given set of specifications [10]. There are two options for textile fault detection [11]. Likewise, the yarn may also be inspected manually and automatically. The first one is the visual inspection that is done manually, and the second one is a computerized vision system.

22.5.1 Analysis of Visual Inspection and it's Quality Control

Visual inspection is a vital part of quality control and quality assurance in the textile Melange yarn industry. In a textile Melange yarn industry, the yarn inspection is mainly done by making knitted fabric from it. The operator checks yarn quality, shade, and appearance. The whole process is done employing appropriate illumination systems. To some extent, other yarn quality parameters such as CV%, count, and twist are appropriately examined by expensive machines. Also, there are spectrophotometers to match the shade and to alter the recipe if necessary. The advanced spectrophotometer and shade matching color booth are shown in Fig. 22.3.

However, the appearance is still done by the operator only. Nonetheless, this technique is rather untrustworthy as it has the chance of human error and varies among operators. Particularly for neppy Melange yarn, usually, the operator cannot locate small differences. As it is well known that the textile Melange yarn engineering possesses various kinds of yarns, i.e., neppy, slub, fancy, marl, and snowy, thus, there are many kinds of pictorial differences that may affect the total appearance.

Herein, the disadvantages of visual inspection and the advantages of automated inspection are discussed to understand the importance of this study.

Quality assurance and textile testing constitute one of the central departments of any yarn spinning operation. Some quality tests, including yarn count, evenness, tenacity, elongation at break, shade matching, variation, and the visual appearance of finished goods, are performed before shipment to avoid the cancellation of orders. A couple of decades ago, shade matching and variation were one of the main reasons for the cancelation of orders. Thus, in past decades, too much research was performed on shade matching and minimizing variation. As a result, various technologies have been developed to avoid the rejections of orders. It is necessary to control the quality at each step of manufacturing. Various stages of Melange yarn, where qualities are checked, are shown in Fig. 22.4.

The quality control process means doing observations, tests, and inspections and thus, making conclusions which progress its performance. Because, a yarn manufacturing or manufacturing process cannot be 100% fault-free, the success of a spinning mill is highlighted by success in reducing yarn faults. The quality of yarn has a direct correlation with further textile products that are not solitary, the primary obligation of the textile producers. Likewise, an essential issue for textile manufacturing that it yields the final product for the customer.

Though humans might work better than machines in some cases, yet there are some disadvantages. These disadvantages may be listed as follows. The technically expert workforce is hard to find any industry, then it needs much time to get them enough trained, and their skills need much time to be enough developed. Once they get trained, there are chances that they change the job or find a job in other industries.

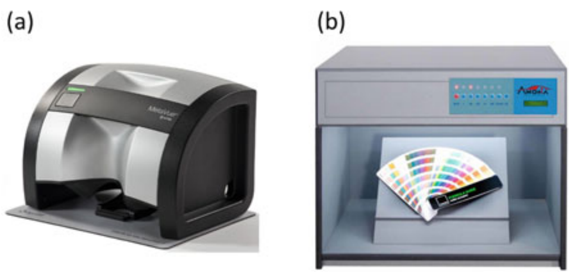

Fig. 22.3 Tools for visual inspection **a** spectrophotometer **b** shade matching the color booth

Fig. 22.4 Quality control at each step of the manufacturing

Generally, visual inspection is boring and tedious; even the devoted employee gets boredom and thus decline efficiency. Inspection done by humans is a time-consuming task due to the slow working speed of humans than machines. Human is prone to get tired quickly. Their tiredness further increases inspection time and decrease accuracy. Besides, the lower speed of inspection often causes a bottleneck in the high-speed production lines. The visual inspection is a very exhausting job, as well as, after some inspection. The eye vision cannot be attentive for a long time. Therefore the inspector may neglect minor faults inevitably and even large ones with the passage of inspection time. There is a wide variety of faults that are due to the breakdown of processes and sometimes due to low-quality fibers. It is almost impossible to make the same level of fault detection between several inspectors. Thus, one fault might be significant in one's eyes but maybe negligible for others. It is just a subjective method that results are difficult to duplicate. The grading process might vary from one industry to another and from one customer to another. Therefore, the worker hired from one industry might not easily follow the requirement of other industries. There is almost no feedback to support manufacturing processes. The operator may only grade as first quality or second, but have nothing to do with the corrective measures. This traditional method cannot give 100% assured inspection. It is labor-intensive and needs more floor space, which is non-value added activity, which makes it also cost-intensive too.

Due to these considerable disadvantages and to increase accurateness, several attempts have been made to substitute labor-intensive visual inspection by computerized one to make a consistent evaluation.

22.5.2 Computerized Inspection Model and System with Quality Controlling

With the rapid development of the Melange yarn industry, on the one hand, it requires the technologists to grasp the fashion trend, conceive and design various Melange yarn varieties, and on the other hand. It also puts forward the requirements of rapid response and shortening the production cycle for the finished products of Melange yarn fabric. The computer simulation of Melange yarn and its fabric emerges as the times require. The computer simulation of Melange yarn can be divided into two uses: one is for the development of new varieties, the other is for the simulation of the yarn surface.

Herein, a new scheme of computer simulation of Melange yarn is studied, developed, and put forward. Yarn is the most basic unit of fabric. The effect of fabric surface simulation dramatically depends on the principle and effect of yarn simulation. Irregular shape, complex material structure, and vibrant color changes or special effects of color make it difficult to simulate the reality of Melange yarn due to the inherent characteristics of Melange yarn.

Melange yarn is beautiful and unique in appearance. Its structure is quite different from traditional yarn. Its color and appearance are various. Through the application of the image processing system, employment is significantly saved, and the employment of ten thousand ingots can reach 15 people. In particular, the operational requirements of the operation line tend to be simplified and specialized, and the period of on-the-job personnel training is further shortened, which significantly reduces the labor intensity of the front-line staff and makes the staff happy to work. However, the application of a large number of advanced technologies requires more and more skilled workers. By using image processing, the operation of employees tends to be simple, and the labor intensity is significantly reduced. Before understanding the computerized inspection model and system with quality control, it is necessary to understand the steps involved in the manufacturing of Melange neppy yarn. All the steps have been discussed in the order in Fig. 22.5.

Since the start, people want to improve the manufacturing methods to attain the best potential advantages like quality, cost, luxury, precision, accuracy, and productivity. The technology was the magic stick that encouraged humanity from manual to mechanical and then from mechanical to automatic to copy the extensive diversity of human jobs. Recently, several researchers have studied computerized yarn inspection [12–16].

Since the late 1990s, the computer-supported automatic quality system has been paid more and more attention all over the world. It is considered to be an essential way to improve the market competitiveness of enterprises. It is an important strategic decision to adopt advanced technology, realize the informatization and automation of the quality assurance system, and adapt to the needs of the new era of quality, to improve the management level and product competitiveness of enterprises.

Kuo et al. [17] have carried out identification experiments on woven fabrics through machine vision. In the experiment, the collected image is pre-processed by 3×3 median filters, and then the fabric texture points in the image were divided into warp and weft texture points by Fuzzy C Means (FCM) algorithm. The matrix of organization points is composed of the numbers 0 (warp organization point) and 1 (weft organization point). Then the matrix is input into the two-step back propagation neural network for training. The experimental results showed a 100% recognition accuracy.

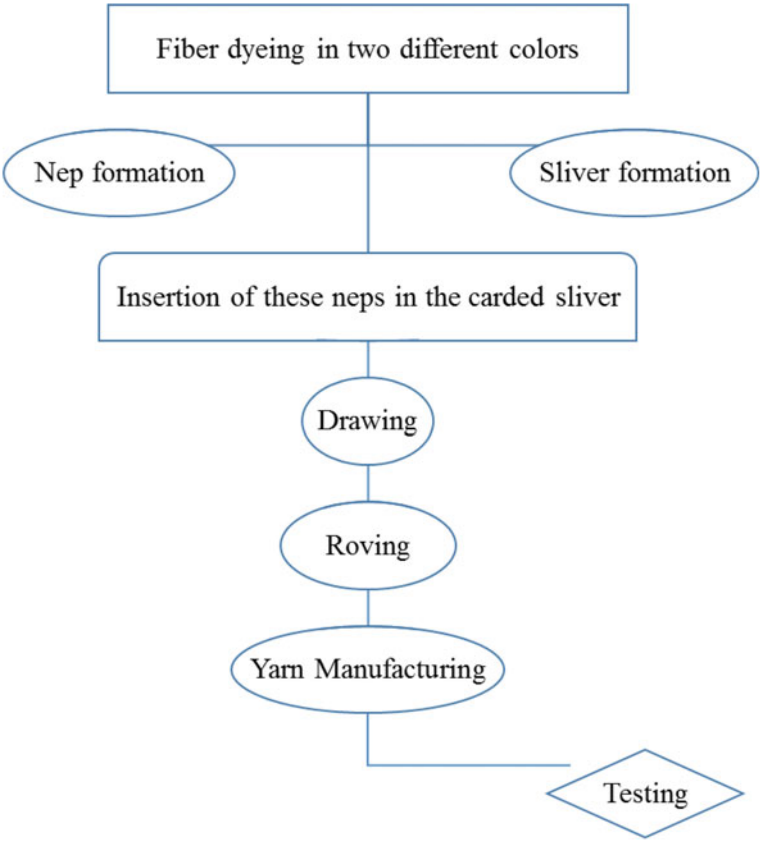

Fig. 22.5 Control system architecture of Melange neppy yarn

The rare presence of computerized yarn testing may be credited to the practices, which are frequently impotent to survive through extensive diversity of yarn quality parameters and faults, yet a sustained decrease in the cost of computers proposes that computerized yarn testing would-be a cost-effective option. The broader application of computerized yarn testing would seem to offer many advantages, including better well-being, cheap labor costs, the removal of human error and subjective judgment, and the formation of well-timed statistical data. So, computerized visual testing is getting importance in the textile spinning industry.

The computerized testing system typically contains a computer-based vision system, as shown in Fig. 22.6. Since they are computer-based, these systems do not undergo the disadvantages related to humans. Computerized systems can check yarn in a nonstop manner. Generally, these computerized systems are offline systems. If any faults are found that are mechanical (i.e., change in the count, change in a twist), the interval time that exists between actual manufacturing and testing. Thus, in the

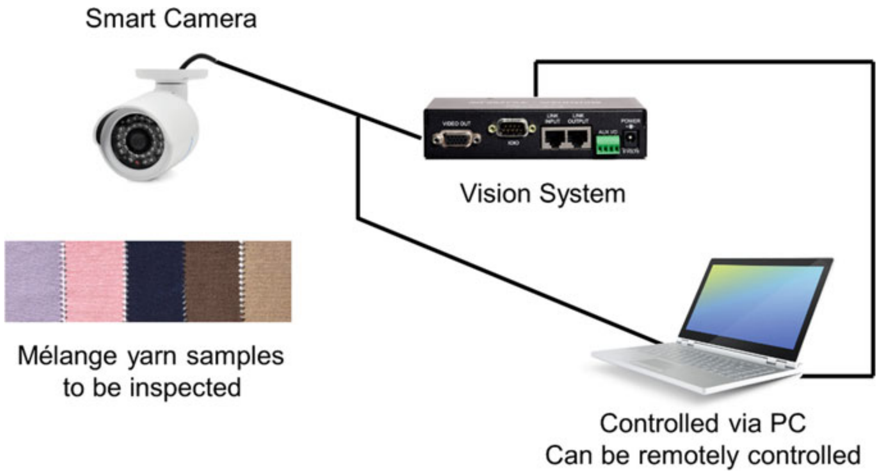

Fig. 22.6 Computer-based vision system for Melange yarn samples

meantime, more faulting yarn is produced on the machine. So, to be more active, testing systems must be applied in real-time.

The computerized inspection system usually contains the following main component:

1. The examination channel equipped with cameras and illumination;
2. The fault investigating computer system, as well as the main CPU (server) and a camera for each workplace;
3. The quality control system for each manufacturing line;
4. The documentation subsystem for the standard and faulty databanks;
5. The wiring of the system together for interfacing the working databank.

The application of digital image-processing is beneficial in yarn manufacturing and testing. In the previous score, it has established to be the most encouraging, quick, and reliable solution for the upcoming development of real-time automatic yarn fault detection. Significant efforts have been made for developing and improving the undertaking of real-time automatic yarn fault detection. It needs high-resolution imaging to allow faults to be noticed. So, the yarn faults can be detected by monitoring the yarn structure.

In the Melange yarn industry, along with all parameters of the conventional yarn manufacturing industry, there are some additional requests for monitoring shade and appearance. To somehow, the color matching has been studied in past years to match the shade of Melange yarn and or to predict the recipe of Melange yarn. However, the appearance of Melange yarn is particularly neglected by researchers doing textile image processing. Herein, the aesthetic appearance of neppy Melange yarn has been studied. A software package written in MATLAB code is used for this procedure as the technique is fast and corresponds to the homogeneity of Melange yarn.

For a spinning industry, in these severe financial times, firstly, quality yarn shows the pivotal role to assure existence in a rivalry market. This lays urbane pressure on the spinning industry to work on the way to a little cost initially quality product as well as timely supply. Qualitative yarn is entirely free of significant faults and almost free of slight physical or apparent faults. The non-detected yarn faults are responsible for at least 40–50% of the second quality in the later weaving and garment production, despite using the same amount of manufacturing resources [18, 19].

Even though quality ranks have been enhanced mainly with the unceasing development of materials and skills, most spinners still it is essential to do 100% testing since customer beliefs have also enlarged and the risk of delivering mediocre quality yarns devoid of testing unsatisfactory. The critical issue, so, is how and under what conditions yarn testing will lead to quality development. To address this issue, one must differentiate between real-time and offline testing systems. The real-time system delivers figures from current production and is located directly on or in the manufacturing line while the offline system is located after the manufacturing line. In recent times, the yarn testing is still done offline and manually by trained staff with a maximum accuracy of only 60–75%.

The current spinning industry faces a lot of problematic challenges to make a high output as well as a high-quality-manufacturing atmosphere [20]. Since manufacturing speeds are more rapidly than ever, manufacturers must be able to recognize faults, find out their causes, and do the essential alterations in less time to decrease the quantity of second quality yarn. Due to factors such as monotony, fatigue, boredom and, carelessness, workforce performance is often changeable and untrustworthy. The examiner can barely control the level of faults that is satisfactory, but linking such a level between several examiners is almost incredible. So, the most significant prospect of objective and reliable assessment by the use of a computerized testing system.

22.5.3 Differences and Advantages of the Proposed Computerized Inspection Approach

Different researchers have performed various approaches to study the computerized inspection approach of the textiles. They have been proposing the model for weaving, knitting, and even for spinning. Some researchers have recently been done on shade matching and color development for textiles too. However, none of the researchers have focused on the homogeneity of neps in the Melange yarn since it is more related to the problem in the industry, and probably the researchers doing image processing are less aware of this issue. However, this research is of much importance to be focused on textile image processing, and thus it would open up a new direction for a researcher in the field of image processing of Melange yarns or textiles.

When we talk about the automated inspection, the industrialist is worried about the cost of testing [21]. To answer them, Nickolay et al. [22] suggested that computerized inspection system is better for the industries in terms of finance as well, if they consider the cost of inspection by persons and other related advantages. Besides, Zhang et al. [23] believe that due to rapid development in the field of imaging technology, i.e., high-quality image acquisition and development in computer technology, automated inspection has become inexpensive, allowing image processing and pattern recognition to be done inexpensively. To date, an adequate computerized inspection is essential to compete in the field of textiles and clothing industry [24–31].

These advantages are the summary of the recent studies [32–36], and they may be listed as follows.

1. The results of the computerized inspection are reliable.
2. The results of these systems are also reproducible.
3. It is free from the subjective deficiencies of the visual inspection.
4. It may increase the effectiveness of production lines.
5. It also helps to improve the quality of final products.
6. The computerized systems mean lower labor cost.
7. In real-time quality control, the machine operator may also serve as an operator to these inspection systems.
8. Due to the removal of bottlenecking of inspection by the automated inspection, these systems offer shorter production time.
9. It helps to settle a dispute between buyers and producers.
10. It helps to decide the standards accurately.
11. It discourages conflicts among inspectors within the same industry.
12. It needs minimum floor space.

Due to these enormous advantages of the automated inspection, it is worth to develop this research domain.

22.6 Future Perspectives

The computerized vision system has several advantages over the traditional inspection system. Therefore, there is a strong potential to explore this research direction further. Image processing in the field of Melange yarn would be fruitful for the personnel working in the industry and the quality of products as well.

This research may be expanded in several ways; some of the possibilities are discussed here. This research may be extended by studying the effect of homogeneity on mechanical properties using an image processing technique. The surficial effect of a fabric, which requires a 3D model and thus, pixel analysis in three dimensions, can also be analyzed. Moreover, multi-colored neps might also be analyzed directly without converting them to greyscale. This research may also be extended for different classes of Melange yarns and to make a comparison among different classes or within a similar class. The homogeneity calculation on single station non-binary images of the shade cards can also be performed.

Most of the companies in the Melange yarn sector are facing an ever-increasing competition by high-quality requirements, lower price imports, and high taxes. Computerization and industrial development are recommended as crucial features for the being of textile industries. The crucial additional issue in the manufacturing of different high-quality Melange yarns, which are not subtle to price competition. Though to somehow, the spinning industry has promoted from technical novelties, mainly in manufacturing. Due to the unambiguous nature of Melange yarns, the faults come across within textile manufacturing must be noticed and improved at initial periods of the manufacturing process. Therefore, visual fault recognition is of supreme significance for the yarn's overall quality and price.

22.7 Conclusion

The application of image processing technology in textile testing has considerable importance. The continuous scientific research on this technology will undoubtedly help the textile industry. The image processing technology is reflected in all aspects of our life, ranging from applications such as aerospace technology, to personal life, to provide people with more convenient and efficient services. Image processing technology will become more and more critical with the growth of science and technology. In the future, digital image processing will certainly develop towards the direction of high precision and speed, and the requirements of real-time image processing on processing equipment will also be correspondingly improved, more intelligent, convenient, of course, to update theoretical research and faster algorithms The future image processing technology will play a more significant role, no matter in which field.

Melange yarn is one of the potential textile industry. The image processing field has been developed at a rapid pace in the past years. There are several software and systems introduced recently to control the shade, color, and quality of Melange yarn by using the technology of image processing. However, none of the researchers have ever tried to solve the problem of homogeneity to assure the aesthetics and appearance of Melange yarn. This determination of homogeneity is important for designers to design their products selectively. The macropixel analysis thus could be fruitful for studying this aspect.

From the review presented in this dissertation, it is understood that the necessity for a complete, reliable way to produce first quality or fault-free yarns has an utmost priority than ever for the Melange yarn industry. Theoretically, this can be achieved with 100% of the quality check before shipment. However, practically it seems impossible due to the enormous disadvantages of the traditional visual offline inspection system. However, this can be achieved by the computerized inspection system.

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