Chapter 17
Cotton Production Beyond 2030

Don Keim, M. Rafiq Chaudhry, Sandhya Kranthi, and Dean Ethridge

17.1 Introduction

Cotton production practices have been continuously changing due to better understanding of the cotton plant behavior, response, and needs coupled with composite efforts to improve lint yield and fiber quality. Thus, changes have occurred in all aspects of production technology including input quantity and their timing. For a long time, development of varieties remained the predominant focus of bringing improvement in production, quality, and suitability to the growing environment. In order to exploit the best of the cotton plant, it needs to be fed properly and protected against vagaries of insect pests, diseases, and weather stress. Over the last about a century, some of the major aspects of producing cotton that have changed drastically are application of fertilizers, use of pesticides and consequences, variety development, machine measurement of fiber quality characteristics, and the latest being the use of biotechnology applications. Agriculture is nearing rapidly to utilization of drone technology as a component of the precision agriculture. Drone could be used for spraying cotton. Additions to the list will continue to increase, while improvement/perfections in the current practices will not stop. How all these developments will impact cotton production practices beyond 2030 is the subject matter of this chapter.

D. Keim
Stoneville, MS, USA

M. R. Chaudhry (✉)
Springfield, VA, USA

S. Kranthi
International Cotton Advisory Committee, Washington, DC, USA

D. Ethridge
Lubbock, TX, USA

Mehboob-ur-Rahman et al. (eds.), *Cotton Precision Breeding*,
https://doi.org/10.1007/978-3-030-64504-5_17

17.2 Cotton Breeding

The state of the art in plant breeding has advanced dramatically in the last 20 years. This is primarily a result of advances in molecular marker technology and data science. The adoption of these and other tools in breeding programs have shown to both (a) enhance genetic gain and (b) reduce the selection cycle time. Advances in data collection automation and analysis have also enabled more efficient programs. Applied breeding efforts in cotton, whether in private- or public-funded organizations, have generally lagged behind other major field crops such as corn, wheat, and soybean. Consequently, adoption of new technologies in cotton programs has generally been slower. But, as these technologies are adapted to cotton breeding, large advances in breeding efficiency have been realized.

The breeding efficiency in cotton is much lower (higher cost per unit of genetic gain) than most field crops due to inherent nature of the cotton plant. In comparison to other field crops, the cotton plant is indeterminate, having sequential blooming and relatively long growing cycles. Cotton is a perennial woody bush, which has been adapted to and commercially grown as an annual field crop. Other characteristics of the crop have added to the high "breeding cost" (Keim 2007). These include requirements for ginning, seed delinting, hand harvesting in early breeding stages, hand self-pollination, and costly fiber evaluation. Because of this high cost, adopting any new technologies, such as genomic selection (GS), that can enable fewer progeny generations to be grown, harvested, and processed will have a major effect on breeding efficiency. Below are described how some of these new breeding technologies are being implemented in some large breeding programs. In doing so, a description will emerge of what an advanced applied cotton breeding program could be like by 2030. Discussion will be limited to varietal breeding, as this is a characteristic of most applied cotton breeding programs worldwide.

17.3 Breeding Goals

The goals established in any breeding programs will dictate which tools will be useful. Fiber productivity (yield of marketable lint per unit area) is typically the primary breeding goal. This includes fiber quality as a critical objective when considering the "marketability" of the end product. Fiber length, strength, and fineness tend to have negative associations with fiber yield. Thus, neglect of these traits in a program can lead to produce high-yield varieties having poor marketable fiber. Other critical goals include adaptability to a range of environments, stress tolerance, and disease and insect resistance. The use of biotechnology in the form of transgenic traits has long been a critical breeding goal in many programs worldwide. Primary transgenic traits commercialized to date have included lepidopteron insect resistance and herbicide tolerance. New traits such as sucking pest tolerance are showing promise (Akbar et al. 2019). Additionally, as pests overcome the resistance traits, a search for new transgenic traits is continuing.

17.4 New Breeding Tools

Tools available to plant breeders have advanced dramatically. Until recently, breeders were limited by the resources necessary to select plants solely on a phenotypic basis. Once initial breeding development and selection were accomplished, costly multiyear wide-scale testing was needed to identify the most productive and most widely adapted genotypes for a given area. In addition, extensive fiber quality evaluation was needed to ensure the released genotypes meet the market needs. Although advanced-stage phenotypic evaluation will continue to be necessary, any tools available to reduce the needed time and effort will be of great advantage.

Off-cycle generation advance. Although this has long been an integral part of breeding in several crops, use of off-season nurseries in cotton, until recently, has been quite limited. Some applied programs are beginning to adopt strategies where early generations (from crossing up to F_4) can be advanced quickly using greenhouses and off-season nurseries. In a traditional breeding program, this can have the advantage of reducing the breeding cycle by up to one-third. Additionally, use of off-cycle generation advance is highly advantageous in marker-assisted backcross programs. Backcross development cycles can be reduced by up to two-thirds.

Because genetic gain is a function of time, use of off-cycle nurseries can be of great advantage. However, large resource commitments are necessary to take full advantage. Development and maintenance of off-season nurseries and greenhouse facilities can be cost prohibitive for some programs.

Advances in phenotyping. Performance evaluation remains a critical part of cotton breeding. Productivity, performance stability across years and environments, maturity, stress response, and fiber quality are characteristics essential to successful varietal development. In recent years, mechanized planting, harvest, and processing have enabled commercial breeding programs to reduce the labor input in their testing programs. Thus, breeders have been able to either expand their program testing footprint or reduce their overall testing costs. The former approach has the advantage of more thorough evaluation of genotypes. Such an approach could reduce the testing cycle by a year or more.

High-throughput phenotyping technology has advanced dramatically in recent years. A recent demonstration using LiDAR (light detection and ranging/light imaging, detection, and ranging) in assessing cotton plant growth was conducted in Georgia, USA (Sun et al. 2018). This technology has the capability of rapid assessment of plant growth characteristics related to productivity on large numbers of genotypes.

Data analysis and management. These new phenotyping technologies have the capability assessing large sets of genotypes but require the acquisition and analysis of a huge amount of data. Statistical and computational methods incorporating GxE effects have advanced dramatically (Perez-Rodriquez et al. 2015).

17.5 Marker-Assisted Breeding Tools

Molecular marker technology has had major breakthroughs in recent years, dramatically reducing the cost per data point, as well as increasing the usefulness of molecular data. This has enabled the use of new breeding approaches in a cost-effective manner.

Marker-assisted selection (MAS). Marker-assisted selection is quite useful in selection for simply inherited traits in cotton but requires the prior establishment of marker-trait associations (QTLs). A particular usefulness of the tool has been in the selection for traits that are very difficult to phenotype accurately. It has also proven beneficial where phenotyping requires destructive sampling of live plants. For example, selection for nematode resistance, both for root knot and reniform nematode, in cotton has been made using DNA markers. To accurately determine whether a plant is resistant to nematode, the plant must be grown in nematode-infected soil. After the plants are infected, the roots must be carefully removed, carried to the lab, and washed carefully. Finally, physical nematode counts must be made. Once QTLs have been identified, MAS for nematode resistance has made breeding for these traits a feasible endeavor. Public and private US breeding programs are currently using MAS for these traits.

Marker-assisted backcrossing (MABC). MABC has the primary advantage of reducing the number of backcrossing cycles needed to essentially recover the recurrent parent genotype. It uses the traditional backcross method to transfer alleles at one or a few loci from a donor parent to an elite variety (recurrent parent). Markers are utilized not only to select the trait of interest but also to recover genotype of the recurrent parent quickly. The trait of interest must have associated a strong link with a small group of markers. To recover the recurrent parent, a set of genome-wide markers that differentiate the two parent genotypes are utilized. Included are markers close to the allele of interest (flanking markers) that are utilized to minimize the carryover donor segments located near the target locus. This allows more complete recovery of the recurrent parent genotype, as well as the elimination of any potential linkage drag.

In cotton, MABC is widely utilized in transferring transgenic traits to elite breeding lines. It is increasingly used to introduce “native” traits that are rare in the elite germplasm breeding pools of a program. Often programs have several traits to transfer using MABC into elite germplasm. The plant numbers needed to genotype and the complexity of the breeding schemes increase dramatically when more than three loci are transferred from a donor parent.

Genomic selection (GS). Genomic selection is being evaluated and initiated in some applied cotton breeding programs (Gapare et al. 2018). A review of GS in plant breeding is presented in Trends in Plant Science (Crossa et al. 2017). The GS uses a set of genome-wide markers to predict the breeding value (BV) of individuals. Genomic selection is enabled by establishing a training population where individuals are both genotyped and phenotyped. The association of performance data and marker data is used to “train” the model used in BV prediction (GP). Individuals from breeding populations are genotyped, and a genomic estimated breeding value (GEBV) is established for each, for use in selection. The accuracy of the GS model is assessed by correlating actual phenotypic values with GEBVs in additional populations.

Genomic selection can reduce the breeding cycle time in two primary ways. First, an initial generation of field phenotyping can be eliminated by reliance on selection solely based on GEBV. Additionally, individuals with high breeding values can be recombined earlier, before multiyear performance testing establishes their true value.

GS is particularly useful for complex traits, such as lint yield and some fiber traits that have many small genetic effects. However, at the same time, MAS can be incorporated for simply inherited traits, such as disease resistance, where marker-trait associations have been previously established. Several schemes can be implemented using combinations of phenotypic selection, MAS, and pedigree information. The cost and time factors in the genotyping are key considerations in the planning of the breeding schemes.

A problem with initiating a GS program is the high start-up costs related to the needed technology, as well as costs associated with development and maintenance of a large training population. Historical phenotype data could be used to initiate GS, reducing the time and cost of maintaining an initial training population (Gapare et al. 2018). This would allow realization of the benefit GS, prior to incorporating contemporary data and recalibrating the model. Breeding goals also change over time due to changing environmental factors, changes in production systems, and changes in biotic and abiotic stresses. This requires the ongoing introduction of new germplasm into the base populations. These changes will necessitate a continual retraining of the model to maintain validity of the GP.

17.6 Cotton Breeding in 2030

Cotton breeding program structures in the future will depend primarily on the resources available. Resources from governmental and nongovernmental (NGO) institutions are now and will continue to be limited. Several NGOs strongly support breeding in major food crops with good reason. In cotton, strong support will come primarily from private industries that will potentially economically benefit directly from the products developed by their associated breeding programs. This direct benefit will come in the form of direct seed sales, sales of associated products (agrochemicals), and/or market share advantages. Direct economic benefit could also come for the end user of fiber and seed.

Ideally, an active commercial breeding program will utilize a combination of breeding schemes utilizing the new tools mentioned above. Because many of these tools are well developed in other crops, it would be a matter of transferring to and further adapting this technology to cotton.

Genomic selection will become the major component of commercial breeding programs. It will be further complemented by the intensive use of off-season nurseries and greenhouses and thus will shorten breeding cycles; both together will enhance the breeding efficiency. GS will be coupled with MAS for common but essential QTLs, which will enhance the efficiencies of the marker technologies.

Because of market demands, transgenic traits will continue an important part of most breeding programs. However, these traits will change or be added to over time. Thus, it will be necessary to uncouple transgenic breeding from breeding for yield and other agronomic traits. Thus, transgenic and other rare “native traits will continue to be added to MABC breeding schemes.

Performance evaluation across years and locations will continue to be an essential part of varietal development program. New tools in the growing, harvesting, processing, data acquisition, and analysis will increase the efficiencies of evaluation leading to final varietal selection. Several breeding programs will not have all the resources needed to implement all these technologies. However, certain technologies can be integrated partially in a breeding program with minimal costs. Examples of breeding schemes utilizing GS in limited programs are well presented in wheat (Bassi et al. 2016). Outsourcing of genotyping is now readily available and is continuing with reductions in cost per data point. Publicly available cotton marker data is also readily available (Yu et al. 2014).

17.7 Cotton Breeding Beyond 2030

Two particular technologies are described that are not yet developed in cotton. However, they have potential in dramatically advancing cotton breeding far into the future.

Doubled haploids (DH). Use of doubled haploids has proved an important tool for breeding few crops (Dwivedia et al. 2015). Haploids are produced and doubled, making the genotype fully homozygous. This takes place in two generations than that of the conventional breeding scheme that may require several years to achieve the acceptable level of homozygosity. Use of doubled haploids in a GS or MABC breeding schemes could substantially reduce the breeding development time.

Semigamy was discovered in *Gossypium* several decades ago (Turcotte and Feaster 1963). The semigametic strain of *G. barbadense* when used as a female parent in crossing produced 1% androgenetic haploids in F_1. Further development in the frequency of haploid production and in chromosome doubling could make doubled haploids a useful tool in cotton breeding.

Apomixis-asexual reproduction of F_1 hybrids. Hybrid cotton had been a commercial reality in India for several decades. Heterosis for fiber yield has been extensively demonstrated. However, hybrid seed production is costly as it is accomplished by hand emasculation and hand pollination of the female parent. This type of hybrid seed production is cost prohibitive in most countries. Any method whereby asexual reproduction of F_1 hybrids occurred could dramatically reduce seed production costs while exploiting the inherent heterosis in the crop. Although proposed, no successful demonstration of large-scale asexual reproduction has been demonstrated in cotton or any other crop plant. A recent study in rice establishes the feasibility of asexual reproduction in crops and could enable the maintenance of hybrids clonally through seed propagation (Khanday et al. 2019).

17.8 Physiological Challenges

The cotton plant has a huge yield potential that has been partially utilized. The physiological aspirations that have a direct bearing on the plant's performance, either in terms of higher yield or better quality, have yet to be materialized. The biggest loss in yield comes from fruit shedding whether it is a tiny invisible bud or a more visible fruiting form. The struggle to avoid this loss is ongoing with only a partial success. A multidimensional approach to this problem will continue and even get more attention.

There are two main theories about shedding of buds (invisible and visible) allude to an imbalance between hormones and the supply of carbohydrates. The imbalance between auxin and growth-retarding antiauxin hormones prevents the plant from producing flower buds. The carbohydrate supply to the existing fruiting load impedes formation of more fruiting forms. There are yet "plant training" commercial practices, wherein the plant is directed to enhance physiological processes by eliminating older/inefficient leaves; biotechnology can induce a characteristic or characteristics whereby the active life of the leaves is extended or the leaves are made to carry out photosynthesis more efficiently. There could be more physiological ways to handle or minimize lost fruiting points on the plant. Other innovative approaches, in particular biotechnological, will become more practical to save physiological losses in terms of empty nodes on the plant.

Cotton is a C3 plant and photorespires about 30% of the photosynthetic rate. During the process of photosynthesis, carbohydrates are formed from water and CO_2 absorbed from the air. The C4 plants have a potential to utilize all carbohydrates formed during photosynthesis and thus have a higher growth rate. The cotton plant is unable to utilize all the carbohydrates and tend either to burn or release into the atmosphere a good percentage of the carbohydrates in different forms. This is what makes cotton to grow slower and produce yield lower than its potential. Efforts have been made in the past to reduce photorespiration through artificial means to increase yield. Just prior to the introduction of transgenic cotton, CO_2 enrichment and methanol application were tried. Methanol application increased water use efficiency, increased leaf surface area and leaf thickness, increased fruiting points, and improved growth rate (ICAC 1994). However, artificially changing the microclimate of the plant does not seem to be a feasible solution for various reasons. The need is still there to lower photorespiration rate, and researchers beyond 2030 will still be struggling to deal with the loss of carbohydrates during photosynthesis.

17.9 Input Use

Almost 3% of the world cotton area does not get any fertilizer application. Two reasons for this are (1) fertilizer applications have no impact on yield and (2) inability to buy inputs. Organic fertilization is used on a limited scale in few countries. Wherever fertilizer is used, nitrogen application is a must over phosphorus and potassium because of the immobility of phosphorus and lack of potassium impact on yield under suboptimal yield levels. Soil depletion under such circumstances will ultimately require farmers to use fertilizer under all circumstances in the next 15–20 years. Nitrogen will continue to be required at current levels, while P and K applications will depend on cropping systems and soil types. Overuse of nitrogen, resulting in excessive vegetative growth, is not yet a common problem, but is expected to increase with the overuse of nitrogen in an effort to further increase yields. Breeders will have to focus on earlier entry by the plant into the reproductive phase in order to further increase yields. More efficient use of nitrogen by the cotton plant will continue to be targeted.

17.10 Irrigation

Scarcity and/or inaccessibility of water preclude complete irrigation of cotton. Almost 40% of the world cotton area is produced under rainfed conditions, in spite of the fact that yields under rainfed conditions are only 40–45% of the comparable irrigated fields. This is why 40% of rainfed area accounts for less than 30% of world production. The lower yield potential and higher yield variability generally dictates reduced costly inputs for rainfed cotton. Water will continue to be limited and will have to be shared with competing crops, in particular with food crops. Conserving the existing available water and using it more efficiently by minimizing losses will receive increasing levels of attention in the future. The current trend to shift from flood irrigation to row/furrow irrigation will continue. The best option will be to supply only as much water as needed or is taken up by the plant. Where feasible, subsurface or above-surface drip irrigation will likely be used to supply only as much water as needed by the plant. However, this will be limited by the large capital investments required to install a system. Biotechnological approaches in breeding offer hope for the development of “drought-tolerant” cottons offering superior performance under rainfed conditions.

17.11 Cotton Pest Management

Insect pests, nematodes, weeds, and diseases cause serious economic losses and deteriorate fiber quality. Since the early 1990s, new pesticide chemistries and biotech cotton have dramatically impacted plant protection in cotton, which in turn contributed directly to increases in yield and production of cotton. Newer strategies to increase seed cotton production will mandate responsible use of biotech approaches through clustered regularly interspaced short palindromic repeats (CRISPR/cas9), ribonucleic acid interference (RNAi), and gene pyramiding. Mechanization, robotics, artificial intelligence, nanotechnology, nano-formulations of agrochemicals, and information technology mainly through the use of mobile applications (apps) will significantly impact plant protection in cotton beyond 2030. These technologies may go hand in hand with the conventional and traditional methods of plant protection that are currently being adopted, not necessarily replacing them.

17.11.1 Protection Technologies of Today

Promising, effective, and "greener" technologies have been made available to cotton growers in many cotton-growing countries in the last 30 years. Biotech cotton has replaced conventional varieties on over 80% of the world cotton area (Kranthi 2018). Novel insecticides, mainly seed treatment formulations of neonicotinoids, have significantly contributed to the control of sap-sucking pests, thereby enabling the bollworm-resistant biotech cotton varieties to realize their genetic potential to a greater extent. However, these technologies have not only been effective but also expensive, thus leading to increased cost of production.

17.11.2 Biotech Cotton

Genetic engineering in cotton leads to the development of biotech cotton varieties, through gene transfer or gene editing methods (RNA interference and CRISPR/cas9 technologies). To date, transgenics generated through gene transfer have played a major role in cotton production where farmers relied heavily on seed industry for obtaining genetically modified (GM) or biotech cottonseeds. A total of 510 genetic-transformation events for improving 40 traits across 30 crops have been reported; of these 7 GM traits have been most popularly commercialized across 44 countries. Of these, two traits have been exploited in cotton, for insect resistance (IR) against lepidopteran and hemipteran pests and herbicide tolerance (HT) against 2,4D, dicamba, glyphosate, glufosinate, isoxaflutole, oxynil, and sulfonylurea herbicides (http://www.isaaa.org/gmapprovaldatabase/eventslist/default.asp). The IR, HT, and IR + HT cottons have been generally associated with target pest suppression (Wu et al. 2008; Carpenter 2010; Lu et al. 2012; Wang and Fok 2018). Though biotech cotton assists only in pest management, it is also perceived as a yield enhancement technology (Thirtle et al. 2003; Qaim and Matuschke 2005; Cattaneo et al. 2006; Traxler et al. 2013). However, these generalizations are debatable in some countries.

Development of resistance in target insects to biotech cotton was anticipated due to widespread and prolonged cultivation, particularly under poor stewardship.

Practical resistance was reported in 16 cases, while no decrease in susceptibility was noticed in 17 cases when data from 16 countries, to 5 toxins expressed in Bt crops, for populations of 9 species of lepidopteran pests was analyzed (Tabashnik and Carrière 2017). The pink bollworm resistance to Cry1Ac (Dhurua and Gujar 2011) and to *Cry1Ac* + *Cry2Ab* (Naik et al. 2018) in India adds to the list of insect pests resistant to Bt cotton. The pink bollworm is the second insect pest to have developed resistance to Bt cotton, the first being the cotton bollworm, *Helicoverpa zea* (Tabashnik et al. 2013).

Cotton diseases have also been pursued with the help of genetic engineering; however, till-to-date disease-resistant cotton has not been commercialized; however, success in lab-scale experiments was claimed. A few examples of disease-resistant biotech cotton are as follows: D4E1, a synthetic peptide expressed in cotton, imparted tolerance to black root rot caused by the fungal pathogen, *Thielaviopsis basicola* (Rajasekaran et al. 2005); an *endochitinase* gene expressed from *Trichoderma virens* enhanced fungal resistance in biotech cotton (Emani et al. 2003); a plant defensin gene *NaD1* expressed in cotton conferred field resistance to *Fusarium oxysporum* and *Verticillium dahliae* (Gaspar et al. 2014); a non-expresser of pathogenic related gene 1 (*npr1*) from *Arabidopsis*, overexpressed in cotton, imparted resistance to *V. dahliae*, *F. oxysporum*, *Rhizoctonia solani*, *Alternaria alternata*, and reniform nematode (Parkhi et al. 2010). Leaf curl-tolerant biotech cotton with antisense against the pre-coat protein *av2* gene has also been reported (Sohrab et al. 2014).

17.11.3 Conventional Technologies

Application of pesticides has emerged as the integral part of the integrated pest management strategies across the world. Window-based, temporally selective pesticide-use strategies were developed to conserve native natural enemies and have been adopted in some cotton-growing countries (Kranthi et al. 2002; Wilson et al. 2004; Dhawan et al. 2009; Silvie et al. 2013). Novel and highly selective pesticide chemistries with low ecotoxicological profiles are recommended in specified temporal windows when the pest exceeds the economic threshold level (ETL). Such pesticides are often expensive and need to be used prudently to ensure economic and environmental sustainability. Integrated pest management strategies across the world incorporate the use of all pest control measures that favor eco-friendly and economically viable crop protection. Apart from the use of synthetic pesticides, biopesticides such as *Bacillus thuringiensis* (*Bt*), nuclear polyhedrosis viruses (NPV), entomopathogenic fungi, neem-based insecticides, and exploitation of natural enemies such as parasites and predators have constituted the main conventional methods of cotton pest management. Adoption of cultural methods such as closed season for the pink bollworm (Watson et al. 1978), use of food sprays to attract native natural enemies (Mensah 2002), use of pheromone lures and traps for monitoring, mass capture, and mating confusants (Lance et al. 2016; Carriere et al. 2017) have also been popular in cotton IPM programs. Eradication of the pink bollworm in the USA is a landmark achievement, where pheromones and lab-reared sterile moths were used on a massive in undative scale in demarcated areas (Simmons et al. 2011; Morrison et al. 2012; Tabashnik et al. 2012).

While no till, conservation tillage, extensive herbicide use, and mechanized weeding have been popular for weed control for many years in developed countries; hand weeding is still adopted in small-scale production systems. Integrated pest management strategies have limitations. Pest-resistant varieties are not very common; novel eco-friendly insecticides are expensive; quality control of biopesticides is a challenge; and availability of biopesticides and biocontrol organisms for augmentative or innundative releases is limited. Moreover, cotton growers, in countries such as China, India, Pakistan, and many African countries, have small-scale holdings where a community approach that would be more effective in pest management is not very feasible and is rarely adopted. Also farmers need guidance for a proactive implementation of IPM strategies, particularly to prevent pest outbreaks and for effective and sustainable pest control. Advances in improving the efficacy of conventional pest management technologies through the use of novel pesticide application technologies, nano-formulations, electrostatic sprays, solar-powered sprayers, food sprays, novel pheromone formulations, and conservation biological control techniques have been made, but more work is needed.

17.11.4 Technologies for the 2030s

The future of cotton pest management would depend on how well production practices are integrated with varietal improvement, genetic engineering, and IPM strategies. Creation of biotech cotton varieties using novel genes, RNA interference, and CRISPR/cas9 technologies fall in the domain of advances in genetic engineering. Transgenics involve introduction of genes across genera. RNAi involves modulating gene expression. CRISPR/cas9 involves gene editing. Biotech cottons using *cry* toxin genes and herbicide tolerance genes are well known throughout the world, as cotton was the first biotech crop approved for commercial cultivation in 1995 in the USA. While *Bt* cotton has been very effective in controlling the target insects, stewardship of the transgenic technology to suit local conditions is of paramount importance to utilize the technology to its fullest potential before resistance sets in. Failure to do so has caused yield stagnation and resistance development as in India or a ban as in Burkina Faso, due to various reasons.

17.11.5 CRISPR/cas9

CRISPR/cas9 is an in vivo genome editing technology in a biologist's tool kit that modifies DNA sequences in a genome to turn on or off specific genes in cells and organisms with relative ease and can also help raise transgene-free genetically modified crops (Soda et al. 2018). Insects from five orders (Diptera, Orthoptera, Coleoptera, Hymenoptera, and Lepidoptera) have been subjected to CRISPR/cas9 study, and *Drosophila* spp. have been extensively studied (Sun et al. 2017). CRISPR/cas9 deployed for targeted mutagenesis in cotton (Chen et al. 2017) was used to design unique and broad-spectrum control of cotton leaf curl disease-associated begomovirus complex and its associated satellite molecules (Ali et al. 2016; Iqbal et al. 2016; Khatodia et al. 2017). Using CRISPR/cas9 as an efficient genome editing tool, HaCad was confirmed as a functional receptor of *Cry1Ac* in *Helicoverpa armigera* (Wang et al. 2016) and also to demonstrate that HaABCA2 played a key role in mediating toxicity of both *Cry2Aa* and *Cry2Ab* in *H. armigera* but remained unchanged with *Cry1Ac* (Wang et al. 2017). CRISPR/cas9 was used to characterize the pheromone-binding protein (PBP1) gene in *H. armigera* to provide the first in vivo evidence that HaPBP1 played an important role in perception of female sex pheromone (Ye et al. 2017). The *or16* gene when knocked out and delivered through plasmid mRNA provided novel strategies to destroy insect pest mating (Chang et al. 2017). While almost all of the plant genome editing is yet to reach a stage of commercialization, in light of the research findings, it is expected that the 2030s would see successful CRISPR/cas9-generated biotech cotton in fields. Most of these strategies could also be meant to target pests resistant to biotech cotton such as Cry toxin-resistant insect pests and herbicide-tolerant weeds.

The rising world population is bound to increase pressure on available arable land, thereby accentuating the need for new technologies that can help to produce more food and fibers from the limited land with less agrochemical inputs. Genetic engineering has the potential to increase yields and reduce input usage by introducing novel traits and modifying existing traits for genetic improvement of crops. Needless to emphasize, the deployment of biotech crops including cotton would be subjected to the condition of proven biosafety of the transgenes and CRISPR/cas9 technologies. An institutional setup for monitoring the release, adoption, and effects of new biotech technologies in crops must be envisioned before its adoption. Biosafety guidelines for biotech crops are available in most countries. Biotech cotton has been cultivated for almost 15–25 years in many developed and developing countries. It would be useful if the experiences were shared and common biosafety-regulatory guidelines developed so as to enable developing and least developed countries to devise their own biosafety-regulatory guidelines based on the common framework by incorporating the local requirements.

17.11.6 RNA Interference (RNAi)

RNAi can generate new crop quality traits or provide protection against insects, nematodes, and pathogens without introducing new proteins into food and feed products (Auer and Frederick 2009). RNAi is an evolutionarily conserved mechanism that, in primitive organisms, protects the genome from viruses and regulates gene expression during development (Dykxhoorn and Lieberman 2005) through gene silencing. The antisense (guide strand) of short dsRNA is incorporated into an RNA-induced silencing complex that can either suppress protein expression or direct the degradation of mRNAs containing homologous sequences. Elucidation of RNAi won Andrew Fire and Craig Mello a Nobel Prize in 2006. RNAi-based control of insect pests of cotton has been targeted by gene silencing of *Cyp6AE14*, *GST*, *trypsin*, *chymotrypsin*, and *JhAMT* through oral feeding or through the development of biotech cotton (Asokan et al. 2011). Cyp6Ae14 is an oxygenation enzyme expressed in the midgut of *Helicoverpa armigera* that enables larvae to tolerate gossypol. When larvae were fed dsRNA specific to Cyp6AE14 through transgenic plants, the level of cyp6ae14 transcripts in the gut decreased, and larval growth was retarded due to gossypol toxicity (Mao et al. 2011a, b). Gong and co-workers (2014) demonstrated that insect-resistant transgenic plants could be obtained through plant RNAi-mediated silencing of insect *carboxylesterase* genes. Expression of dsRNA from ECR (ecdysone receptor complex) of the cotton bollworm in tobacco improved its pest resistance (Zhu et al. 2012). RNAi was explored for the control of whitefly, *Bemisia tabaci*, for which dsRNA and siRNA were synthesized for five different genes and evaluated using a simplified oral route of feeding that caused 29–97% mortality after 6 days of feeding. Phloem-specific expression of dsRNA of PPLq and VATPase in transgenic plants for protection against whiteflies has been generated and is currently being evaluated in trials (Upadhyay et al. 2011). The dsRNA microinjection of chitin synthesis in *Anthonomus grandis* female moths resulted in normal oviposition of unviable eggs and malformed live larvae that were unable to develop on artificial diet (Firmino et al. 2013). RNAi was used against a molt regulating transcription factor gene HaHR3 of *H. armigera* through transgenic plants to disrupt its development (Xiong et al. 2013). The dsRNA of the gene governing the expression of 3-hydroxy-3-methyl-glutaryl-CoA reductase (*hmgr* gene) that catalyzes an enzymatic reaction in the JH (juvenile hormone) biosynthesis pathway in bollworms was expressed in cotton. When *H. armigera* larvae fed on these transgenics, transcription levels of HMGR were reduced unto 81%, and expression of vitellogenin was reduced by 76% reduction that resulted in impaired larval growth and development. Odorant-binding proteins (AgOBP2) in *A. gossypii* play a crucial role in host location, selection, and oviposition. Silencing it through RNA interference would play a crucial role in *A. gossypii* control (Rebijith et al. 2016). However, RNAi-mediated knockdown of expression of polygalcturonase (*pg1*) mRNA in adult salivary glands of *Lygus lineolaris* was not very successful in impacting feeding (Walker and Allen 2010).

New approaches to gene silencing involve generation of biotech crops, which is expensive, oral feeding of the dsRNA that is impractical in fields or through the virus-induced gene silencing (VIGS). VIGS is a method where a recombinant virus is used as a silencing vector to target host plant genes by triggering the antiviral RNA silencing pathway with little induction of viral disease symptoms in the host plant. Its silencing effect is transient since genetic material does not integrate in the plant genome.

17.11.7 Gene Pyramiding

Trait pyramiding and gene pyramiding are instrumental in extending the trait value, to enhance efficacy and to extend the durability of the trait. Gene pyramiding for cotton crop protection is adopted to ensure redundant killing of the target insect pests that are not controlled by one toxin which will be killed by the other. Pyramiding toxins is particularly effective when resistance is recessive. The chances of the target pest being resistant to both toxins are rare especially if populations of the pest have not been exposed to any of the toxins (Brévault et al. 2013). Factors such as a decline in toxin expression as the plant ages (Greenplate 1999; Kranthi et al. 2005; Knight et al. 2013) and asymmetric cross resistance (Wei et al. 2015) negatively impact the effects of gene pyramiding. Introducing *Bt* genes as pyramids is fairly common and has been proven effective thus far. Cowpea trypsin inhibitor genes expressed along with *Cry1Ac* in biotech cotton enhanced resistance to *Helicoverpa armigera* though it did not lead to increased mortality of the pest in the field (Cui et al. 2011). Four methods of gene pyramiding are hybrid stacking (where each of the parent involved in the cross carries transgenes of interest, e.g., Roundup Ready Flex Bollgard II), co-transformation (different constructs carrying desired transgenes are introduced simultaneously into the plant cell), multigene cassette transformation (two or more transgenes are present within the same construct), and retransformation (where a transgene is introduced into a transgenic plant, e.g., generation of Bollgard II). Gene pyramiding for pest control is the immediate future for transgenics where multiple genes for insect pest resistance would be expressed along with multiple genes for herbicide tolerance and/or disease resistance. In fact 95% of transgenic cotton being cultivated in India carries two genes for pest resistance, and more than 80% of the cotton in the USA carries stacked genes for lepidopteran and herbicide tolerance. For example, the new biotech cotton called Bollgard® 3 XtendFlex® technology has two traits and six trait-specific functional genes with three genes (*cry1Ac* + *cry2Ab* + *vip3Aa*) for insect resistance and three genes, *epsps, bar*, and *demethylase*, for tolerance to the herbicides glyphosate, glufosinate, and dicamba, respectively. Recently, biotech cotton, carrying a new event, was developed to express a modified Bt *Cry51Aa2* protein conferring tolerance to hemipteran insects. Genes for hemipteran, lepidopteran pest tolerance and herbicide tolerance have together been stacked in cotton that is under evaluation.

Stewardship of the stacked gene technology is of utmost importance. Caution must be exercised to ensure that populations of the pest have not been exposed individually to genes in the stack prior to the introduction of stacked product. Introduction of the two-gene (*cry1A*c + *cry2Ab*) biotech cotton after 3 years of cultivation of *cry1Ac*-based biotech cotton led to a sequential exposure of the worms to the toxins, as a result of which both the genes became ineffective to the pink bollworm within 10 years of cotton cultivation. However, though Bt cotton is still effective on the polyphagous pest *H. armigera*, modeling results show that the pest may soon develop resistance to the two genes sooner because of the sequential exposure. Also, transgenes deployed in biotech cotton must be homozygous. Currently almost all the biotech F_1 hybrid plants produce bolls that have a small proportion of non-*Bt* seeds in the bolls, which allow the survival of a few larvae, thereby permitting compromising bollworm protection.

Gene pyramiding using the RNAi approach along with conventional transgene expression could be the next-generation approach to develop durable biotech cotton. Pyramiding of RNAi with *Bt* cotton was done by silencing *juvenile hormone methyltransferase* and the JH-binding protein that are crucial for JH (juvenile hormone) synthesis and transport of JH to the organs, respectively, for effective control of *H. armigera* (Yu et al. 2016). Results from modeling experiments demonstrate that combining RNAi protection with one or more Bt toxins can delay the evolution of resistance but the gain in durability depends on the percentage of the refuge (Ni et al. 2017).

17.11.8 Introduction of New Pesticides

Significant changes in cotton crop protection have occurred through introduction of new chemistries. Novel insecticides with new modes of action and new formulations were introduced and registered for use on cotton in the past 20 years. Insecticides based on their mode of action have been classified into 32 groups of which insecticides belonging to 14 groups are permitted for use on cotton by the Insecticide Resistance Action Committee. Many of the new insecticides are highly specific to the targeted site in the insect and are necessary to be used in milli- and micro-quantities of the active ingredient per hectare. New formulations have also been introduced, thus facilitating the handling of lower volumes of pesticides. Typically, large containers of formulated products that once occupied market shelves are currently being replaced with less than 100 mL containers for one-time use in small-scale cotton production systems, which not only prevents insecticide misuse but also makes it more cost-effective for the end user. Novel formulations also include nano-formulations that facilitate increased solubility of the active ingredient, thereby enhancing its bioavailability ensuring targeted delivery, controlled release, and protection against degradation (Hazra 2017).

Old chemistries are being replaced with new molecules, especially of those active ingredients whose patents are set to expire and would be phased out beginning 2020. Also insecticides whose negative impact on human health or environment was hitherto unknown may also be replaced. Glyphosate as a possible carcinogen and its fate as the most popular weedicide are being debated (Andreotti et al. 2018; Berezow 2018). Pesticides that are being phased out are usually more inexpensive than the new active ingredients that are being registered. The new molecules meet stringent regulatory requirement, are effective, are patent protected, and are therefore expensive.

Novel technologies to enhance the efficacy of biocontrol agents in the field may also become popular. Evidence of food sprays (to attract native natural enemies) and behavior-modifying compounds (e.g., magnet) that provide long-range attraction of

Helicoverpa moths through plant volatiles have been demonstrated to be effective in field trials. A new product called Sero X was developed based on short-range, non-volatile compounds and was found to be effective against *Helicoverpa*, whiteflies, mirids, and other homopterans. The product is in the advanced stage of commercialization (Mensah et al. 2013). Noctovis is a tank-mixed formulation designed to target both sexes of multiple species of noctuid moths. It is a blend of plant-based volatile kairomones and has been demonstrated to reduce insecticide inputs by more than 98% in soybean in Brazil (Borges et al. 2015). Noctovis may be recommended for cotton in the days to come. Specialized pheromone and lure application technology (SPLAT) comprises of food-safe, organic, and inert ingredients, has a thixotropic property, and facilitates fast and simple application, either manually or mechanically, thus producing a series of environmentally hardy, rainfast point sources affixed firmly to substrates. It can carry active ingredients responsible for mating disruption; attract and kill, push and pull strategies; and more. Such advancements may have a positive impact on cotton crop protection in the next decade.

17.11.9 Mechanization and Robotics

Advances in pesticide application technology have been made with electrostatic sprays, nano-formulations, battery-operated solar sprays, and sensor-based drone sprays. Digital technology is currently being used to perform agricultural tasks and facilitating data-driven decision-making. Robotics in agriculture is in the development stage. Use of sensors is becoming popular in some countries particularly for detecting nutrient anomalies, insect pest, and disease damage. Drones are used for survey and scouting in cotton fields through automated systems using a range of sensors to assess crop health matrixed with global positioning system (GPS). This would ensure timeliness of operation and would also be cost-effective especially when trained manpower is a constraint. The use of drones could help to measure crop fields, determine the best strategy for more profitable planting, gather data which then could be used to determine the fertilizers or inputs required for certain stages of the crop, collect aerial images, detect diseases and pests, forecast yields, and provide recommendations for water management, among other uses. Xiongkui et al. (2017) reported experiments with drones also in cotton fields of Southeast Asia. Agriculture is moving into an area of digital farming (Korres et al. 2019), and this is applicable to cotton as well. Information on cotton crop protection that was being disseminated through conventional methods such as posters and farmer fairs is now also being disseminated in real time, using the mobile technology.

Personal digital assistants (PDA) and handheld GPS have become important in cotton-growing countries, especially where farmers use complementary remote sensing, plant mapping and grid information of soil nutrient status, and infield decision support system such as COMAN impacted adoption of site-specific management (Walton et al. 2010).

Digitized weed maps for weed monitoring through artificial intelligence (AI) and to carry out real-time weed detection are mounted on field spraying machines resulting in weed-activated sprays. A real-time precision robotic weed control system was developed and tested in commercial cotton fields where it was capable of distinguishing grasslike weeds from cotton plants and applying a chemical spray only to targeted weeds while traveling at a continuous speed of 0.45 m/s. The robot consisted of a real-time machine vision system, a controlled illumination chamber, and a precision chemical applicator. In commercial cotton fields, the system correctly sprayed 89% of the weeds while correctly identifying and not spraying 79% of the cotton plants while traveling at 0.45 m/s (Lamm et al. 2002). Such technologies have not yet been adopted widely, and it remains to be seen if digital technology can make a difference in cotton crop protection.

17.11.10 Harmonization of Integrated Pest Management and Regulatory Guidelines for Biotech Cotton

Every cotton-growing country has developed and implemented sound integrated pest management (IPM) in cotton, particularly after 1990 (Kogan 1998). In fact, IPM was the key to pest management till the introduction of biotech cotton. Integrated pest management now needs to be harmonized taking into consideration the IRAC (Insecticide Resistance Action Committee), WHO (World Health Organization), and IOBC (International Organization for Biological Control) ratings of insecticides and their safety to human beings and natural enemies.

Some countries devised excellent stewardship for biotech cotton that included IPM strategies. Stewardship was compromised in other countries where poor attention was paid to pest management leading to problems with sustainability of biotech cotton. Unviable refuge recommendation and its poor adoption is often an example of poor stewardship. Monopolization of biotech cottonseed trade led to unfair trade practices such as the use of fake unauthorized seed with poor plant protection. Patent laws on biotech cotton were unclear that led to the exploitation of small-scale producers in developing countries.

Guidelines governing the strategies of integrated pest management need to be revised in light of large-scale adoption of biotech cotton that has led to a change in the pest scenario. New diseases and pests and development of pest resistance to biotech crops are the two factors that are most likely to emerge as serious concerns in the next decade and beyond. The threat of the fall armyworm looms large on crops including cotton. Emphasis must be laid on the use of stochastic models to determine the timeline of likely probability of resistance in insect pests and weeds based on the existing data, in each country. Patent laws must be upheld across countries, and clean, transparent, and harmonized systems must be established to prevent economic, social, and ecological exploitation that leads to the failure of technologies in the field.

17.12 Picking of Cotton

According to the study conducted by the International Cotton Advisory Committee (ICAC) and published in October (2017), 62% of cotton produced was picked by hand and 38% with machines. The ICAC data on cost of production have shown that machine picking is less expensive compared to manual picking, though the data is limited to picking operations and does not analyze the subsequent effects on quality and costs involved in handling cotton loaded with trash. As a share of the total cost of production, picking cost, at 13%, ranks just behind fertilizer costs, which accounts for 14% (ICAC 2016). Scarcity and cost of labor are pushing more countries toward machine picking. However, cotton harvesting machines are much easier to use under large-scale commercial production. Factors limiting the use of mechanical harvesters include small field size, unsuitable morphology of varieties, row spacing, lack of defoliation, and lack of requisite cleaning equipment at gins. Machine picking has the biggest disadvantage of huge picking losses, which is a direct loss in yield.

Countries that have yet not adopted machine picking need smaller machines that can accommodate differing row spacing, can be operated in a manner similar to small spray machines, and require few if any additional costs in allied operations. Ideally, the harvesters would collect a minimal amount of vegetative and trash contamination. Perhaps advancing robotics will enable small harvesters to pick boll-by-boll without grabbing dry or green leaves.

Three characteristics that create demand for small-scale picking machines are advancing industrialization, improvements in social structures, and urbanization. Developing countries that are increasingly exhibiting these characteristics will increasingly pursue mechanical harvesters. But the size will not compare to the harvesters used in the advanced cotton-producing countries. The objective will be to increase harvesting capabilities from 25 to 30 kg per person per day with hand picking to a few hundreds of kilograms per person per day. The need for such small-scale mechanical cotton harvesters is generally accepted, and development work is ongoing. It is likely that commercialization of such harvesters will be evident by 2030.

17.13 Engineering of Ginning

Cotton is produced for fiber, though seed itself has a tremendous value and still underutilized and much less explored. Lint fiber is only about 35–40% of the total seed cotton production. The only two processes of separating lint from seed are roller ginning and saw ginning, and both were developed when hand picking was the only procedure of picking cotton. Saw ginning which was considered to be an improvement over roller ginning for higher efficiency was the need of time. The saw gin developed by Eli Whitney and patented in 1794 is truly the last development in the process of removing fiber from the seed coat. The inabilities to gin huge quantities of seed cotton had become a constraint for expanding production. Saw ginning efficiency revolutionized cotton production in the world. The two processes of ginning, saw ginning and roller ginning, are a harsh way of removing fibers from the seed. The roller ginning that has gone through many changes, as has been saw ginning, removes fibers by pulling fibers against the stationary seeds. The engineering of saw ginning is a mix of pulling and beating actions. There is no doubt that the roller ginning has a gentler process of pulling fibers over saw ginning but it has some limitations. Saw ginning is not recommended for long and extra-long fiber because fiber breakage degrades the length distribution.

Without going into the impacts of the two methods of ginning, the focus here continues on actual method of removing fibers from the seed coat. Almost 2/3 of cotton produced in the world is ginned on saw gins and 1/3 on roller gins. It is so because no other better options are available. Efforts have been continuously made to find better mechanical means of removing fibers from the seed without sacrificing efficiency and preservation of quality but without any success. The target is to make the pulling and beating actions as gentler as possible without any physical damage to the state of fiber achieved in production. In this regard the two processes that provided hope for a better ginning were Cage ginning and Templeton ginning. The two processes airstream pressure (Cage ginning) and improved double roller mechanism with leather and knife (Templeton ginning) were close to be commercialized, but it never happened due to various reasons. Currently, there are no new technologies, not even in the offing, that have potential to replace neither roller ginning nor saw ginning.

Cotton ginning beyond 2030 will in no way be different from today. What has changed in ginning is the type of gin stands used and the amount and type of handing and cleaning equipment used in a particular ginning system. How softer and longer fibers you may produce, you have to treat them at the mercy of saws and rollers. The monitoring and control of ginning processes have changed and will continue to be improved without any change in the harsher process of removing fibers from seeds. The future thrust will continue to be the focus of exploring new methods of separating lint and seed with these targets:

- Develop a ginning method that reduces fiber damage and maintains fiber length properties.
- Avoid fiber breakage and improve length uniformity data.
- Improve ginning efficiency and lower cost of ginning.

17.14 Spinners Needs, Quality Traits, and Cotton Classing

Cotton classing is a unique manifestation of time-honored systems for sorting and grading that are done on commodities to improve efficiency of a marketing system. All such systems are justified when the important properties—that determine the use value, or “quality,” of the commodity or product—are not easily and readily identified by the buyers. Methods for sorting and grading may be descriptive and/or quantitative. Cotton certainly qualifies as a candidate for a *sophisticated* classification system, because efficient marketing requires the critical properties of cotton fibers to be specified with a degree of *precision*. Such precision is especially challenging when using only *thousands* of fibers to represent *billions* of fibers with multiple properties having nontrivial distributions across the individual fibers. The *distributional characteristics* of the fibers make cotton classification unusually difficult.

Sophistication notwithstanding, it must be that cotton classing is a *commercial* task—not a *research* task. The procedures used and the results communicated by cotton classing should be predicated on research results to the extent possible. But both procedures used and results produced from cotton classing are substantially constrained by *economic* and *time* considerations. The value of information must be commensurate with the cost of information; a research project cannot be funded for each bale of cotton sold. Furthermore, the natural flow process of cotton marketing does not allow much time for intensive evaluation of properties.

The cotton fiber properties needed by yarn spinners are generally well known throughout the industry; however, substantial confusion still exists within the global industry about actual fiber properties versus the limitations of commercial measurements of these properties. Such confusion emerged with the very first commercial instrument measurement of cotton more than 50 years ago, the micronaire. Commercial interest in micronaire measurements was driven by a desire of spinners to get information on the *maturity* of the cotton fibers. But an education process still continues regarding the micronaire’s ambivalent measurement of the *combination* of genetic *fineness* versus *maturity* of the fibers. Fiber fineness (characterized by the linear density or the circumference of individual fibers) is determined genetically, while fiber maturity (characterized by the amount of cellulose deposition in individual fibers) is determined by the interaction between genetics and environmental factors.[1] The micronaire measurement indicates the *specific surface area* of a compressed bundle of cotton fibers. As such, it does not provide distinct estimates of either fineness or maturity, but a conflated estimate of the combination.

This distinction between the fundamental fiber properties and the measurement of these properties is important when trying to predict future progress in (1) achieving genetic improvements in cotton fiber quality and (2) commercially useful measurements of improved fiber quality. From the standpoint of fiber technology, the three iconic fiber properties that are the benchmarks for superior fiber quality are fiber *length*, *strength*, and *fineness*. Thus, these are the three defining properties for premium cotton fibers provided by the “extra-long staple,” or ELS, types of cotton. These include the Pima, Giza, and Sea Island types, which all belong to a tetraploid, *G. barbadense* species and are the longest, strongest, and finest cotton fibers available. Nevertheless, more detailed information is needed for efficient purchasing and handling by yarn spinners.

---

[1] This interaction is in the domain of phenomics, while fiber fineness is in the domain of genomics.

17.14.1 Current State of Commercial Measurement Technology

The current paradigm for providing commercially useful measurements is the HVI (High-Volume Instrument) system, which was developed starting in the late 1960s in the USA and became the basis for classification of US-produced cotton in the early 1990s. The HVI machine used by the Agricultural Marketing Service of the US Department of Agriculture[2] is comprised of a cluster of computer-controlled instruments that provide measurements for length (L), micronaire (Mic), strength (Str), length uniformity index (UI), leaf grade, color Rd, color +b, color grade, and trash percent area.[3] In addition, human classers provide identification of any extraneous matter among the fibers.

Strictly speaking, measurements for leaf grade, trash, and extraneous matter are not inherent cotton fiber properties; nevertheless, these are important quality issues for yarn spinners and weavers. Indeed, cotton fibers that are baled and shipped with little or no contamination are always in demand by the global spinning industry. The large-scale growing and machine-harvested cotton production sectors, as in the USA, Australia, and Brazil, have reputations for low contaminations, which give these countries a competitive advantage in global cotton sales.

The color measurements are used in various ways. The most basic use is to assess deterioration of the fibers from weather or other postharvest damage. An abnormal "grayness" of the fibers (based on the +b reading) indicates weather or water damage that has degraded fiber strength and partially removed the natural finishes of waxes and pectins on the fiber surfaces. These finishes are necessary for efficient processing through opening, cleaning carding, drawing, and spinning.

Another use of color measurements is for blending to achieve more efficient dyeing. Even "white" cottons exhibit different shades of white. Healthy cotton fibers may have differing "yellowness" readings (the Rd measurement) based on inherent properties. If these differ significantly, then blended fibers are supposed to bleach more heavily to bring the colors close enough together to achieve a consistent shade in dyeing. High levels of leaf and other vegetative contaminations may also result in staining, spotting, and off-color fibers (affecting both color measurements and the color grade).

The HVI measurements for L, Mic, Str, and UI relate to key fiber properties that are targeted—or should be targeted—by all cotton plant breeders. Improvement in the fiber properties that are related to such measurements as these will continue to preoccupy everyone focused on continuous improvements in cotton fibers as an industrial raw material in textile manufacturing. By implication, new or improved measurements related to these properties should be the future focus of measurement research to increase the use value of cotton fibers.

---

[2] AMS, USDA, uses Uster HVI systems, made by Uster Technologies, Inc. in Charlotte, North Carolina, USA. A comparable system is offered by Premier Evolvics in Coimbatore, India.

[3] See "Cotton Classification: Understanding the Data," www.ams.usda.gov/cotton/UnderstandtheData.

17.14.2 Limitations on Commercial Measurements of Fiber Properties

While there have been substantial improvements in sensory precision, greatly enhanced computational capacities, useful algorithmic enhancements, and time-saving automation of the HVI measurements, there have been few fundamental changes made in commercial HVI machines since the USDA began using these for cotton classification. All measurements except the UI are measures of central tendencies; i.e., these do not give information on the distribution of the fiber properties. The UI relates to the length distribution but is a very rudimentary indicator, being expressed as a simple ratio of the mean length of fibers in a sampled fiber bundle divided by the upper-half mean length of that fiber bundle, expressed as a percentage.[4]

The overriding reason for the lack of more sophisticated fiber measurements is revealed by the measuring system's name: *high-volume* instrument. Any additional measurement provided to the marketing system must not add more than a few seconds to the total time required to run the fiber sample through the HVI. There is an unavoidable inverse relationship between the sophistication of a measurement and the time required to obtain it, which inevitably increases the cost of measurement. Participants in the marketing system are notoriously reluctant to bear the added cost.

The spinning also requires some additional information about the extent of neps and short fiber content (SFC)[5] in cotton fiber before buying. This response reflects production managers' observed problems and conventional thinking regarding the yarns made in the spinning plants. Both manifestations of these quality problems are magnified by broken fibers, which always result to some degree from mechanical action on the fibers—whether at harvesting, ginning, or during the opening and cleaning processes in yarn spinning plants. Therefore, the *propensity* of fibers to break under mechanical stress is the underlying metric. To complicate matters, this propensity toward breakage is impacted by a complex of other fiber properties. For example, weaker fibers, whether due to genetic reasons or to fiber immaturity, are much more susceptible to breakage. This helps explain why yarn spinners are vitally interested in measurements of both fiber strength and micronaire.

The foregoing explanation illustrates the prevalence of autocorrelation among the critical fiber properties. The length distribution of cotton fibers received by yarn spinners reflects both (1) unnecessary mechanical breakage and (2) the impacts of any faults in other fiber properties. Thus, the genetic staple length and distribution, the maturity, the strength, the elongation, etc., all contribute to the length distribu-

---

[4] The upper-half mean length (UHML) measurement from the HVI is analogous to the traditional staple length of fibers when hand classing is used. Both of these measurements are intended to identify the "dominant long fibers" in the length distribution of the fiber sample.

[5] Neps are hopelessly entangled masses of fibers that protrude from the yarns and fabrics, degrading both appearance and touch. Short fiber content (SFC) is a traditional benchmark based on the share of the fibers that are one-half inch or shorter in length. The short lengths do not incorporate well into the yarns, degrading the strength and appearance. Problems caused by SFC include low yarn strength, unevenness, thick places, thin places, and neps.

tion confronted by yarn spinners. It is well known, however, that the more *uniform* is the length distribution of the cotton fibers received by spinners, the less problems they will have with neps and short fibers, the more efficient will be the spinning process, and the higher quality will be the yarns.

Pre-spinning, measurement-based indicators of the potential for making neps and short fibers are feasible, but the measurements are interdependent with the measurement techniques, which must control the stress put on the fibers prior to and during measurement. While useful measurements may be done, rapid measurement is not currently feasible. The most common commercial laboratory instrument for assessing neps and SFC is the AFIS (Advanced Fiber Information System) instrument made by Uster Technologies. This instrument separates the fibers from a technician-prepared sliver and takes electro-optical measurements of individual fibers. Sample preparation requires operator consistency to achieve sample consistency, and each sample requires several minutes for measurement. In addition to neps and SFC, measurements are produced for length, fineness, maturity, trash, and dust. More advanced spinning plants around the world have used an AFIS instrument on a limited basis to screen fibers either before these are subjected to spinning process or to monitor performance of the processing machinery over time. Use for monitoring in textile mills has decreased in recent years, however, as other in-line measurement technologies are increasingly used by spinners to monitor neps during the spinning process.

The spinning industry's fixation on SFC is explained by the fact that, until recent history, it was impossible to obtain more precision in measurement of the *distributions* of the cotton fiber lengths. Arduous hand extraction and arrangement of fibers from single seeds demonstrated long ago that cotton fibers exhibit a natural frequency distribution that mimics a bell curve, with a relatively small percentage of shorter fibers, a predominant percentage of medium-to-long fibers, and then trailing off to a smaller percentage of longer fibers. With commercial handling of the cotton, the tail of the distribution with short fibers typically is elevated; i.e., there is a larger percentage of very short fibers than there is of very long fibers. This result is due to the breakage of fibers from the mechanical stresses required in commercial handling. Thus, the observed length distribution of any cotton sample is determined by a combination of natural biological distribution and fiber breakage.

The observed length distribution of large quantities of cotton is also complicated by variations across the cotton boll positions on the plants. Given the indeterminate fruiting behavior of cotton, different bolls will be of different ages, which brings the likelihood of different maturity levels, different strength levels, different staple lengths, etc. All of these differences would be "captured" in the length distributions of these fibers.

Cotton spinners have always known about the importance of reducing short fibers for producing high-quality yarns. Combing machines were developed to remove most of the short fibers, with the machine settings targeting the one-half inch threshold of fiber lengths for removal. Commercial combing of cotton generally removes 15–25% of the fibers by weight. The waste fibers, called noils, are clean fibers that find other uses, but the value of these noils is significantly reduced. The combination of a costly mechanical combing process and the loss of valuable fibers makes combed cotton textiles expensive. But eliminating the short fibers elevates the quality of textiles made from yarns to a new level. Quality characteristics—dye uptake, color fastness, softness, shedding, and durability—are all notably improved.

17.14.3 The Fourth Fundamental Fiber Property: Length Uniformity

Looking to the future, the three iconic fiber properties of length, strength, and fineness may become four properties with the addition of length uniformity. Measuring length uniformity requires measuring the entire distribution of fiber lengths in a cotton sample. The ideal length distribution would be a uniform distribution; i.e., all fibers should have the same length. This is impossible, but some cotton varieties produce fibers that are genetically more uniform than others and are more resistant to breakage. Thus, weak fibers will break more often when mechanically stressed. Fibers that are immature will be weak. Therefore, weakness that is due either to genetics or to immaturity will be manifested in distorted length distributions. HVI measurements of both strength and micronaire are "bundle" or "central-tendency" measurements, but fiber breakage occurs from stresses applied to *individual* fibers and will be manifested in the length distribution.

The use of SFC as an important fiber property by yarn spinners is due to the historical infeasibility of commercial measurement of the length distribution of cotton fibers. The half-inch benchmark used for SFC is arbitrary; it represents a heretofore practical compromise between fiber wastage and yarn quality. But the entire frequency distribution of fiber length has important implications for both spinning performance and yarn quality. Combining advanced sensor technology with computer technology has made measurement of the entire length distribution more feasible. While it cannot be accomplished at a speed or a cost level required for the HVI, it can be done for more limited purposes. For example, it can be achieved when developing new cotton varieties. Although the HVI cannot detect the difference, varieties with more uniform fiber length distributions will definitely exhibit superior performance.

Looking to the future, it seems inevitable that the length distribution of cottons will command a greater focus by both cotton plant breeders and by cotton spinners. To better understand why, some explanation of the alternative spinning technologies is needed.

17.14.4 Three Major Spinning Technologies and Their Fiber Requirements

The three major spinning technologies are, in order of dominance:

1. Ring spinning
2. Rotor spinning
3. Air-jet spinning

Ring spinning is the oldest technology among these three. It also yields the slowest throughput, requires the greatest amount of labor, and has the highest cost per unit of yarn produced. However, it produces the highest quality of textiles, with strength, appearance, and “feel” (called “hand” in the industry) that sets the standard for comparison. It is also the least capital-intensive technology and requires the least technical expertise to keep the spinning machines functioning satisfactorily. Given the persistent migration of textile manufacturing toward less-developed, cheap-labor, low-skilled countries and the policy of the governments of these countries to provide large numbers of jobs, the labor requirements are not a definitive barrier to the continuing use of ring spinning.

Rotor spinning became a commercial technology during the 1970s and during the 1980s and 1990s captured a significant share of the total spinning capacity, based on its productivity in making larger-sized yarns. It is more capital- and energy-intensive than ring spinning but produces about ten times more throughput, requires only a fraction of the labor, and is the lowest cost per unit of yarn produced of the three technologies. However, its advantages are available only for large- and medium-size yarns, and both its strength and hand are inferior to the other two technologies. Trained technicians are required to get good performance from rotor spinning machines. Use of rotor spinning generally increases its share of spinning capacity as a country develops and labor costs become a major factor in the per-unit cost of yarn production.

Air-jet spinning also became commercial technology during the 1970s, not long after rotor spinning. It is the most capital- and energy-intensive of the three technologies, costs somewhat more per unit of yarn production than does rotor spinning, but produces the highest throughput (1.5–2 times that of rotor spinning). Air-jet yarns more closely approximate the appearance and hand of ring-spun yarns than does the rotor spinning. The comparative advantage of this technology is maximum for making small yarns, and it cannot adequately spin larger yarn sizes. Air-jet spinning is also the most demanding of technical expertise and requires precise maintenance to deliver consistent performance. These factors have limited its market penetration.

Of these three technologies, only ring spinning can commercially produce a full range of yarn sizes. Approximate share of global capacity of ring spinning is between 70 and 75%. Rotor spinning accounts for between 20 and 25%, while the share of air-jet spinning is not more than 5%. These shares are changing slowly if at all and are not expected to be significantly different a decade from now.

Using the four basic measurements of cotton fibers—length, length uniformity, strength, and fineness—these may be ranked in order to their importance for each of the three existing spinning technologies. It must be emphasized that all four of these properties are critically important to yarn spinners; thus, if any one of these is unacceptable, spinning performance and yarn quality will be unacceptable. Nevertheless, the three spinning systems exhibit different *sensitivities* to each of these properties, which allow a useful 1-through-4 ranking, as shown in Table 17.1.

Length uniformity is ranked third for ring spinning, fourth for rotor spinning, but first for air-jet spinning. The importance of length uniformity explains why air-jet spinning of cotton is most often done in a blend with synthetic fibers, for which length uniformity is more controllable. It also explains the fact that combed cotton is most often used for air-jet yarns.

Table 17.1 Ranking importance of four fiber properties for three spinning systems

Rank	Ring spinning	Rotor spinning	Air-jet spinning
1	Length	Strength	Length uniformity
2	Strength	Fineness	Length
3	Length uniformity	Length	Fineness
4	Fineness	Length uniformity	Strength

Superior length uniformity is critical for enabling cotton fibers to penetrate further into air-jet spinning. Furthermore, length uniformity belongs among the top four cotton fiber properties for all commercial spinning technologies. For both ring spinning and air-jet spinning, cottons with a shorter staple length but a higher length uniformity can outperform cottons with a longer staple length but lower length uniformity. Within limits, these systems can be set to accommodate different staple lengths, and then superior length uniformity will produce superior yarns. Rotor spinning is the most tolerant of a lack of length uniformity, but superior uniformity results in superior rotor-spun yarns.

17.14.5 Status and Potential of Length Uniformity Measurements

As a matter of historical focus on commercial measurement of important cotton fiber properties, length uniformity was neglected, owing to difficulty in its measurement. Fiber length, strength, and fineness are more amenable to useful measurements of central tendencies, while length uniformity is overtly a *distributional* property. As previously emphasized, the ratio of mean length to upper-half mean length that is currently provided by the HVI, denoted as the uniformity index (UI), does not begin to capture the complexities of fiber length distribution.[6] Nevertheless, this measurement has increasingly become a factor in determining the market prices of cotton in recent years, which testifies that informed participants in the commercial spinning industry are increasingly aware that they need information on length uniformity.

Ironically, dominance of the HVI measurements for marketing cotton has inhibited a proper focus on length uniformity in the research and development of improved cotton varieties. This is understandable, since the HVI was a giant step in measurement technology and cotton breeders naturally tended to utilize the low-

---

[6] For example, a simple ratio of mean length to upper-half mean length does not inform about fiber distributions below the mean length, yet this information is important for spinning performance and yarn quality. Moreover, the UI lacks precision, meaning that the interval of uncertainty around the point estimate of the UI is quite wide. Thus, it may be that a UI estimate for a single cotton sample of 80 is not significantly different from an estimate of 81. See "Cotton Classification: Understanding the Data," www.ams.usda.gov/cotton/UnderstandtheData.

cost data it provided to guide development of cotton fibers that classed well on the HVI (and which sold for higher prices in the market). It is regrettable, however, because slower and more costly measurement technologies are available to reveal superior length uniformity and neither the slowness nor the cost is prohibitive within the context of a plant breeding program. Furthermore, research suggests that length uniformity can be selected within cotton breeding programs if it can be adequately measured.[7]

Looking to the future, a combination of computer power, advancing sensor technologies, and sophisticated algorithmic programs has potential to enable high-volume length distribution measurements that provide more detailed, precise, and accurate guidance on spinning performance and yarn quality. Incorporation of these measurements into existing HVI technology would be one of the most significant advancements in commercial measurement technology since the inception of the HVI. Furthermore, this would influence cotton breeding programs and encourage increased utilization of more sophisticated, lower-volume measurement technologies that could provide better guidance toward achieving genetic improvements in the uniformity of the fiber length distributions.

17.15 Enhancing Cotton Utilization

Fiber is the primary reason cotton is produced, but the seed is a significant byproduct that has potential for further value-added developments. For every kilogram of cotton fiber produced, about 1.4 kg of cottonseed is produced. Furthermore, cottonseed is a unique oilseed that yields premium oil, along with valuable meal, linters, and hulls. When *G. hirsutum* cottonseed is processed through state-of-the-art oil mills, approximate yields are as follows:

- Oil—16%
- Meal—46%
- Linters—8%
- Hulls—27%
- Waste—3%

These percentages are somewhat dependent on varieties, but differences between species are more significant. The *G. barbadense* varieties have minimum amounts of “fuzz” and produce minimum amounts of linters. *G. hirsutum* varieties typically require two operations to remove linters, usually called first cut linters and second cut linters. Linters are almost 100% cellulose and as such are valuable for a multitude of chemical and nonchemical commercial uses.

---

[7] Research has indicated that genetic components significantly impact within-plant variability of fiber length and maturity. See “Evaluating the within-plant variability of cotton fiber length and maturity,” by A. Ayele, B. Kelly, and E.F. Hequet, *Agronomy Journal*. 110(1) 47–55.

Unprocessed, whole cottonseed is also a premium ingredient for feeds to dairy cattle as well as for other livestock. In recent years, the value of cottonseed has accounted for 15–20% of the total revenue to farmers from cotton production. Dowd and Wakelyn (2010) have extensively discussed the current and future utilization of cottonseed products. They have also discussed enhanced uses of cottonseed oil including some of the hindrances to make it more valuable. Whole cottonseed, as well as cottonseed meal and flour consumption by both animals and humans, has generally been limited by the trace presence of gossypols—polyphenolic disesquiterpene compounds that are seen as dark brown to blackish dots on the plant parts. The plant body having gossypols also transmits gossypols to the seed. The presence of gossypols in the seed carries toxicity and prohibits livestock producers limit the quantity of cottonseed fed to animals. Gossypols are desirable for defense against insects but they are also transmitted to the seed. Nonruminant animals such as poultry cannot handle much gossypol before toxicity signs develop. Cattles have the ability to detoxify but to a certain extent. On the other hand, gossypol-free seed kernels can be used in combination with wheat and corn flours to enrich the protein content of these products. Breakthrough genetic engineering research (Rathore et al. 2008) has successfully produced cotton with gossypol eliminated from the seeds; therefore, a research barrier to widespread human consumption of cottonseed flour has been broken, and it is possible that commercial varieties that have gossypol-free cottonseeds would be in combination with wheat and corn flours, in order to enrich the protein content of these products.

The production of baled cotton fibers at gins results in waste byproducts that are underutilized in most of the world. These waste byproducts include linters, burrs, and sticks. Significant research and development has been carried out at the USDA Gin Lab in Lubbock, Texas, USA, to capture, process, and exploit these waste products in various ways. Examples include processing as compost and for hydro-mulch suitable for land filling and cattle feed. The benefits are twofold: (1) additional revenue is generated and (2) waste disposal costs and pollution are eliminated. The large-scale, technology-oriented ginning sectors are already acting to utilize these waste products, and these actions will increase and spread in upcoming years.

The harvest index as measured in terms of dry mass of seed cotton to total dry mass of the cotton plant is only 0.33, and the index will vary greatly depending on growing conditions and production practices. Not counting sugarcane, which has a different harvesting, cotton's harvest index is only 65% of wheat, rice, and maize. Bulk of the dry matter left in the cotton field is cotton sticks that are not properly utilized. Mulching back cotton stalks into the soil is a genuine return to the soil but cotton stalks can find better uses. One such use that has been explored to some extent is making particle boards from cotton stalks. The International Cotton Advisory Committee with funding from the Common Fund for Commodities undertook a pilot project in India aiming to produce hardboards. The work done by local researchers involved chipping stalks to an appropriate mesh of 1.5–2.0 cm, mixing chips with urea formaldehyde or phenol formaldehyde, and preparing coarse and fine layer mats. A coarse layer mat and two fine chip mats, on either side of the coarse mat, were pressed with a hydraulic pressing having heated platens. The boards thus made under standard conditions of resin concentration, pressure and temperature, etc. produced an acceptable quality of board. This aspect of the raw materials produced by the cotton plant will get higher attention beyond 2030.

References

Akbar W, Gowda A, Ahrens JE, Stelzer JW, Brown RS, Bollman SL, Greenplate JT, Gore J, Catchot A, Lorenz LG, Stewart SD, Kerns DL, Greene JK, Toews MD, Herbert DA, Resig DD, Sword GA, Ellsworth PC, Godfrey LD, Clark TL (2019) First transgenic trait for control of plant bugs and thrips in cotton. *Pest Manag Sci* 75(3):867–877

Ali Z, Ali S, Tashkandi M, Zaidi SS, Mahfouz MM (2016) CRISPR/Cas9-mediated immunity to Gemini viruses: differential interference and evasion. *Sci Rep* 6:26912

Andreotti G, Koutros S, Hofmann JN, Sandler DP, Lubin JH, Lynch CF, Lerro CC, De Roos AJ, Parks CG, Alavanja MC, Silverman DT, Freeman LEB (2018) Glyphosate use and cancer incidence in the agricultural health study. *J Natl Cancer Inst* 110(5):509–516. https://doi.org/10.1093/jnci/djx233

Armijo CB, Whitelock DP, Thomas JW, Hughs SE, Gillum MN (2017) Roller ginning. *J Cotton Sci* 21:199–209

Asokan R, Chandra GS, Manamohan M, Krishna Kumar NK (2011) Effect of diet delivered various concentrations of double-stranded RNA in silencing a midgut and a non-midgut gene of *Helicoverpa armigera*. *Bull Entomol Res* 103:555–563

Auer C, Frederick R (2009) Crop improvement using small RNAs: application and predictive ecological risk assessment. *Trends Biotechnol* 27(11):644–651

Bassi FM, Bentley AR, Charmet G, Ortiz R, Crossa J (2016) Breeding schemes for the implementation of genomic selection in wheat (Triticum spp.). *Plant Sci* 242:23–36

Berezow A (2018) California's glyphosate judgement—emotion, bad science and Greed Win the Day. *Outlooks Pest Manag* 29(5):204–205

Borges R, Oliveira Da Silva R, Bernardi C, Urrutia W, MafraNeto A (2015) Noctovi, an effective food based attractant for lepidopteran pests. Poster presented at Entomological Society of America

Brévault T, Heuberger S, Zhang M, Ellers-Kirk C, Ni X, Masson L, Li X, Tabashnik BE, Carrière Y (2013) Potential shortfall of pyramided transgenic cotton for insect resistance management. *Proc Natl Acad Sci* 110(15):5806–5811

Carpenter JE (2010) Peer-reviewed surveys indicate positive impact of commercialized GM crops. *Nat Biotechnol* 28:319–321

Carriere Y, Antilla L, Liesner L, Tabashnik BE (2017) Large-scale evaluation of association between pheromone trap captures and cotton boll infestation for pink bollworm (Lepidoptera: Gelechiidae). *J Econ Entomol* 110(3):1345–1350

Cattaneo MG, Christine Y, Schmidt C, Huang C, Rahman M, Olson C, Kirk CE, Orr BJ, Marsh SE, Antilla L, Dutilleul P, Carrière Y (2006) Farm-scale evaluation of the impacts of transgenic cotton on biodiversity, pesticide use, and yield. *Proc Nat Acad Sci* 103(20):7571–7576. https://doi.org/10.1073/pnas.0508312103

Chang H, Liu Y, Ai D, Jiang X, Dong S, Wang G (2017) A pheromone antagonist regulates optimal mating time in the moth *Helicoverpa armigera*. *Curr Biol* 27(11):1610–1615

Chen X, Lu X, Shu N, Wang S, Wang J, Wang D, Guo L, Ye W (2017) Targeted mutagenesis in cotton (*Gossypium hirsutum* L.) using the CRISPR/Cas9 system. *Sci Rep* 7:44304

Crossa J, Perez-Rodriguez P, Cuevas J, Montesinos-Lopez O, Jarquin D, de los Campos G, Burgueno J, Gonzalez-Camacho JM, Perez-Elizalde S, Beyene Y, Dreisigacker S, Singh R, Zhang X, Gowda M, Roorkiwal M, Rutkoski J, Varshney RK (2017) Genomic selection in plant breeding: methods, models, and perspectives. *Trends Plant Sci* 22(11):961–975

Cui J, Luo J, Van Der Werf W, Ma Y, Xia J (2011) Effect of pyramiding Bt and CpTI genes on resistance of cotton to *Helicoverpa armigera* (Lepidoptera: Noctuidae) under laboratory and field conditions. *J Econ Entomol* 104:673–684

Dhawan AK, Singh S, Kumar S (2009) Integrated Pest Management (IPM) helps reduce pesticide load in cotton. J Agric Sci Technol 11:599–611

Dhurua S, Gujar GT (2011) Field-evolved resistance to Bt toxin Cry1Ac in the pink bollworm, *Pectinophora gossypiella* (Saunders) (Lepidoptera: Gelechiidae) from India. *Pest Manag Sci* 67:898–903

Dowd, M. K. and P. J. Wakelyn. 2010. Cottonseed: current and future utilization. In the Cotton: technology for the 21st century. Phillip J. Wakelyn and M. Rafiq Chaudhry, International Cotton Advisory Committee, Washington, DC

Dwivedia SL, Britt AB, Tripathi L, Sharma S, Upadhyaya HD, Ortiz R (2015) Haploids: constraints and opportunities in plant breeding. *Biotechnol Adv* 33(6 Part 1):812–829

Dykxhoorn DM, Lieberman J (2005) The silent revolution: RNA interference as basic biology, research tool, and therapeutic. *Ann Rev of Med* 56(1):401–423

Emani C, Garcia JM, Lopata-Finch E, Pozo MJ, Uribe P, Kim DJ, Kumar GS, Cook DR, Kenerley CM, Rathore KS (2003) Enhanced fungal resistance in transgenic cotton expressing an endochitinase gene from *Trichoderma virens*. *Plant Biotechnol J* 1:321–336

Firmino AAP, Fonseca FCDA, de Macedo LLD, Coelho RR, Antonino de Souza JD Jr, Togawa RC (2013) Transcriptome analysis in Cotton Boll Weevil (*Anthonomus grandis*) and RNA interference in insect pests. *PLoS One* 8(12):e85079. https://doi.org/10.1371/journal.pone.0085079

Gapare W, Liu S, Conaty W, Zhu Q, Gillespie V, Llewellyn D, Stiller W, Wilson I (2018) Historical datasets support genomic selection models for the prediction of cotton fiber quality phenotypes across multiple environments. *G3 (Bethesda)* 8(5):1721–1732

Gaspar YM, McKenna JA, McGinness BS, Hinch J, Poon S, Connelly AA, Anderson MA, Heath RL (2014) Field resistance to *Fusarium oxysporum* and *Verticillium dahliae* in transgenic cotton expressing the plant defensin *NaD1*. *J Exp Bot* 65(6):1541–1550. https://doi.org/10.1093/jxb/eru021

Gong Y-H, Yu XR, Shang QL, Shi XY, Gao XW (2014) Oral Delivery Mediated RNA Interference of a carboxylesterase gene results in reduced resistance to organophosphorus insecticides in the cotton aphid, *Aphis gossypii* Glover. *PLoS One* 9(8):e102823. https://doi.org/10.1371/journal.pone.0102823

Greenplate JT (1999) Quantification of *Bacillus thuringiensis* insect control protein Cry1Ac over time in Bollgard cotton fruit and terminals. *J Econ Entomol* 92:1377–1383

Hazra DK (2017) Nano-formulations: high definition liquid engineering of pesticide for advanced crop protection in agriculture. *Adv Plant Agric Res* 6(3):1–2

Hughs SE, Parnell CB Jr, Wakelyn PJ (2010) Cotton harvesting and ginning in the 21st century. In: Wakelyn PJ, Chaudhry MR (eds) Cotton: technology for the 21st century. International Cotton Advisory Committee, Washington, DC

Iqbal Z, Sattar MN, Shafiq M (2016) CRISPR/Cas9: a tool to circumscribe cotton leaf curl disease. *Front Plant Sci.* https://doi.org/10.3389/fpls.2016.00475

Keim DL (2007) Industry highlights: cotton breeding. In: Principles of plant genetics and breeding. Blackwell, Malden, p 569

Khanday I, Skinner D, Yang B, Mercier R, Sundaresan V (2019) A male-expressed rice embryogenic trigger redirected for asexual propagation through seeds. *Nature* 565(7737):91–95

Khatodia S, Bhatotia K, Tuteja N (2017) Development of CRISPR/Cas9 mediated virus resistance in agriculturally important crops. *Bioengineered* 8(3):274–279. https://doi.org/10.1080/21655979.2017.1297347

Knight K, Head G, Rogers J (2013) Season-long expression of Cry1Ac and Cry2Ab proteins in Bollgard II cotton in Australia. *Crop Prot* 44:50e58

Kogan M (1998) Integrated pest management: historical perspectives and contemporary developments. *Annu Rev Entomol* 43(1):243–270

Korres NE, Burgos NR, Travlos I, Vurro M, Gitsopoulos TK, Varanasi VK, Duke SO, Kudsk P, Brabham C, Rouse CE, Salas-Perez R (2019) New directions for integrated weed management: modern technologies, tools and knowledge discovery. *Adv Agron* 155:243

Kranthi KR (2018) Biotech cotton-relevance for Africa, *ICAC Recorder* 29–34

Kranthi KR, Russell D, Wanjari R, Kherde M, Munje S, Lavhe N, Armes N (2002) In-season changes in resistance to insecticides in *Helicoverpa armigera* (Lepidoptera: Noctuidae) in India. *J Econ Entomol* 95(1):134–142. https://doi.org/10.1603/0022-0493-95.1.134

Kranthi KR, Naidu S, Dhawad CS, Tatwawadi A, Mate K, Patil E, Bharose AA, Behere GT, Wadaskar RM, Kranthi S (2005) Temporal and intra-plant variability of Cry1Ac expression in Bt-cotton and its influence on the survival of the cotton bollworm, *Helicoverpa armigera* (Hübner) (Noctuidae: Lepidoptera). *Curr Sci* 89:291–298

Lamm RD, Slaughter DC, Giles DK (2002) Precision weed control system for cotton. *Trans ASAE* 45(1):231

Lance DR, Leonard DS, Mastro VC, Walters ML (2016) Mating disruption as a suppression tactic in programs targeting regulated lepidopteran pests in US. *J Chem Ecol* 42(6):590–601

Lu Y, Wu K, Jiang Y, Guo Y, Desneux N (2012) Widespread adoption of Bt cotton and insecticide decrease promotes biocontrol services. *Nature* 487:362–365

Mao YB, Tao XY, Xue XY, Wang LJ, Chen XY (2011a) Silencing a cotton bollworm P450 monooxygenase gene by plant-mediated RNAi impairs larval tolerance of gossypol. *Nat Biotechnol* 25:1307–1313

Mao Y, Tao X, Xue X, Wang L, Chen X (2011b) Cotton plants expressing CYP6AE14 double-stranded RNA show enhanced resistance to bollworms. *Transgenic Res* 20:665–673

Mensah RK (2002) Development of an integrated pest management programme for cotton. Part 2: integration of a lucerne/cotton interplant system, food supplement sprays with biological and synthetic insecticides. *Int J Pest Manag* 48:95–105

Mensah RK, Peter AF, Gregg C, Alice B, Del Socorro P, Christopher BJ, Moore D, Hawes JAC, Watts N (2013) Integrated pest management in cotton: exploiting behaviour-modifying (semiochemical) compounds for managing cotton pests. *Crop Pasture Sci* 64:763–773

Morrison NI, Simmons GS, Fu G, O'Connell S, Walker AS, Dafa'alla T, Walters M, Claus J, Tang G, Jin L, Marubbi T (2012) Engineered repressible lethality for controlling the pink bollworm, a lepidopteran pest of cotton. *PLoS One* 7(12):e50922

Naik VC, Kumbhare S, Kranthi S, Satija U, Kranthi KR (2018) Field-evolved resistance of pink bollworm, *Pectinophora gossypiella* (Saunders) (Lepidoptera: Gelechiidae), to transgenic *Bacillus thuringiensis* (Bt) cotton expressing crystal 1Ac (Cry1Ac) and Cry2Ab in India. *Pest Manag Sci* 74:2544–2554. https://doi.org/10.1002/ps.5038

Ni M, Ma W, Wang X, Gao M, Dai Y, Wei X, Zhang L, Peng Y, Chen S, Ding L, Tia Y, Li J, Wang H, Wang X, Xu G, Guo W, Yang Y, Wu Y, Heuberger S, Tabashnik BE, Zhang T, Zhu Z, Ni M et al (2017) Next-generation transgenic cotton: pyramiding RNAi and Bt counters insect resistance. *Plant Biotechnol J* 15:1204–1213

Parkhi V, Kumar V, Campbell LM, Bell AA, Shah J, Rathore KS (2010) Resistance against various fungal pathogens and reniform nematode in transgenic cotton plants expressing Arabidopsis NPR1. *Trans Res* 19:959–975

Perez-Rodriquez P, Crossa J, Bondalapati K, De Meyer G, Pita F, de los Campos G (2015) A pedigree-based reaction norm model for prediction of cotton yield in multienvironment trials. *Crop Sci* 55:1143–1151

Qaim M, Matuschke I (2005) Impacts of genetically modified crops in developing countries: a survey. *Q J Int Agric* 44:207–227

Rajasekaran K, Cary JW, Jaynes JM, Cleveland TE (2005) Disease resistance conferred by the expression of a gene encoding a synthetic peptide in transgenic cotton (*Gossypium hirsutum* L.) plants. *Plant Biotechnol J* 3:545–554

Rathore KS, Sunilkumar G, Stipanovic RD, Wedegaertner TC (2008) RNAi-mediated, selective and substantial reduction in gossypol levels from cottonseed to enhance its food and feed value. In: Proceedings of world cotton conference, September 10–14, Lubbock

Rebijith KB, Asokan R, Hande HR, Kumar NKK, Krishna V, Vinutha J, Bakthavatsalam N (2016) RNA interference of odorant-binding protein 2 (OBP2) of the cotton aphid, *Aphis gossypii* (Glover), resulted in altered electrophysiological responses. *Appl Biochem Biotechnol* 178(2):251–266

Silvie PJ, Renou A, Vodounnon S, Bonni G, Adegnika MO, Héma O, Prudent P, Sorèze J, Ochou GO, Togola M, Badiane D, Ndour A, Akantetou PK, Ayeva B, Brévault T (2013) Threshold-based interventions for cotton pest control in West Africa: what's up 10 years later? *Crop Prot* 43:157–165

Simmons GS, McKemey AR, Morrison NI, O'Connell S, Tabashnik BE, Claus J, Fu G, Tang G, Sledge M, Walker AS, Phillips CE (2011) Field performance of a genetically engineered strain of pink bollworm. *PLoS One* 6(1):e24110

Soda N, Verma L, Giri J (2018) CRISPR-Cas9 based plant genome editing: significance, opportunities and recent advances. *Plant Physiol Biochem* 131:2–13

Sohrab SS, Azhar EI, Kamal MA, Bhattacharya PS, Rana D (2014) Genetic variability of Cotton leaf curl beta satellite in Northern India. *Saudi J Biol Sci* 21(6):626–631

Sun D, Guo Z, Liu Y, Zhang Y (2017) Progress and prospects of CRISPR/Cas systems in insects and other arthropods. *Front Physiol* 8:608

Sun S, Li C, Paterson AH, Jiang Y, Xu R, Robertson JS, Snider JL, Chee PW (2018) In-field high throughput phenotyping and cotton plant growth analysis using LiDAR. *Front Plant Sci* 9:1–17

Tabashnik BE, Carrière Y (2017) Surge in insect resistance to transgenic crops and prospects for sustainability. *Nat Biotechnol* 35:926–935

Tabashnik BE, Morin S, Unnithan GC, Yelich AJ, Ellers-Kirk C, Harpold VS, Sisterson MS, Ellsworth PC, Dennehy TJ, Antilla L, Liesner L (2012) Sustained susceptibility of pink bollworm to *Bt* cotton in the United States. *GM Crops Food* 3(3):194–200

Tabashnik BE, Brévault T, Carrière Y (2013) Insect resistance to Bt crops: lessons from the first billion acres. *Nat Biotechnol* 31:510–521

Technical Information Section (1994 Sept) Methanol use in cotton. THE ICAC RECORDER, vol XII, no. 3. International Cotton Advisory Committee, Washington, DC

Technical Information Section (2016 Oct) Cost of production of cotton. International Cotton Advisory Committee, Washington, DC

Technical Information Section (2017 Oct) Cotton production practices. International Cotton Advisory Committee, Washington, DC

Thirtle C, Beyers L, Ismael Y, Piesse J (2003) Can GM-technologies help the poor? The impact of Bt cotton in Makhathini Flats, KwaZulu-Natal. *World Dev* 31:717–732

Traxler G, Godoy-Avila S, Falck-Zepeda J, Espinoza-Arellano J (2013) Transgenic cotton in Mexico: economic and environmental impacts. In: Kalaitzandonakes N (ed) Economic and environmental impacts of first generation biotechnologies. Kluwer Academic Publishers, New York, pp 183–202

Turcotte EL, Feaster CV (1963) Haploids: high frequency production from single-embryo seeds in a line of Pima cotton. *Science* 140:1407–1408

Upadhyay SK, Chandrashekar K, Thakur N, Verma PC, Borgio JF, Singh PK, Tuli R (2011) RNA interference for the control of whiteflies (*Bemisia tabaci*) by oral route. *J Biosci* 36:153–161

Walker WB, Allen ML (2010) Expression and RNA interference of salivary polygalacturonase genes in the tarnished plant bug, *Lygus lineolaris*. *J Insect Sci* 10(1):173. https://doi.org/10.1673/031.010.14133

Walton J, Larson J, Roberts R, Lambert D, English B, Larkin S, Marra MC, Martin SW, Paxton KW, Reeves J (2010) Factors influencing farmer adoption of portable computers for site-specific management: a case study for cotton production. *J Agric Appl Econ* 42(2):193–209. https://doi.org/10.1017/S1074070800003400

Wang G, Fok M (2018) Managing pests after 15 years of Bt cotton: farmers' practices, performance and opinions in Northern China. *Crop Prot* 110:251–260

Wang J, Zhang H, Wang H, Zhao S, Zuo Y, Yang Y et al (2016) Functional validation of cadherin as a receptor of Bt toxin Cry1Ac in *Helicoverpa armigera* utilizing the CRISPR/Cas9 system. *Insect Biochem Mol Biol* 76:11–17. https://doi.org/10.1016/j.ibmb.2016.06.008

Wang J, Zhang H, Wang H, Zhao S, Zuo Y, Yang Y, Wu Y (2017) Functional validation of cadherin as a receptor of Bt toxin Cry1Ac in *Helicoverpa armigera* utilizing the CRISPR/Cas9 system. *Insect Biochem Mol Biol* 87:147–153

Wei J, Guo Y, Liang G, Wu K, Zhang J, Tabashnik BE, Li X (2015) Cross-resistance and interactions between Bt toxins Cry1Ac and Cry2Ab against the cotton bollworm. *Sci Rep* 5:7714

Wilson LJ, Mensah RK, Fitt GP (2004) Implementing integrated pest management in Australian cotton. In: Insect pest management. pp 97–118

Wu KM, Lu YH, Feng HQ, Jiang YY, Zhao JZ (2008) *Suppression* of cotton bollworm in multiple crops in China in areas with Bt toxin-containing cotton. *Science* 321:1676–1678

Xiong Y, Zeng H, Zhang Y, Xu D, Qiu D (2013) Silencing the HaHR3 gene by transgenic plant-mediated RNAi to disrupt *Helicoverpa armigera* development. *Int Biol Sci* 9(4):370–381. https://doi.org/10.7150/ijbs.5929

Xiongkui H, Bonds J, Herbst A, Langenakens J (2017) Recent development of unmanned aerial vehicle for plant protection in East Asia. *Int J Agric Biol Eng* 10(3):18–30

Ye ZF, Liu XL, Han Q, Liao H, Dong XT, Zhu GGH, Dong SL (2017) Functional characterization of PBP1 gene in Helicoverpa armigera (Lepidoptera: Noctuidae) by using the CRISPR/Cas9 system. *Sci Rep* 7:8470. https://doi.org/10.1038/s41598-017-08769-2

Yu J, Jung S, Cheng C, Ficklin SP, Lee T, Zheng P, Jones D (2014) CottonGen: a genomics, genetics and breeding database for cotton research. *Nucleic Acids Res* 42:D1229–D1236

Yu XD, Liu ZC, Huang SL, Chen ZQ, Sun YW, Duan PF, Ma YZ, Xia LQ (2016) RNAi-mediated plant protection against aphids. *Pest Manag Sci* 72:1090–1098

Zhu J-Q, Liu S, Ma Y, Zhang JQ, Qi HS, Wei ZJ (2012) Improvement of pest resistance in transgenic tobacco plants expressing dsRNA of an insect-associated gene *EcR*. *PLoS One* 7(6):e38572. https://doi.org/10.1371/journal.pone.0038572