Proven Technologies for Doubling Cotton Production in India and Enhancing Quality of Lint and Seed

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Abstract

India is no less inferior to many advanced countries in R&D achievements under public sector, private sector seed industry and also the technological and textile institutions all over the country. If the realistic evaluation is made, except for improved cultivars, the farmers' adoption rate of the recommended technologies for planting, production and processing have been awfully low, poor and inadequate, given the wide diversity of Indian cotton farming conditions. Hardly 15−20% of the cotton growers have adopted the wholesome technology. The urgent need is to organize the national cotton farming on a highly scientific and technology-oriented. India can achieve its goals on highest yield and high quality of cotton lint and cottonseeds and their effective utilization.

Keywords: Adoption, cotton, lint, production, quality, seed, technology

1. Introduction

Diploid Asiatic cottons (*Gossypium arboreum* L. and *G. herbaceum* L.) were grown in India from time immemorial. Due to periodical efforts of various foreign and Indian agencies from 17-19th century for the introduction of the American Upland cotton (*G. hirsutum* L.) and the Sea Island or Egyptian cottons (*G. barbadense* L.), India had been growing varieties of all the four cultivated species of *Gossypium* in substantial proportions by 1960s. In the entire 20th century, cotton breeding research and technology development were concentrated on improvement of all the four cultivated species. Until around 1980s, purebred varieties were predominantly grown and thanks to the innovation of hybrid cotton technology in the 1960s-70s followed by aggressive and competitive hybrid cotton development by both the public and private sector, F_1 commercial hybrids of *G. hirsutum* (H)×*G. hirsutum* (H) became predominant in cultivation, besides a small area with *G. hirsutum* (H)×*G. barbadense* (B) hybrid cottons by the end of 2001. The further boost to cotton production was witnessed when after 2002–03, Bollgard (BG) or bollworm tolerant transgenic cottons, with Bt-gene (genes from *Bacillus thuringiensis*) versions of the H×H and H×B cotton hybrids first as BG-I (Cry1Ac) and a few years later as BG-II (Cry1Ac+Cry2Ab stacked version) dominated the cotton production scenario. Currently over 93% of the total area under cotton production is that of G. *hirsutum* (H×H hybrids) with Bt-genes and these represent the superior medium to long and some near extra-long staple categories.

The area grown under cotton in India after partition of Pakistan was 4.40 mha and by 2014–15, the area has increased to 12.6 mha. Production that was 2.2 m bales or 0.38 mt of lint increased to 6.90 mt of lint and productivity from 88 kg lint to 568 kg lint ha^{-1} (in 2007–08). The production has increased multifold i.e., by 18 times, while the productivity or yield of lint ha^{-1} increased only 6–7 times from 1950–51 to 2014–15. This mismatch or discrepancy between production and productivity increases may be attributable to expansion in areas with soils not very conducive for cotton cultivation, besides inefficiencies in the cultivation of bollgard hybrid cottons by the farmers and disparities in regional rainfall and cropping patterns. Out of nearly 12.6 mha, only 38% (4.8 mha) appears to be irrigated and rest dependent completely on rainfall which, range from 450 mm to 900 mm during the cotton crop season. In 2014–15 and thereafter, India, which is already the holder of first rank in global cotton area, is set to replace China as the world's largest cotton producer and consumer as its textiles sector continues to expand.

2. Global Cotton Production and Technology Adoption

World cotton yield rose from 400 kilograms of lint per hectare in the 1980s to 600 kilograms in the 1990s and to nearly 800 kilograms by 2007–08. However, the world yield had trended lower since 2007–08 and is estimated at only 760 kg ha^{-1} in 2012–13. In 2014–15, it may increase to 800 kg ha^{-1} again. Successful cotton production requires water in the form of rainfall 450–600 mm during the growing period plus light at Compensation point of 1000–2000 lux and Saturation point of 70000-80000 lux and temperature range of 14 °C–35 °C, the optimum being 25 °C–30 °C. Drought makes farming dismal and has a pervasive impact on the farming community. Cotton production is facing numerous challenges like lack of water and to keep the cotton crop safe from sucking pests and viruses that adversely affect its yield levels. Light availability also gets affected in critical growth stages due to continuous cloudy weather without adequate rainfall in many regions. Major area under cotton grown in India is dependent on rainfall completely for the cultivation and its erratic behavior either insufficient rainfall, untimely or excess rainfall at critical stages of the crop is a regular feature. Australia though with highest yield levels as well as India that ranks much below the global average yield and some parts of the USA are affected by drought often. Still by adopting ingenious water management techniques, Australia produces highest average yields (1800 to 2300 kg lint ha^{-1}) in the world. In USA, California farmer produces 35 times more cotton litre^{-1} of water as compared to India. Israel with poor rainfall and shortage of water also adopts rain water harvesting and drip irrigation and achieves yields of over 1950 kg lint ha^{-1}. Brazil also with large rain-fed area recoded higher average yields (1400–1500 kg ha^{-1}) by proper and unique management systems.

Complete dependence on genotypes and quality seeds alone in India have not helped to reach higher levels of national average like many countries. Notwithstanding various innovative research outputs from time to time by the release of superior genotypes under public and private sector and quality seeds made available to the growers in each crop season, certain basic strategies like advanced agricultural practices and their faithful and systematic adoption by all farmers has been considered essential to maximize the yield levels of various farmers and regions and hence the national average yield under all circumstances. Some of these are presented below:

3. Primacy of Agronomic Practices, Genetic and Recoverable Potential

3.1. Soil and water Management

India grows cotton predominantly under rainfall dependence to the extent of 62–65%. Hence the soil and water management assumes first priority in successful cotton cultivation. When rainfall is unpredictable, it is better to plan for efficient rainwater harvesting and soil moisture management. Compared to many other countries, rainfall quantum in India is by and large higher. Rain Water Harvesting (RWH) can replenish 10 years' consumption in one season. Furrow irrigation can reduce water consumption by 50–70% and drip irrigation at critical periods of crop in boll maturation stages to double the yields by recycling the rainwater harvested and stored. Deep chiselling once in 2 or 3 years with adoption of good package of practices can double crop yields and reduce water usage by 50%. All these techniques would help to achieve higher WUE and also effectively utilize the available rain water for obtaining superior yields.

3.2. Fertilizer usage

This is an important factor for high yields and quality of fibre and seed. Cotton crop requires more than 12 essential nutrients. The same hybrid cotton generates 1900 kg ha^{-1} lint in Gujarat, 1700 in AP, Telangana (TS) and Tamil Nadu and national average of 900 kg ha^{-1} under irrigation and nearly half of it under rain fed conditions under proper fertility and crop management compared to national average of 560–590 kg lint ha^{-1}. The methods employed by predominant farmers in India for application of fertilizers lead to low absorption, low fertilizer use efficiency, high wastage and high cost. Farmers can easily double the yields of the same hybrid or variety seed by scientific management of soil fertility and crop nutrition. The ideal ratio of NPK fertilization is of the ratio of 4:2:1 followed by the intelligent use of Boron, Zinc and other nutrients. Drip (Micro) irrigation and drip fertigation strategies should be adopted wherever possible for achieving higher efficiency in use and benefit realization from applied water and nutrients.

3.3. Breeding

Top performing countries in breeding tend to be those similarly rated high for agronomic practices. This category emphasizes the proprietary aspect of seed development and the general lack of saved seed, both of which are general indicators of investment by both public and private sectors. However in India, there are wide disparities in agronomic technology adoption, which should be considered as the chief constraint in registering high yields. Some of the genotypes released from time to time in last two decades have demonstrated high potential yields under superior management technology applications, but on an average not even 40−50% of the recoverable yield potential is realized by vast majority of farmers in our country. Some of the genotypes which had a wide area coverage and also high yield as well as fibre quality so far include MCU5, LRA 5166, DCH32, RCH2, Bunny, Mallika, Dyna, sigma, Ankur 651, Narasimha, Brahma, JKCH99, Suvin, MECH Hybrids, Thulasi and certain others of Bio-seeds, Krishidan, Cauvery and other seed companies proprietary hybrids. These genotypes are cited because the authors have visited several farmers' fields in various locations in southern and central zone states and also in Punjab and high yield levels of 50–65 q of seed cotton (*kapas*) equal to 1650–2100 kg lint ha^{-1} (coupled seed yield of 33 q to 42 q ha^{-1}). Though replication of this high yield levels by all farmers may not be easy, still the national average yields have not increased significantly as a result of adoption of poor crop management by majority of the growers. The difference lies in agronomy and efficient crop management by the intelligent farmers, who have adopted the recommended technologies.

3.4. Biotechnology

The criteria for rating a top tier and low tier country are fairly straightforward given the presence or absence of biotechnology approvals and biotech crop penetration in a given country. Most European countries, while rated high in other respects, are rated low due to their aversion to biotechnology. Some other countries were rated high for one crop and low for another in this category. An example is India, where cotton has been widely adopted and multiple products approved, but food products are not approved. This discrepancy is evident in the ratings. The following four factors would support a "High" rating for biotechnology: high levels of adoption, high trait intensity, efficiently functioning regulatory approval process and multiple approvals and ability to protect and enforce protections for intellectual property.

The most critical factors for successful and high output high quality cotton production plans may therefore be stated as follows:

(1) Water and moisture management (2) Good quality seeds of superior and reliable brands and proper gene deployment strategies in various locations (3) Optimum planting technologies (4) Vegetative and reproductive period crop management (5) Best harvest practices and post-harvest handling and (6) Scientific processing and quality management techniques.

For each of the above, several institutions in the country (ICAR-CICR, AICCIP, SAUs and CIRCOT) have experimented upon technologies and evolved the most relevant and practical considerations and conclusions. These are discussed item-wise in the following:

4. Rain Water Harvesting and Recycling

There are numerous positive benefits for harvesting rainwater. The technology is low cost, highly decentralized empowering individuals and communities to manage their water. It has been used to improve access to water and sanitation at the local level. In agriculture rainwater harvesting has demonstrated the potential of doubling agricultural production by 100% compared to the 10% increase from irrigation. Rain-fed agriculture is practiced on 80% of the world's agricultural land area, and generates 65–70% of the world's staple foods and other crops. The biggest challenge with using rainwater harvesting is that it is not included in water policies in many countries. In many cases water management is based on renewable water, which is surface and groundwater with little consideration of rainwater. Rainwater is taken as a 'free for all' resource and the last few years have seen an increase in its use. This has resulted in over abstracting, drastically reducing water downstream users including ecosystems. This has introduced water conflicts in some regions of the world. For the sustainable use of water resources, it is critical that rainwater harvesting is included as a water sources as is the case for ground and surface water. Sudden and heavy rains tend to wash off the fertile top soil; moisture holding capacity of the soil is also affected. It arrests soil erosion and soil moisture loss by suitable interventions. Rainwater harvesting- recharges the ground water and retain soil moisture by using recharge pits. Farmers in Coimbatore and other areas of TN have sunk bore wells up to several hundred feet depth faced disappointment after a few years. Hence RWH is a very beneficial technique at least cost with high dependability.

5. Cotton Plucking Machine

New equipment is ready for commercialization. A low-cost cotton plucking machine has been developed by the SIMA Cotton Development and Research Association for the benefit of farmers. The machine, costing ₹ 20,000, can be operated through solar panel and battery and pluck 10 kg of cotton in one hour, as against eight hours required by manual plucking. The machine was under trial for the last two years in various fields owned by SIMA across Tamil Nadu, and the machine is almost ready for commercialization and a Bengaluru-based company would produce it. There would be only one per cent trash content, as only cotton was plucked by the machine and straight away goes to a non-woven material bag, almost with nil contamination, as claimed. The association was ready to supply any number of machines in the cotton-growing regions of the country (Coimbatore, Sept.19; Source: "Tecoya Trend"). Many Companies like John Deere etc., are in the process of developing suitable mechanical harvesters for cotton for Indian conditions and breeders and agronomists are developing suitable genotypes and harvest management practices.

6. Potential Technologies under Development

Potential Technologies under development for Achievement of the Target as extracted from Report of FICCI, February 2012 New Delhi and other agencies are detailed below:

6.1. The genomics of *Gossypium* is being unraveled by the International Cotton Genome Initiative Groups (ICGI) and whole genome sequencing of cultivated cottons will be available within a few years from now. The role of plant biotechnology in the improvement of cotton in rapidly evolving and stakeholders must keep pace with technologies to realize the full potential. Major technologies for the country to effect crop improvements in cotton are transgenic varieties, Marker Assisted Selection (MAS), Mutagenesis and TILLING. Knowledge gained from genome decoding will improve understanding of genes at molecular levels and help to unlock the mystery of genetics for improving the yields and fibre quality.

6.2. Plant architecture plays an important role in improving the production potential of improved genotypes whether it be varieties or hybrids in managing much higher planting density and enable the adoption of machine harvesting technology. Despite then good progress made by public and private seed industry sector research and development, it is a matter of concern that productivity started declining from 568 kg ha^{-1} in 2007 to 540 kg ha^{-1} in 2013–14. Developing varieties or hybrids which are of short to medium duration, with erect compact plant architecture will offer valuable opportunity to improve yield and land use efficiency facilitating the much needed mechanization for intensive operations like sowing, inter-cultivation, effective crop management and picking. Transgenic cottons using genes like GAI, MADS Box and molecular markers or Quantitative Trait Loci (QTLs) linked to compactness, erect plant types offer reliable means for developing the desired plant architecture using the most suitable germplasm.

6.3. Cotton plant is known for its tolerance to drought and salty soils. Still the climate change envisaged is expected to aggravate erratic distribution of rainfall, prolonged heat and cold, CO2 and other stresses. Research support for development of stress tolerant genotypes based on susceptibility and sustainability index, identification of drought-linked QTLs and pursuing other technology leads in a collaborative mode is of paramount importance.

6.4. The biggest gain from Bt-hybrid cotton technology is in the form of reduced usage of highly potent chemical insecticides; the share of pesticides on cotton crop at 46% in 2001 was halved to less than 21% during 2013–14. While Bt-cotton hybrids helped control bollworms, there is need to develop new genes or transgenic versions to better manage the bollworm complex and associated changes in the pest management systems that lead to the resurgence of sucking pests. The Cotton leaf-curl virus disease (CLCuV) in north zone aggravated by white fly and the seriousness of mealy bugs' incidence, both seriously affecting cotton crop and its yields require special efforts.

6.5. Improvements of nutrition use efficiency (NUE) are an essential pre-requisite for expansion of cotton crop into marginal lands with low nutrient availability and have enormous impact on sustainable cotton cultivation in India. NUE can be advantageously analyzed through QTL analysis in recombinant inbred lines or near isogenic lines derived from crosses between wild and cultivated accessions. Besides transgenic approach, the screening of germplasm and induce mutants growing better at low input of nitrates, sulphate and phosphate can be exploited.

6.6. Weed-free cotton farms can ensure better yields and increase the income of the farmers. RRF cotton is close to commercial approval in India and will help Indian farmers immensely by allowing use of herbicides at all growth stages and a potential opportunity to reduce the cost of cultivation and remove the problems in labour availability and management. There is an urgent need to develop new molecules and resistant genes for herbicides. Appropriate programs under a national or PPP mode will go a long way in weed management solutions to increase the yields and reduce the cost of production.

6.7. Advances and the levels of automation in spinning technologies demand improved fibre traits including length, strength, uniformity and maturity and limited variation in the predominantly cultivated *G. hirsutum* species is a challenge in way of improving desired fibre traits. Asiatic cottons, the Egyptian *G. barbadense* species and some such properties inherent in the wild species offer fibre characteristics that can be introduced into *G. hirsutum,* while improving upon the high adaptability and yield potential of the latter. Advances in Single Nucleotide Polymorphism (SNPs) or Single Sequence Repeats (SSR) markers linked to fibre traits and other technologies can be leveraged by stakeholders to effect the desired fibre quality improvements.

6.8. De-risking cotton production that is cotton growing without having to take high risks should form an important mile stone in cotton R&D. The bollworm resistant transgenic cottons introduced in 2002 have since then brought significant increase in area under cotton from 9 m to 11.5 mha, production from 2.7 mt to 6.7 mt and average yield of lint from 300 kg ha^{-1} to 540–570 kg lint ha^{-1}. The new technology also reduced the environment pollution considerably and increased the incomes and profitability to the cotton growers. It is imperative that cotton farmers are relieved of their high risks and enabled to earn decent prices and profits. Costs of all inputs including labour have escalated in all field operations. Programs and policies such as promoting mechanization, rehabilitation of irrigation systems, adoption of improved technologies, rain water harvesting and recycling, strengthening of extension, reducing risks in cotton production can play a vital role in achieving sustainably higher levels of production with assurance of stability of performance in the next decade and successive future decades.

6.9. Sustainable cotton production is required for balancing the economy and environment. The core sustainability challenge is to improve (double and further) our cotton yield without further increasing the area under cultivation. High density planting systems using varieties is an option for sustainably increasing or improving yields and also improves the input use efficiency. More research is required into multiple cropping systems for Bt-hybrids to improve biological diversity and achieve production stability. Drip system is an option to efficiently use the scarce irrigation water and policy support and stakeholder focus to disseminate drip is highly recommended since more than 62% of the cotton area is cultivated under rain-fed conditions.

6.10. Promoting mechanization in cotton cultivation seem a logical choice especially when the country is wishing for improvements in the quality of fibre, yields, farm productivity and determined to address labor concerns. Picking operation is plagued by child labour issues and thousands of children often young girls are forced to pick cotton every season. Policy can have a significant play on speed of harvest mechanization by encouraging research, robust extension support and financial incentives for growers and ginners. Growing interest for value addition to co-products like cotton stalks will necessitate innovations in cotton stalk pulling mechanization.

6.11. In the wake of spiraling labour demand for cotton during peak harvest, mechanical picking of cotton seems logical and necessary from multiple perspectives. Use of harvest aids like defoliants is a pre-requisite for mechanical picking and preserving high fibre quality. Harvest-aid materials are complicated to use and requires robust policy, research and extension support. It is important to resource the efforts in developing and adopting defoliation techniques ideal for cotton grown in sustainable systems.

6.12. Hybrid cotton and especially transgenic hybrid cotton seed production is highly labor- intensive and cross pollination is the main activity that accounts for90% of labor used in seed production. Focus on developing viable seed production technologies like CMS, GMS and TGMs can reduce the labor demands and will bring cheer to the farmers and seed industry alike and also sustainably address social issues like child labor. TGMS system may be exploited for *desi cotton* hybrids, if it proves advantageous. This will include choosing ideal locations for TGMS based seed production systems for commercial success.

6.13. TMC helped immensely in upgrading our ginneries. However the present DR (Double Roller) Gins are not energy-efficient. Policy and research support is critical for sustainably lowering the energy requirements of gins in future periods. Potential strategies to lower gin energy includes engineering interventions, developing robust quality standards for gin machinery, and crop improvements to reduce fibre-seed attachment force. Genotypes with reduced fibre-seed attachment force have the potential to be ginned faster with less energy resulting in lower cost and less fibre damage.

6.14. Cotton is at present sold on the subjective assessment of quality by the collection agent and at gin level; lint (bale) is not classified. Marketing cotton primarily as lint rather than as seed cotton will have several advantages. Quality-based marketing of cotton using fibre data helps providing the cotton growers with remunerative prices and enable spinner to minimize variation in yarn (fibre) quality from lot to lot. Advanced countries like Australia, Brazil, China, Uzbekistan and the USA have either fully implemented or are very close to fully implementing instrument-based classification of 100% of their cotton crops and ICAC has also recommended the same for all cotton growing countries.

6.15. At the current level of cotton yields, India produces about 12 mt. of cotton seeds, which are rich in oil (16–20%) and protein (13%) and their effective usage is handicapped by the presence of toxic chemical Gossypol that prevents its use in human consumption without refining and de-gossypolization. Technologies today exist to significantly reduce cottonseed gossypol levels in a stable and heritable manner. Research and policy support to reduce the gossypol levels in commercial varieties and hybrids adds value to the co-products of cotton seed oil and protein and has the potential to increase the net returns to the farmers, edible oil refineries using cotton seed and provides substantial quantity of edible oil and high energy protein for human consumption. The linter obtained cause good value addition and commands good export markets.

6.16. Technologies like novel biomass destruction and enzyme saccharification offer efficient ways of capturing value from cotton co-products like cotton stalks. Conversion of biomass to high volume, low value products like biofuels, bio-chemicals, and bulk food products offer sustainable post-harvest processing opportunities. Recovering low-volume, high value products like tocols, sterols from DOD and protein isolates and hydrolysates from cotton meal will help create new value to stakeholders. Technologies mentioned are developed at DBT-ICT Centre for Energy Biosciences at Mumbai and are being evaluated at commercial scale. Cotton stalks can be broken down into lignin (power), glucose (HFS) and xylose (*Xylitol). Cotton stalk biomass has been demonstrated for raising edible mushrooms, production of biogas and valuable wood blocks for making furniture and construction materials as proved by the CIRCOT Mumbai.

6.17. Special efforts are required to grow ELS cottons especially Supima type cottons, Organic cotton and naturally coloured cotton types with superior quality and stability of performance are required for special uses in textiles and special arrangements are required for their production and processing.

6.18. Effective coordination of various entities already established for R&D and extension and all other commercial aspects involving farming, input industries, processing and marketing agencies and the various industrial segments connected with spinning, weaving, knitting, garments under the various ministries will be ensured with a unity of purpose to make India globally topmost and competitive in all respects.

6.19. Knowledge-driven transgenic solutions to problems are on the anvil. Hundreds of candidate trait genes identified namely - Biomass yield-Plant architecture-Tolerance to environmental stresses-Nitrogen use efficiency-Disease resistance and are identified and evaluated and Monsanto has pledged to produce seeds that would double yields of cotton by 2030 and that would require 30% less water, land

and energy per unit of yield to grow. Similar expectations are there from Dow by playing with genes of economic benefits and yield enhancement.

6.20. Training of women farmers from cotton growing villages is a future strategy for introducing high technology adoption and participation in mechanization of farm operations. Training in Agricultural Mechanization of farming for youth, especially women with skills and contractual business of operations in cotton is a new development initiated by Tractors and Farm Equipment Limited (TAFE), Chennai in 2013–14. Close on the heels of the success of its lab-to-land initiative to train the farming community, India's second largest tractor company TAFE has decided to extend the program to women peasants. A pilot project to train women farmers in farm management - soil conservation, pest management, yield improvement, tractor driving and implement usage will soon be launched; TAFE conducted sessions on best farm practices leveraging technology and equipment. Over 350 farmers, including women farmers, participated in a day-long program. To encourage farmers to accelerate the pace of development in fulfilling the national task of achieving self-reliance in crop production, TAFE has a mission is to lead farming communities at the local and national levels towards sustainable, organic stewardship of land, food and fiber while respecting nature, upholding social justice and protecting natural resources.

7. Advantage of High Technology Orientation of Cotton Farming

Cotton farming in India is being carried out under challenging diversity. Being a long duration crop with continuous flowering habit, it somehow survives under several constraints from fluctuating and highly erroneous rainfall pattern and pest dynamics of a high order by not disappointing the farmers completely unlike many other crops. No other country like India would have undertaken such massive research and development on cotton under the state department research centres from 1901AD and under the State Agricultural Universities (SAUs) and the All India Coordinated Cotton Improvement Project (AICCIP) and several other special R&D Projects since 1960s. The Central Institute for Cotton Research (CICR) established in 1976 with a southern regional station at Coimbatore representing the south zone and one in Sirsa (Haryana State) representing the north zone has evolved several cost effective technologies. The Central Institute for Research on Cotton Technology (CIRCOT) at Mumbai has been monitoring the quality of fibre in genotypes proposed for release from time to time and also evolved guidelines in management of quality during production, harvesting and post-harvest handling and processing of seed cotton. From 1970 through 2014 till date, the private seed companies' prominent ones numbering around 40 have played a significant role in developing hybrid and transgenic cotton hybrids and meeting the 100% demand for quality seeds of proprietary hybrids year after year. A small role has also been played in cotton development by Mill industry and trade body cotton development and research associations.

Technologies, which have emerged from the integrated research approaches have yielded valuable information on successful management of various constraints and indicated the highest potential for doubling the yield levels compared to the present national average yield of 540 to 570 kg lint ha^{-1}, besides the co-product seed yield of 1100 to 1200 kg ha^{-1}. These however are achievable subject to unanimous adoption of all the package of prescribed situation-specific technologies all over the cotton growing farms of the country. However, since these have been neglected and implementation is sporadic rather than concentrated and systematic, India with the largest area of 12.6 mha under cotton is still lagging behind China, Australia, Brazil and other countries in national average yield.

8. Changes Useful in Implementation of Advanced Cotton Farming

Recent changes mentioned below have come in handy for effective implementation of advances in cotton farming:

8.1. Over 93% area of 12.6million ha is grown to a single and high yielding *Gossypium* species namely *G. hirsutum* and India has achieved correspondence with all the major cotton growing countries in predominance of this cotton species in world cotton farming.

8.2. The huge losses in cotton farming in India have occurred from the most serious pest of the bollworm complex led by *Helicoverpa armigera* followed by pink bollworm *Pectinophora gossypiella,* spotted bollworm *(Earias vitella)* and the tobacco cutworm*Spodoptera spp.* Since 2002–03, the cultivation of the Bt-hybrid transgenic cottonsin the form of BG-I and BG-II have by and large helped to almost completely mitigate this loss and harvest at least 35% higher outputs without hassles of many pesticide sprays, environmental pollution and higher costs on plant protection. This is one excellent proven technology and its adoption for over a decade now has helped to nearly double the yield from 300 kg lint ha^{-1} in 1999–2000 to 540–570 kg ha^{-1} as in 2014–15. However, the technology adoption as a wholesome package has been wanting in many respects and only about 20–30% of the elite farmers could get high benefits. Wholesome approach to production technology consolidation has been delaying expected or potential yield gains in India in the last one decade.

8.3. An input that can double or treble the yields is water coupled with proper soil and nutritional management. Rainwater harvesting when it pours heavily, its scientific conservation and recycling to the cotton crop after cessation of rains or intermediate drought periods is a proven technology recommended by the FAO, CICR (ICAR) and state agricultural universities in highly rain-fed cotton growing states. For irrigated area cotton crop, the advanced technologies in water management especially drip irrigation, fertigation through drips, alternate furrow or skip irrigation, soil mulching with in situ crops and ex-situ leaf mulching and increased Water Use Efficiency (WUE) have been developed and demonstrated to save water as well to enhance the yield and quality of fibre. Even sprinkler irrigation is recommended in certain areas. Soil preparation demands good adoption of recommended practice like soil chiseling once in 2–3 years to get rain-water soaked in to the sub-soil and retain soil moisture for longer time. All these technologies are very much proven to benefit the farmers, but are rarely adopted only by a few farmers.

8.4. Optimum plant density and plant stand is essential for maintaining high yields. Ever since hybrid cotton was introduced in the 1970s, for various reasons the casualty was plant population and the plant stand per ha was often limited to planting of 10,000 seeds only ha^{-1} (1.125 kg ha^{-1} de-linted seeds) and getting a plant stand ranging from 9000±plants ha^{-1}. Only in the last 5 years, the farmers have been encouraged by the seed industry to increase the plant population by 60 to 100% more with transgenic cotton hybrids. Many farmers reported higher yields of about 30 to 50% in efficiently managed fields of cotton crop. These have not gone into adoption faithfully and constraints for adoption by farmers have not been investigated.

8.5. Planting time and planting technologies also offer significant gains in crop outputs. Timely planting in ideal conditions is an important requirement. CICR and SAUs have developed advanced sowing technology ahead of the rains, sowing along the contours at 0.2%–0.4% gradient, transplanting of transgenic hybrids by raising the seedlings 3–4 weeks in advance in plastic bags or paper cups and planting as soon as rainfall is received and a few other modifications in rain-grown cotton areas like Vidarbha, Marathwada, Karnataka, MP, Gujarat etc. These have not gone into adoption faithfully and constraints for adoption by farmers not investigated.

8.6. Planting the best suited genotype in specific regions as tested by the developers is often ignored and farmers resort to too many genotypes in their fields leading to wrong gene deployment strategies.

8.7. Several encouraging propositions are available to double and even the triple the current national average yield level and maximization of united efforts in the Identified some key result areas is essential. Development of an institutional mechanism for driving cotton research and cotton farming especially in areas, where the farmers do not have adequate opportunities for accessing modern technology and scientific methods of cotton cultivation especially through Frontline Demonstration (FLD) programs, high density planting to improve yield and quality etc. India is set to surpass China as world's top cotton producer with harvest estimated at 6.74 mt (40 plus million bales) in the season 2014–15 as against 6.22 mt estimated for China and China is also prioritizing on food crops.

8.8. Internet based easy to understand and practice educational aids and Courses for cotton farmers with unique contents and modules to upgrade the skills of the farmers will bring in the required national level integration in cotton farming by ingenious ways of clustering of farmers in individual villages or Mandals can help integrated technology adoption and reaping the benefits using the digital revolution.

Superior management practices developed by the agricultural research institutions in the country have demonstrated the high potential for yield explosion and ease of adoption in various agro-ecological situations, vide Table 1.

9. Undue Yield Disparity between Countries

Cotton yield had been more than one tonne of lint per hectare in only Australia, China (Mainland), Greece, Israel, Spain, Syria and Turkey. For almost two decades cotton yields have been the highest either in Australia or Israel (±2 t ha^{-1}). India, with the largest area devoted to cotton, is among one of the lowest yielding countries in the world even after the large scale adoption of transgenic cottons than in any other country in terms of area. India has only less than 40% cotton irrigated unlike most other countries. New hybrid genotypes of the 21st century (since 2002–03) have shown lint yields of ranges 1100 to 2100 kg ha^{-1} under experimental trials and still higher under competitive conditions. Indian cotton breeder achievement in terms of genetic potential for yield is none the less inferior to advanced countries; Genotype Improvement and yield realization i.e., Recoverable Yield Potential (RYP) is much low because of poor technology adoption and crop management practices. Cost of production per kg lint varies widely on account of wide yield disparity among farmers across fields and regions and the same is due to huge gaps in wholesome technology adoption and the percentage of farmers adopting all advocated practices much low. The National average yield as at 2007–08 was 560 kg lint ha^{-1} and 540 kg ha^{-1} in 2013–14, but production at 2014–15 is estimated by CAB at 40.0 m bales (over 6.8 mt) and somewhat higher by the industry and trade.

10. Adoption of High Density Planting System in India coupled with Machine Harvesting

Past experience may give some guidance for planning, but since other advanced countries have adopted the system coupled with chemical hastening of uniformity of maturity of crop and mechanical harvesting, India must aim to adopt the high density planting system in the near future. However, it requires adoption in suitable areas or with suitable land pooling system on voluntary basis by adjacent farmers in areas based on proof of experimentation under AICCIP & SAUs based on 3-year trials simultaneously in SAU centers and KVKs adopting suitable plant types and varieties as well as Hybrids, both with BG systems, appropriate harvest maturity hastening systems and other essentials. Some information based on past experiences in India on Plant Populations and Seed rates for varieties and hybrids (non-transgenic as well as transgenic) are presented in Table 2.

Table 1: Superior Management -Estimated Yield Enhancements from Proven Technologies

Sl. No.	Superior management practices	Expected additional yield % over conventional	Effective demonstrated technologies
1.	Water use efficiency & soil moisture management based on newly recommended situation and location-specific technologies	50%	Soil chiseling once in 2–3 years, in-situ & ex-situ mulching Rainwater harvesting and recycling, drip or sprinkler irrigation systems adoption,
2	Good quality seeds of superior and reliable brands and use of adequate seeds to secure sufficient plant density	60–80	Highly efficient genotype with good fibre quality, proper genotype deployment within a region,
3	Planting technologies for optimum plant population density and planting architecture for proper aeration and light intensity	40–60%	higher plant density of 30–50% with recommended plant spacing and planting methods such as on 0.2% contour gradients, raising seedlings in advance and transplanting, dry sowing, etc.
4	Vegetative and reproductive period crop management in terms of IPM, IRM, soil and fertilizer management	60–70%	Most critical for pest management, growth and reproductive structures management and overall high yield and fibre quality.
5	Best harvest practices and post-harvest handling inclusive of mechanization wherever feasible	40–60%	Mechanization at various stages of cotton farming from land preparation to harvesting has become an urgent necessity in the present and visualized future scenario. Many constraints are overcome
6	Scientific processing of produce and quality management techniques	25–35%	Quality is of paramount importance in cotton production and scientific practices will help to secure high quality produce
7	Regular training to equipping farm youth of both sexes in mechanization, soil, fertilizer, IPM, IRM & scientific water management technologies, product quality maintenance etc.		
8	Quality-based marketing of cotton and strive for organizing scientific ginning and handling practices and direct sales as lint	15–20%	Improvement in quality of produce and therefore higher incentives in prices offered to farmers
9	Pooling of resources of networked framers in establishing linkages with textile mills and input suppliers for securing various benefits in input and output prices and technical guidance.	Overall benefits in income, profits and quality	Provides good linkage and higher income levels to farmer and quality lint to the textile mills
10	Taking advantages in co-products like seed and linters, besides crop biomass after picking of cotton is completed	10–20% higher income to farmers	Due to value added products industrial developments will be accelerated

Gujarat was the first state to show significant adoption of improved water management and large scale adoption and successful production of Bt. (GM)-cotton boosting the yield levels and profits of the farmers (especially the success story of water harvesting and micro-irrigation projects in the dry regions). The rapid spread and yield enhancement from Bt-cotton technology in India and elsewhere indicated clearly that farmers are realistic. Cotton farmers realized the advantages and enabled the cotton boom in India by preventing pest attacks, reducing costs and making cotton farming more remunerative than earlier. Punjab farmers frustrated by cotton pests and abandoning cotton returned to cotton farming vehemently due to increased benefits from new gene technologies.

Cotton in Australia is an example of highly technologically advanced farming system. Cotton requires different

Table 2: Yield and Genotype Improvements over the Years and Plant Populations

Genotypes	Period of data or observation	Seed rate	Estimated plant population ha^{-1} after thinning operations	National average yield of lint (kg ha^{-1})	Reported highest yields lint
Varieties (Non-transgenic)	1950s–1960s	15–18 kg acid delinted seed ha	40,000 to 60,000 ha^{-1} @ one plant & even sometimes two per hill	160	600–800 kg ha^{-1}
Varieties (Non-transgenic)-plant population experiments in TN and other states	1960–1970 (no hybrid Vigor & No transgenic protection from Bollworms	Spacing 75, 60 & 30 between Rows×10,20 & 30 cm within rows with I, 2 & 3 plants per hill	25–35% higher than normal population & higher fertilizer applications	Selected locations only	No significant differences in yields from the plant population trials with minor increases
Non-transgenic (H×H) hybrid cotton	1970–2001 Hybrid Vigour tapped to maximize boll load $plant^{-1}$	1.12 kg delinted seeds ha^{-1} (rarely up to 2.0 kg ha^{-1})	12,000 to 15,000 plants ha^{-1}	450 kg ha^{-1}	1100–1450 kg
Transgenic H×H hybrid cotton	2002–2014 in over 93% national area of 12.6 mha	1.12 kg ha^{-1} (Normal) to 1.68 kg ha^{-1} (assuming 50% higher seed rate)	25–35% higher plant density than non-transgenic hybrids	570 kg ha^{-1} (540 kg ha^{-1})	1200–1750 kg ha^{-1} (some reports 2100 kg ha^{-1})

NB: National authorities and Seed Industry have to consider the advantage of varieties rather than hybrids as the better alternative for high density planting system, since the yield $unit^{-1}$ area is more important with higher populations rather than yield maximization $plant^{-1}$ with lower plant density under hybrid technology.

approaches in different agro-climatic regions of Australia and the country has improved the water use efficiency by 40% in 2004–2014 and the yields are around 10 bales ha^{-1} (2270 kg lint plus 4540 kg seeds ha^{-1}).

Hence, the potentiality for more than doubling the current National average yield of cotton in India within a decade period is great and a suitable plan may be implemented nation-wide to achieve the goal.

11. Suggested Novel Workable Plan for Indian Cotton Farming

Suggested novel workable plan of voluntary landholdings integration for cotton alone for nationwide adoption of all proven technologies on a Cooperative-Contract System on seasonal basis without affecting Legal ownership of Land Holdings:

The limitations for large scale farms are primarily ownership of small farms and land legislations standing in the way of quick consolidation. Advanced countries like USA, Australia, Brazil and even certain African countries with per cotton farmer's land holdings are high as a result of which mass production technologies are easily adopted with advantage. Hence India has to overcome this shortcoming by ingenious ways of consolidation without affecting land ownerships for which a plan of action is suggested below:

11.1. The total area under the country is 12.6 mha in cotton at present and that could be assumed to stabilize at 10m. ha in the most optimum land holdings sooner or later due to additional importance required for food production to maintain food and nutritional security of the nation in the era of emerging climate changes and resultant effects on farming. Cotton crop should also be grown in more suitable locations only.

11.2. These 10 mha could be suitably grouped in to 5000 to 6000 cluster farms of cotton, each cluster varying from 2000 to 3000 ha range, depending on contiguity, state and regional borders and soil types and fertility, rainfall patterns and farmers' compatibilities and concurrences for mutual and national benefit with incentives derived from such grouping. With Experts' support, the Village Level Workers (VLWs) will attend to this demarcation and each cluster will have about one field assistant per 500 ha in each cluster and maintenance of block-wise records. Each farmer also may be encouraged to maintain a record for his landholding area and general scenario.

11.3. The entire cotton season crop production will be monitored and guided by the local agricultural officers, cotton experts or consultants. VLWs and contractual service providers like for example, private seed companies (whose genotypes are deployed in the cluster concerned), fertilizer distributors, plant protection chemical and equipment suppliers, irrigation management tools and equipment like drip systems or sprinkler systems as per area needs, Tractors and harvesting machinery companies, Nationalized Banks, NABARD as well as Gramin Banks of the area, Ginning and Pressing Factories in consultation with farmer clusters and the textile mills agreeing to procure the cotton at incentive prices etc. Textile Mills interested in procuring the cotton in the various clusters shall also guide the farmers and ginners in the area to production for quality maintenance of cotton without contamination etc.

11.4. All other minor details may be worked out by holding initial and mid-term meetings of all stakeholders in each cluster and determining the best action plan and adoption of latest technologies and those proven technologies and a concrete plan to involve all farmers in technology adoption in a wholesome manner and reaping full benefits.

11.5. Cotton availability is no issue now, but the Cotton Producers' voice should be strengthened for sustainability and increasing production and global and domestic prices of cotton should be favorable and economical to spinners also, both should be enabled to stay with cotton production and consumption respectively for cotton industry to be viable. Cotton production and Textile industry have been traditionally labor-intensive, but in the last few decades, we have increase mechanization and automation and still high hopes for further streamlining and shifts have been welcomed to improve the returns, reduce dependency on too much labor use and improving yield and quality of fibre and seeds.

11.6. By suitable strategies, empower rural women work-force and also deploy them in new areas of field and factory operations and deploying women in cotton farming by imparting new skills including farm operations using mechanical equipment to avoid drudgery for them besides improving their efficiency and earning capacity.

12. Conclusion and Recommendation

12.1. India is no less inferior to many advanced countries in R&D achievements under public sector, private sector seed industry and also the technological and textile institutions all over the country. The various production technologies including superior cultivars evolved based on very realistic experiments and front line demonstrations and the quantitative and qualitative improvement of lint and seed for cotton growing regions represented by various distinct agro-climatic regimes all over the country in the years till date since independence have been demonstrated to increase the yield potential and quality on par with advanced countries like USA, Australia, China and Brazil.

12.2. If the realistic evaluation is made, except for improved cultivars, the farmers' adoption rate of the recommended technologies for planting, production and processing have been awfully low, poorand inadequate, given the wide diversity of Indian cotton farming conditions. Hardly 15–20% of the cotton growers have adopted the wholesome technology in the country and those who have adopted all advanced technologies have harvested much higher yields of lint than the national averages of several advanced countries as brought out in this paper. As a result, India has lagged behind and failed to harvest the recoverable potential yield over the decades.

12.3. The urgent need is to organize the national cotton farming on a highly scientific and technology-oriented basis in a cooperative-contract farming mode without legally manipulating the ownership of holdings of the individual farmers and pooling themselves in to an integrated whole in clusters of convenient sizes on a functional basis every cotton season in association with various agencies. Pilot and commercial basis experiments by major seed companies and the Cotton Corporation of India in the last one decade have brought out that it benefits all cotton farmers in the clusters to obtain higher economic yield and the industry to get high quality cotton at reasonable prices due to higher uniform yields coupled with cost advantages and narrowing the yield gap as well as gap in production cost of lint ha^{-1} in India. Recovered potential yield levels had been observed to the extent of 5–70% higher under this system. Replicating this model will prove a dynamic action for India.

12.4. The constitution of a National Cotton Board of India (NCBI) by integrating the various organizations and involving public-private sector participation and entrusting the planning, monitoring, guidance and effective execution would help speed up the progress and improve cotton farming, trade and textile industry greatly for the mutual benefit. By these, India can achieve its goals on highest yield and high quality of cotton lint and cottonseeds and their effective utilization.

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