

Bt cotton (*Gossypium* sp.) in India and its agronomic requirements - A review

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ABSTRACT

India has emerged as a major global partner in the production, processing and trade of raw cotton and its finished products. The genetically modified Bt cotton, containing the *cry* gene sourced from the soil bacterium *Bacillus thuringiensis* sub-species *kurstaki*, providing resistance against boll worms, represents a landmark in cotton research and development. The large-scale adoption of Bt cotton by Indian farmers in a span of 7 years is the power of this technology. Introduction of the Bt gene has altered the morphological, phenological and physiological characteristics of these introgressed cultivars. The development and commercialization of Bt cotton varieties like BN Bt and incorporation of herbicide tolerance are likely to further revolutionize the cotton production scenario. To harness the benefits of the Bt cotton and to sustain their yield potential, sound agro-techniques need to be standardized. This review provides an update on the agronomic research undertaken on Bt cotton especially under the diverse growing conditions in India and the effect of these agro-techniques on *Cry* toxin expression and fibre quality parameters.

Key words: Agronomic characters, Cotton, *Cry* toxin, Fibre quality

The world cotton (*Gossypium* sp.) market is witnessing an increased concentration in its production and trading. Since the beginning of 21 century, the production and processing of cotton grew at a faster pace in Asia than the rest of the world and this trend is likely to continue in near future. While cotton is produced in about 80 countries, only 6 countries (China, India, U.S.A, Pakistan, Brazil and Uzbekistan) account for over 85% of the global supplies. During 2007-08, these countries together produced 22.36 million tonnes (m t) of lint. Among them, the South-east Asian countries *viz.*, China, India and Pakistan accounted for 57% of the world's cotton production. During 2007-08, the global area and production of cotton were 33.3 m ha and 26.3 m t respectively with a productivity of 787 kg lint/ha. During 2008-09, India had the largest area under cotton (9.37 m ha) whereas China was the leading producer (8.1 m t). With current production of 4.93 m t in 2008-09, India ranks second in cotton production after China, but, even with its best productivity of 560 kg/ha, it ranks 24th among the cotton producing countries.

Global demand for cotton is projected at 33.3 m t in 2010 which will further increase to 42.75 m t by 2020 (Sreenivasan, 2009). Currently about 6.0-6.3 m t of cotton is traded annually, with U.S.A. being the major exporter

(2.0-2.3 m t). India exported around 1.4 m t of raw cotton in 2007-08. Despite being a major producer of cotton, China continues to import around 1.5 m t of raw cotton annually to support its growing domestic demand. The share of Asia in the world cotton mill use is around 75%.

Despite a stiff competition from synthetic fibres, the share of cotton to the global textile pool is 45% (Srinivasan, 2009) and this is higher in India (65%). It provides about 85% of the raw material to almost 1,000 textile mills and also provides employment to 70 m people (Khadi, 2009) in the country. The foreign exchange earned from the export of cotton amounts to Rs 760 billion which is one-third the total foreign exchange earnings of the country (Kranthi *et al.*, 2009). Apart from fibre, cotton seed is next in importance due to its oil and protein content. The cotton seed obtained after ginning, if scientifically processed, yields 4 important by-products *viz.* linters (short fibres clinging to the seeds), hull (protective kernel coating), oil and meal (residue after extraction of oil). Around 0.9-1.0 m t of cotton seed oil is produced annually. As farmers can't use the Bt hybrid seeds for resowing, it is presumed that marketed surplus is higher than pre-Bt era. Presently in India, whole seeds are crushed and consequently the oil recovery is only 11 to 12%. The cake contains 25 to 27% crude protein which is mainly fed to cattle. The cake is also a good source of manure with 6.45-2.85-2.15 and 3.95-1.85-1.65% N-P₂O₅-K in decorticated and undercorticated cake respectively. About 20 m t of cotton stalks are generated annually

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(Srinivasan, 2009), which can be utilized for the production of particle boards, corrugated boxes, paper and other value added products. Value added products can also be obtained from linters, hulls and also the processing wastes generated during ginning and spinning.

Transgenic cotton was introduced for commercial cultivation in 1996 in the USA, Australia, China, Mexico and Argentina (James, 2006). The global adoption of transgenic cotton has risen dramatically from 0.8 (1996) to 15.5 m ha in 2008 (James, 2008). Australia, South Africa and U.S.A. planted more than 90% of their cotton area under biotech cotton and India and China planted about 75% of their cotton area to biotech cultivars (ICAC, 2009).

Impact of Bt cotton on the cotton scenario of India

The development of Bt cotton containing a genetically introgressed endotoxin gene from the gram negative soil bacteria (*Bacillus thuringiensis* Hubner) represents a significant technological landmark in the global cotton research. India, adopted this technology in 2002-03 and amongst those countries that adopted Bt cotton, it derived the greatest benefit from the insect resistance trait. Prior to the introduction of Bt cotton, about 40,672 t of pesticides were sprayed on this crop which occupied only 5% of the cultivated area (Bambawale and Jeyakumar, 2009). The insecticides were primarily targeted against the 3 bollworms- American bollworm *Helicoverpa armigera* (Hubner), pink bollworm *Pectinophora gossypiella* (Saunders) and spotted bollworm *Earias vitella* (Fabricius). In the post Bt cotton era, between 2002 and 2006, there was a reduction in the insecticides to the tune of 9,000 t valued at Rs-17,500 million (ISAAA, 2009).

The Genetic Engineering Approval Committee (GEAC) approved 5 events for commercial release in India that are *cry 1Ac* (Mon 531), *cry 1Ac* and *cry 2Ab* (Mon 15985) stacked gene event both developed by Mahyco Monsanto Biotech Limited and sourced from Monsanto, *cry 1Ac* (Event 1) developed by JK Agri Genetics Seeds Limited and sourced from Indian Institute of Technology, Kharagpur, West Bengal and *cry 1Ab* and *cry 1Ac* (GFM event) developed by Nath Seeds and sourced from China featuring fused genes and *cry 1Ac* (Dharwad event). The first public sector Bt transgenic cotton variety BN-Bt using the Dharwad event was approved for commercial cultivation in 2008.

Commercial cultivation of Bt cotton in India began in 2002-03 with 3 hybrids viz., MECH-12Bt, MECH 162Bt and MECH 184Bt (APCoAB, 2006) and in 2008 there were 274 hybrids officially approved by the GEAC. Majority of these hybrids belong to intra *hirsutum* category and the rest to the inter specific (*Gossypium hirsutum* G.

barbadense) category. The area under Bt cotton increased from a mere 50,000 ha during 2002 to 7.6 m ha in 2008-09 (Fig. 1) i.e. 82% of cotton area (ISAAA, 2009). The national cotton productivity increased by over 85% in the last 5 years, from 302 kg lint/ha in 2002-03 to 560 kg lint/ha in 2007-08 (ICAC, 2009). Recent surveys indicate multiple benefits from the adoption of Bt cotton including increase in yield, decreased production costs, reduction in pesticide use and plant-protection costs, improved population of beneficial insects, substantial environmental and health benefits to farmer along with socio-economic benefits (Ahuja, 2006; Ramasundaram *et al.*, 2007 and Monga, 2008). The other spin-offs have been a net increase in the area under hybrid cotton, transfer of cotton seed production and distribution into the private sector, higher seed costs (Dong *et al.*, 2004), emergence/resurgence of secondary pests like mealy bugs [*Phenacoccus solenopsis* (Tinslay)], mirid bugs [*Creontiades biseratense* (Distant)] and disorders like wilt and leaf reddening (Hebbar *et al.*, 2007).

Performance of Bt hybrids in India

Several studies have been made on the field performance of Bt hybrids, initially by the seed companies and later by the public research organizations and finally by independent institutions (APCoAB, 2006). The initial results indicated a 78.8% increase in the value due to yield improvements and 14.7% reduction in the pesticide costs through the adoption of Bt cotton (Naik, 2001). Initial multilocation trials conducted under the aegis of Indian Council of Agricultural Research on 3 Bt hybrids (MECH12, MECH 162 and MECH 184) indicated yield increases over the local and national checks in the magnitude of 60 to 92% and an average increase in the gross income to the tune of 67% (ISAAA, 2002). Later, several studies supplemented these findings (Ahuja, 2006; Ramasundaram *et al.*, 2007 and Monga, 2008). A survey on rainfed farmers growing MECH 184 and MECH 162 Bt cotton in Nagpur and Wardha districts of Maharashtra, India indicated that that average yield was 1,173 kg/ha in Bt as against 972 kg/ha in the conventional hybrid (Ramasundaram *et al.*, 2007). Not all reports on the performance of Bt cotton in India are positive. A survey of cotton growers in some regions of Maharashtra and Andhra Pradesh indicated that Bt hybrids yielded 15 to 17% less than the conventional hybrids (Sahai and Rahman, 2003). Such reports have opened up more comprehensive studies, examining the performance of Bt hybrids (Showalter *et al.*, 2009).

Bollgard II which produces two proteins (with *cry 1Ac* and *cry 2Ab* genes) that provide effective control of major lepidopteran pests especially the cotton bollworm com-

plex and *Spodoptera litura* (Fabricius), is being promoted as an effective resistance management strategy. Bhemanna *et al.* (2008) compared the performance of BG I and BG II at research farm, Raichur and in farmers field in Nelahal village in Raichur, Karnataka from 2006 to 07. They obtained 193 and 229 kg/ha of more seed cotton yield (SCY) in BG-I (MRC 6322) cotton in research farm and farmers field respectively when compared with BG II cotton 'MRC 7201' (3,729 and 3,765 kg/ha). Bhalerao *et al.* (2008) at Akola, Maharashtra also reported 123 kg/ha higher SCY with 'Brahma BG' than 'Atal BG II' (1,166 kg/ha), but these yields differences were statistically not significant. All India Co-ordinated Cotton Improvement Project (AICCIP) trails conducted for 2 years (2006 to 07) at 6 locations in Northern zone revealed that 'RCH-134 BG-II' produced only 1.4% higher yield than 'RCH 134 BG-I' (AICCIP, 2008). This was in contrast to the superior performance of BG II when compared with BG I cottons outside India. Therefore the utility of BG II should be reassessed both for enhanced yield advantage and enhanced pest control traits.

Soil and climatic requirements

Cotton can be grown on any soil provided water is not limiting. However, soils subjected to water logging are not conducive particularly during the early stages as it is a semi-xerophyte. It prefers a deep, friable soil with a good fertility and moisture holding capacity. Sehgal (1991) developed a soil-site suitability criteria for rainfed cotton grown on Vertisols and Vertic inter-grades using multivariate regression models and quadratic equations. A mean annual rainfall of 1,000 mm, soil depth of 60 to 100 cm,

and CaCO₃ content (nodular form) up to 20% can support a good cotton crop. The critical limit of available water capacity is 100 mm/m below which the yields are often uneconomical. Rainfed cotton gives best yields on deep, fine textured soils with a good structure. However, very fine (>60% clay) soils are sub-optimal (Mandal *et al.*, 2005). Based on these considerations, Naidu *et al.* (2006) proposed a criteria for determining the suitability of soils for cotton cultivation.

Cotton is successfully grown in India over a wide range of soil and agro-climatic conditions (Table 1) due to its morphological plasticity and a wide species/genetic variability. It adapts to diverse growing conditions by shortening, lengthening or even interrupting its effective blooming period. Rainfall, latitude and elevation are the dominant factors governing its distribution and growth. The length of the growing period, climatic and soil factors determine the biotic and abiotic stresses, actual crop duration and the ultimate yield. Cotton, being a sub-tropical plant is very sensitive to temperature. The climatic requirements for successful cotton production are: a mean annual temperature of over 15.5°C, mean annual rainfall of at least 500 mm with a favourable distribution (not a limitation for irrigated cotton), abundant sunshine (400-500 cal/cm²/day) during boll formation and boll bursting, a frost free period of at least 180 days and an altitude limit of 900 m due to its susceptibility to frost.

The optimal and cardinal limits of climatic and soil parameters for cotton production is summarized in Table 2. In Agro-eco-sub-region 10.2 (hot, dry sub-humid), Vertic Haplustepts (deep Inceptisols) were better than Typic Haplusterts (Vertisols) for rainfed Bt (Ramamurthy and

Table 1. Features of cotton growing regions in India

Zone/states	Share %		Agro climate (AESR)	Soils	Irrigated area share, species and hybrids	Rainfed area share, species and hybrids
	Area	Production				
North zone (Punjab, Haryana and parts of Rajasthan and Uttar Pradesh)	16	20	Hot, semi-arid climate with hot summers and cold winters	Entisols, Inceptisols	100%, <i>G. hirsutum</i> <i>G. arboreum</i> intra <i>hirsutum</i> hybrids and diploid hybrids	
Central zone (Madhya Pradesh, Maharashtra and Gujarat)	68	60	Hot arid (dry) to semi-arid (dry, moist) to sub-humid (dry) climate with dry summers and cold winters	Entisols, Inceptisols, Vertisols	23%, <i>G. hirsutum</i> and intra <i>hirsutum</i> hybrids	77%, <i>G. herbaceum</i> , <i>G. arboreum</i> , <i>G. hirsutum</i> , intra <i>hirsutum</i> hybrids and diploid hybrids
South zone (Andhra Pradesh, Karnataka and Tamil Nadu)	15	18	Hot arid to semi-arid (moist) to sub-humid (dry) climate with dry summers and mild to very mild winters	Inceptisols, Vertisols, Aflisols	40%, <i>G. barbadense</i> , intra <i>hirsutum</i> hybrids and inter specific hybrids (<i>G. hirsutum</i> X <i>G. barbadense</i>)	60%, <i>G. arboreum</i> , intra <i>hirsutum</i> hybrids, inter specific hybrids (<i>G. hirsutum</i> x <i>G. barbadense</i>) and diploid hybrids

Venugopalan, 2009) as well as conventional cotton (Mandal *et al.*, 2005). Singh *et al.* (2004) observed that the productivity of rainfed Bt cotton was higher on medium-deep than shallow soils. The productivity of Bt cotton in Tungabhadra project, Karnataka was high (80%) in the left bank canal area compared to that in the right bank canal area (Yeledhalli *et al.*, 2008). This was attributed the variations in soil parameters like texture, clay and organic carbon content and cation exchange capacity.

Bt cotton plant and its implication on agronomy

Agronomic performance of Bt cultivars may vary substantially from their non-Bt counterparts (Jenkins *et al.*, 1997). When a transgene is introgressed into an elite genetic background, the agronomic performance may be altered as all the donor DNA from the originally transformed line is not eliminated through back-crossing (Falconer, 1989). Additionally, a host of factors related to the transformation process and the background genotype may contribute to the altered transgenic expression and agronomic performance (Showalter *et al.*, 2009).

Bt cottons showed changes in their morphological, phenological and physiological characteristics (Chen *et al.*, 2002). In India, Bt hybrids had short stature (Mayee *et al.*, 2004), lower leaf area index (Rekha, 2007) due to smaller leaves and fewer branches (Sahai and Rahman, 2003), had shallower roots and produced less dry matter (CICR, 2002) than their non-Bt counterparts. But they were more efficient in mobilizing photosynthates to reproductive sink (Prakash *et al.*, 2008) and also in retaining more bolls particularly the early formed ones at lower nodes (Hebbar *et al.*, 2007, Rao and Alapati, 2007). Zhao

et al. (2002) observed that although Bt cotton accumulated less dry matter/plant, the accumulation rate was high as a result of early and concentrated boll retention and high fruiting efficiency. Higher sink in Bt cotton leads to lower source to sink ratio, faster senescence and crop maturity compared to the non-Bt version (Hebbar *et al.*, 2007). Sometimes, the increased assimilate demand of early high fruit retention reduces the resources for continued growth and fruiting, leading to early maturity and reduced yields (Bange *et al.*, 2008).

Inbuilt resistance to bollworm leads to retention of early formed fruiting parts and promotes earliness in Bt cotton hybrids (Mayee and Rao, 2002) to extents varying from 5 days (Rekha, 2007) to 20-30 days (Mayee *et al.*, 2004). Bartlett's earliness index was higher (0.80) in Bt hybrid than conventional hybrid's 0.67 (Deosarkar *et al.*, 2004). In another study, Shankaranarayanan *et al.* (2004b) observed a 10% increase in earliness index of Bt (0.7) than non-Bt hybrids (0.64). Even in China, the peak squaring, blooming and boll setting dates were early in Bt hybrids when compared with conventional cotton (Justic *et al.*, 1999).

Now that Bt cotton is widely adopted, special attention must be paid to its agronomic management, so as to fully harness its economic benefits, delay the process of resistance development and help production system to sustain high productivity levels. Today, the coverage under Bt hybrids in India is almost saturated and further improvement in cotton yield is possible only through agronomic manipulations (Rao and Alapati, 2007). This review provides an update on the agronomic aspects of Bt cotton with special reference to India.

Table 2. Climatic and soil requirements for upland (*G. hirsutum*) cotton

Parameter	Optimum	Minimum	Maximum	Reference
Temperature (°C)				
Germination (air)	18.0-30.0	15.0	42.0	Doorenbos and Kassam (1979), and Kulandaivelu (1980)
Germination (soil)	33.0-36.0 34.0	19.0 16.0	40.0 39.0	Arndt (1945) Tharp (1960)
Vegetative growth	21.0-28.0	15.0	43.0	Kulandaivelu (1980) Thind (2007)
Flowering and fruiting	22.0-27.0	21.0	35.0	Tharp (1960), Basinski (1963), and Sikka and Dastur (1960).
Reproductive growth				
Day temperature	27.0-32.0		38.0	Waddle (1984), Doorenbos and Kassam (1979), and Reddy <i>et al.</i> (1991)
Night temperature	20.0	12.0	27.0	
Soil texture	Fine			
Soil Depth* (cm)	100-120	50		Sehgal (1991)
Free Ca CO ₃ (%)			15-20	
Soil pH	6.5-8.0	4.5	8.5	Doorenbos and Kassam (1979)
Soil EC (dS/m)			9	Hake <i>et al.</i> (1996)

* For rainfed cotton

Tillage and crop residue management

Most studies on tillage practices also compare the effects of mulch or crop residue management and it is difficult to discuss these effects individually, hence, their effects are discussed together. Traditionally, a bullock drawn plough was employed for cultivation. Development of moldboard and disc plough led to intensive tillage and these were recommended for cotton owing to its deep rooting nature (Kairon *et al.*, 2002). Tillage practices vary according to region and soil type. In rainfed Vertisols of Central and South India, conventional tillage (CT) practice involves deep ploughing once in 2 to 3 years followed by harrowing and planking (Blaise and Ravindran, 2003). Inter-row cultivation is also done 4 to 6 times, with a bullock drawn blade hoe. In sandy loams of North India, seed bed is prepared by disking twice followed by two cultivator passes and planking (Jalota *et al.*, 2008). Tillage practices are not likely to be different for Bt hybrids.

Intensive tillage operations are energy consuming, accelerate soil erosion and loss of soil organic C and nutrients. Consequently, conservation tillage (CsT) systems are evolved. These systems became acceptable only after the availability of selective herbicides. Cotton is a low residue producing crop and CsT increases the amount of residue remaining after harvest. It (CsT) is a system which leaves a minimum of 30% residue cover on the soil surface and soil disturbance is reduced. Retention of crop residues increase plant available soil water by way of increased infiltration and reduced evaporative losses. This is of great significance in rainfed situations, where the crop depends on rainfall and water stored within the soil profile.

Due to a wide diversity in soils, climate, species and cultivars grown in our country, no single CsT system is applicable. In the rainfed regions of Central India, CsT systems *viz.*, reduced tillage (RT) have been found to be equal or better than CT systems in yield (Blaise and Ravindran, 2003 and Blaise *et al.*, 2005). In a long-term tillage experiment at Nagpur, Maharashtra, Blaise (2008) observed that the RT was better than CT in 7 out of 11 years. The Asiatic cotton (*G. arboreum*) were found to perform well under the CT than the RT, whereas converse was true for the upland cotton (*G. hirsutum*). Differences in maturity and rooting habit probably contributed to the 2 species differing in their tillage requirement. The upland Bt hybrid performed better with the RT than CT (Blaise, 2008). In the irrigated cotton-wheat sequence of North India, Jalota *et al.* (2008) reported maximum productivity of cotton-wheat with RT (23-39% higher yield) than no-tillage system. Yield improvements with the RT systems could be due to either or a combination of factors: (i) better weed control and reduced competition to natural resources (Blaise and Ravindran, 2003), (ii) con-

served soil moisture, better water extraction and (iii) improvements in soil physical and chemical properties (Causarano *et al.*, 2006).

Clean cultivation is the prevalent practice in all the cotton growing states. Cotton crop residues are removed off the field and are either used as fuel or disposed off by burning to facilitate tillage and reduce pest incidence (Prasad and Power, 1991). Very little crop residue remains after cotton is picked. Furthermore, cotton crop residue is of poor quality (wide C/N ratio, high lignin content) and decomposes very slowly (Blaise and Bhaskar, 2003). Decomposition rate of the Bt and non-Bt cotton crop residue did not differ significantly (Lachnicht *et al.*, 2004).

In the sandy loams of North India (Sirsa, Haryana), incorporation of shredded cotton stalks and wheat straw resulted in a 0.2 t/ha higher yield than their removal (Bhaskar *et al.*, 2002). In an earlier study in the cotton-wheat system, Shekhawat and Singh (1985) reported higher SCY where wheat straw was mulched over the no-mulch treatment. Under rainfed conditions, recycling cotton stalks lowered SCY significantly than recycling cotton leaves and cotton leaves and stalks in a 1:1 proportion (Blaise and Ravindran, 2003). Decomposition of the wide C/N ratio material can be hastened by incorporating microbial cultures like *Trichoderma viride* (Babou *et al.*, 2005).

Cotton is a low residue producing crop and it is difficult to maintain a 30% ground cover in a monocrop as is prevalent in rainfed Central and South India. Planting a cereal or legume cover crop is an option. However, cropping during off season is not possible in the rainfed regions. But during the crop season an *in situ* green manure can be raised and later left as mulch (Venugopalan and Tarhalkar, 2003). This not only protects the soil from the impact of rain drops and reduce erosion but also improves soil water storage and thus crop productivity.

Among the chemical properties, tillage influences organic matter content and nutrient availability (Prasad and Power, 1991 and Causarano *et al.*, 2006). Howard *et al.* (1999) reported a vertical stratification of P and K in cotton grown on the silty loam soils of USA. In Vertisols of Nagpur, Blaise (2003) reported a horizontal and vertical stratification of soil organic carbon (SOC) and nutrients. SOC declined with depth and was significantly more in the intra-row than the inter-row. RT treatments had more SOC in the inter-row than the CT treatment.

Crop establishment

Proper crop establishment and a good crop stand is a pre-requisite for realizing good yield. Crop geometry and in turn seed rate depends upon the nature of the cultivar,

soil, its depth, fertility, and implement available etc. (Venugopalan and Blaise, 2001). Being expensive, a single Bt cotton seed is dibbled at 3-4 cm depth. Wherever crusting is a problem, this seed is dibbled along with a seed of pulse/castor/sunhemp to facilitate emergence and later the extra non-cotton plant is clipped off. It is also recommended to raise seedlings in a nursery using trays or plastic cups and use them for transplanting wherever gaps arise (TMC, 2008). In the Yellow River Valley, China, transplanted Bt cotton yielded 31% more than the direct seeded one (Dong *et al.*, 2005).

The early maturity and resistance to bollworms should offer more flexibility in planting time and make Bt cotton hybrids suitable for delayed planting (Sankaranarayanan *et al.*, 2004b). However, there is little research evidence from India to confirm this. Limited reports from AICCIP indicated that a 20-day delay in sowing caused a reduction in the yield of Bt cotton by 18% at Surat, 22% at Khandwa (Singh *et al.*, 2008) and 31% at Dharwar (AICCIP, 2009). However, Prakash *et al.* (2008) observed that a 10-day delay in sowing time (from the optimum date of 12 August) did not significantly affect the SCY of Bunny Bt and RCH 2 Bt in the winter irrigated tract of Southern zone. Under delayed sowing condition (1 October), Bt hybrid (MECH 162) performed better with enhanced yield (42.3%) over non-Bt hybrid (Sankaranarayanan *et al.*, 2004b). When sowing is delayed, leaves of Bt hybrids had a higher concentration of reducing sugars compared to their non-Bt counterparts up to 140 days at Surat (AICCIP, 2009).

The sowing time recommended for non-Bt cotton is also recommended for Bt cotton. Mid-May is optimum time for sowing of irrigated cotton in the entire North zone. In Central zone, recommended sowing period for irrigated areas of Maharashtra and Madhya Pradesh is 15 to 25 of May. Second fortnight of March is the optimum time for Deccan canal tract of Maharashtra. For rainfed cotton, last week of June to first week of July is the optimum period in Vidarbha and Khandesh regions of Maharashtra and Adilabad region of Andhra Pradesh. Sowing is commonly done in second fortnight of June in Gujarat and Marathwada region of Maharashtra coinciding with the onset of monsoon. In South zone, second fortnight of April to first fortnight of May and second fortnight of July to first fortnight of August is recommended for sowing in Ghataprabha and Tungabhadra tracts of Karnataka, respectively. Winter and summer irrigated cotton of Tamil Nadu are sown between August and January-February respectively. Spring Bt cotton (sown between late February and early March) was also found promising in North zone (Ahlawat and Gangaiah, 2009).

Rainfed cotton is sown in the South zone from mid to end of June in Karnataka, second fortnight of July to first fortnight of August in the coastal districts of Andhra Pradesh, August to September in drier central districts of Andhra Pradesh and mid September to first week of October in black soil area of Southern Tamil Nadu. The high temperature between September and October in Srirangapatna than Abhoar, was found to cause forced boll opening (*Tirak*) in Bt cotton (Sekhon *et al.*, 2008) that needs to be managed through evolving proper planting schedules.

The compact growth habit of Bt hybrids provides an opportunity for closer spacings to accommodate a higher plant population. Due to mobilization of nutrients to the developing bolls, the vegetative growth is restricted and the canopy size reduced, offering scope for planting Bt cotton at higher densities. Farmers were not willing to adopt this, because Bt hybrid seeds were expensive (Ramasundaram *et al.*, 2007) and increased seed rates to accommodate higher plant population may not always be profitable.

Rapid adoption of hybrid Bt cotton has reduced seed costs over the years and this in turn, kindled an interest increasing plant population for maximizing yields both in China (Dong *et al.*, 2005) and India (Rao and Alapati, 2007). Hybrid cotton seed production is dependent upon labour-intensive emasculation and pollination, which enormously increases the seed costs (Dong *et al.*, 2004). To strike a balance between increased seed cost and increased profits through additional plant population, several trials were conducted at different AICCIP centres and elsewhere and their results are summarized in Table 3. The release of new Bt cotton variety BN-Bt (with *Cry IAc*), developed jointly by Central Institute of Cotton Research, Nagpur, University of Agricultural Sciences, Dharwar, Karnataka and National Research Centre on Plant Biotechnology, New Delhi for North, Central and South zones of the country in 2008 may address the issue of high cost of Bt hybrid cotton seeds as the farmers will be able to reuse the seeds.

Ultra narrow row (UNR) cotton (planting in 30 to 50 cm rows) is an economical means to increase cotton production efficiency (Atwell *et al.*, 1996). It is not advisable to adopt this technique in Bt hybrids in India where the seeds are still exorbitantly priced. However, several studies with Bt indicate the scope for narrowing inter- and intra-row spacing in Tamil Nadu (Sankaranarayanan *et al.*, 2004a), canal command areas of North Western Rajasthan (Nehra *et al.*, 2004), Bathinda, Punjab (Buttar and Singh, 2006), Karnataka (Vishwanath, 2007) and Akola, Maharashtra (Bhalerao *et al.*, 2008). Bt cotton hybrids

Table 3. Optimum crop geometry for Bt hybrids

Zone	Bt hybrid	Location	Spacing (cm)	Reference
North	RCH 134	Faridkot, Punjab (I)	90 x 67.5	Singh <i>et al.</i> (2007)
	RCH 134	Ludhiana, Punjab (I)	100 x 75	Singh <i>et al.</i> (2008)
	RCH 134	Hisar, Haryana (I)	67.5 x 60	AICCIP (2009)
	RCH 134	Bathinda, Punjab (I)	67.5 x 90	Buttar and Singh (2006)
	RCH 317	Bathinda, Punjab (I)	67.5 x 75	Buttar and Singh (2006)
Central	RCH 2	Khandwa, Madhya Pradesh (R)	90 x 60	Singh <i>et al.</i> (2008)
	RCH 2	Indore, Madhya Pradesh (R)	90 x 60	Singh <i>et al.</i> (2008)
	RCH 2	Nanded, Maharashtra (R)	90 x 60	Khargharate <i>et al.</i> (2008)
	RCH 2	Akola, Maharashtra (R)	90 x 45	Bhalerao <i>et al.</i> (2008)
	RCH 2	Rahuri, Maharashtra (I)	90 x 90	Singh <i>et al.</i> (2008)
	RCH 2	Surat, Gujarat (R)	120 x 45	AICCIP (2009)
	RCH 2	Nagpur, Maharashtra (R)	90 x 45	Singh <i>et al.</i> (2007)
	RCH 2	Junagarh, Gujarat (I)	120 x 45	AICCIP (2009)
	RCH 2	Parbhani, Maharashtra (R)	60 x 60	Giri <i>et al.</i> (2008)
	RCH 2	Parbhani, Maharashtra (R)	60 x 60	Giri <i>et al.</i> (2008)
South	Bunny	Guntur, Andhra Pradesh (R)	90 x 30	Narayana <i>et al.</i> (2008a)
	Bunny	Adilabad, Andhra Pradesh (R)	60 x 60	Sree Rekha <i>et al.</i> (2008)
	Bunny	Siruguppa, Karnataka (I)	90 x 60	AICCIP (2009)
	Bunny	Warangal, Andhra Pradesh (R)	90 x 30	Reddy and Gopinath (2008)
	Bunny	Dharwar, Karnataka (R)	90 x 90	AICCIP (2009)
	Bunny	Siruvilliputtur, Tamil Nadu	90 x 45	Srinivasan (2006)

* I: Irrigated; R: Rainfed

with tall, erect and open plant type with shorter sympodia were more amenable for planting at a closer spacing of 90 cm × 30 cm (Rao and Alapati, 2007). The Bt cottons would be ideal for high density planting in India.

Cropping systems

The GEAC has made it mandatory to plant 5 rows non-Bt isogenic line or a synchronous (phenology/agronomy) non-Bt version at the border as refugia for every acre of Bt hybrid planted. As a partial modification of this regulatory requirement, the GEAC has now permitted planting strip crop of pigeonpea as a refugia. This strip cropping of cotton + pigeonpea, a widely adopted system in Central India (Blaise *et al.*, 2005) will continue even with Bt hybrids. The earliness associated with Bt hybrid could be exploited to design more efficient cotton-based cropping systems. Introduction of Bt cotton also gives scope for raising some short duration sequential crop wherever supplemental irrigation is available, to increase production efficiency and land use efficiency (Narayana *et al.*, 2008 c). Research in these directions indicated that Bt cotton and lady's finger (*Abelmoschus esculentus*) intercropping produced the highest seed cotton equivalent and land equivalent ratio and cost benefit ratio (Sankarnarayanan *et al.*, 2004c). Inter-cropping of cotton with vegetables is also common in the South zone. To offset the inconsistency in the performance of vegetables and economic losses due to constant fluctuation in the

prices of vegetables, multi-tier intercropping with vegetables of different durations and growth habits is recommended. One such system (Bt cotton + radish + amaranthus) at Coimbatore (Tamil Nadu) provided very high seed cotton equivalent yield (4.35 t/ha) when compared with SCY of 2.19 t/ha by sole cotton and benefit cost ratio of 2.9 (Sankarnarayanan *et al.*, 2008). Similar yield advantages with spring Bt cotton intercropping with mungbean were reported in North zone (Ahlawat and Gangaiah, 2009).

Raju (2008) identified some innovative intercropping systems like cotton + marigold, cotton + radish, cotton + maize and cotton + cluster bean for black soils of Nagpur. Studies under the Technology Mission on Cotton (TMC) identified cotton + beans (1:1) and cotton + coriander (1:2) in normal planted cotton and cotton + beans (1:3) in paired row planting for Northern Karnataka (rainfed) and cotton + green gram (1:3) or cotton + pigeonpea (4:2) or cotton + soybean (1:1), cluster bean in 1:1 cotton + maize (green cobs) and cotton + marigold on black soils of Central zone (TMC, 2008).

On black soils of Guntur, cotton followed by field crops like sesamum and maize or horticultural crops like cucumber or watermelon + fenugreek were promising (Narayana *et al.*, 2008b). For irrigated tract of Maharashtra, Bt cotton followed by bengalgram/okra was promising whereas for black soils of Karnataka irrigated Bt cotton followed by vegetables (ridge gourd and to-

mato) or field crops (maize and pearl millet) was promising. In the north zone, even with Bt hybrids, cotton-wheat system remained more efficient and profitable than either cotton-barley or cotton-mustard systems (TMC, 2008). Spring Bt cotton + mungbean-baby corn (Ahlawat and Gangaiah, 2009), Bt cotton+groundnut/soybean-wheat (Ramanjeet Singh *et al.*, 2009; Seema Sepat and Ahlawat, 2009) systems were found promising in North zone. The earliness associated with Bt hybrids ensures timely sowing of the succeeding wheat crop and enhanced wheat yields (Mayee *et al.*, 2008).

Nutrient management

The large-scale cultivation of Bt cotton is likely to usher in an era of eco-friendly cotton cultivation with reduction in the number of insecticidal applications. However, to sustain the benefits of Bt cotton, a sound nutrient management programme is essential. While 60 to 90 N kg/ha

et al., 2004a). Fertilizer response was observed up to 135: 29.5:56.0 kg N: P: K/ha for the summer irrigated Bt cotton hybrids at Srivilliputtur (CSM, 2005). Significant differences were not observed in SCY in the first picking but, in the second picking, 125% RDF resulted in significantly higher yield when compared with RDF (Singh *et al.*, 2003). Vishwanath (2007) reported significantly higher SCY with 150% RDF (2.42 t/ha) as compared to RDF (2.14 t/ha). In MECH 162 and RCH 2 Bt hybrids, 125% RDF recorded significantly higher SCY as compared to RDF of 120:26.4:50 kg N:P:K/ha (Kalaichelvi, 2009). On the contrary, field trails at Guntur in Andhra Pradesh (Narayana *et al.*, 2008a), Dharwar in Karnataka (Hallikeri *et al.*, 2004) and Warangal in Andhra Pradesh (Reddy and Gopinath, 2008) did not indicate any significant yield increase by applying nutrients beyond RDF. On vertic Ustropepts of Coimbatore, Bandhopadhyay *et al.* (2009) observed 60 kg N/ha as optimum dose for high yield and

Table 4. Response of Bt cotton hybrids to fertilizer application

Locations	Soil	Nutrient	Optimum dose (kg/ha)	PFP*	AE**	Reference
Srivilliputtur (I)	Sandy clay loam	N	100	15.2		Srinivasan (2006)
Coimbatore (I)	Red loam	N	90	24.5	4.4	CICR (2008)
Bathinda (I)	Sandy loam	Zn	10	382.0	81.2	Brar <i>et al.</i> (2008a)
Guntur (R)	Clay	N	120	23.9		Srinivasulu <i>et al.</i> (2006)
Warangal (R)	Clay	N	120	28.0		Reddy and Gopinath (2008)
Parbhani (R)	Clay	N	100	21.1		Giri <i>et al.</i> (2008)
Punjab (I)	Sandy loam	K	60	50.0	1.83	Brar <i>et al.</i> (2008b)

*PFP, Partial Factor Productivity (seed cotton yield, (kg/ha/nutrient applied kg/ha); **AE, Agronomic Efficiency [(yield at opt dose-yield in control)/nutrient applied]; I: Irrigated R: Rainfed

was adequate for conventional hybrids in most of the locations except Gujarat, Bt cottons are slightly more responsive to N application (Table 4). Moreover, Bt cotton had a higher N content than non-Bt cotton suggesting that they may have a greater N uptake and metabolism than non-Bt cotton (Showalter *et al.*, 2009).

Systematic trials are being conducted under the AICCIP at 17 centers across the 3 zones to elucidate whether the existing fertilizer recommendations need to be modified for Bt cotton. Results (Table 5) indicated at least a 5% improvement in Bt cotton yield with 125% recommended N: P: K fertilizer dose (RDF) than the dose currently recommended for non-Bt hybrids under irrigated conditions at Hisar (Haryana), Junagarh (Gujarat) and Srivilliputtur (Tamil Nadu) and under rainfed conditions at Nandyal (Andhra Pradesh), Surat (Gujarat), Dharwar (Karnataka) and Indore (Madhya Pradesh).

Application of 150% of the RDF *i.e.* 135: 29.5:56.0 kg N: P: K/ha was on par with 125% RDF (Sankaranarayanan

Table 5. Response of Bt cotton to NPK application (mean of 2006-07, 2007-08 and 2008-09)

Location	Yield (kg/ha)			% increase over RDF at 125% RDF
	75% RDF	RDF	125% RDF	
Faridkot (I)	2,897	3,159	3,274	3.7
Ludhiana (I)	3,010	2,753	2,813	2.2
Hisar (I)	2,926	3,448	3,658	6.1
Sirganganagar (I)	2,794	2,856	2,873	0.6
Khandwa (R)	1,616	1,921	1,975	2.8
Indore (R)	1,301	1,358	1,438	5.9
Nanded (R)	2,018	2,291	2,444	6.7
Junagarh (I)	1,992	2,190	2,338	6.8
Surat (R)	2,604	2,571	2,708	5.3
Akola (R)	682	873	910	4.2
Rahuri (I)	2,256	2,370	2,462	3.9
Guntur (R)	3,087	3,373	3,339	-
Coimbatore (I)	2,384	2,401	2,436	1.5
Dharwar (R)	1,860	2,187	2,349	7.4
Srivilliputtur (I)	1,529	2,133	2,255	5.7
Siruguppa (I)	1,720	2,123	2,180	2.7

I: Irrigated R: Rainfed

N use efficiency in RCH 2 Bt. For Bt cotton on sandy loam soils of North zone, Brar *et al.* (2008a) recommended a dose of $N_{150} P_{22} K_{25} + Zn_3$ kg/ha and substitution of 25% of the above recommended dose of N through FYM was found significantly superior to RDN alone for Bt cotton in this zone (Ramanjeet Singh *et al.*, 2009). For summer irrigated tract of Sirivilliputtur, 100:22:41.6 kg N:P:K/ha was the optimum dose for MECH 162 and MECH 184 hybrids (Srinivasan, 2006). Further research is needed to confirm these findings. Moreover, it is not yet clear whether the yield advantage in Bt hybrids is a result of a more efficient nutrient uptake or an efficient utilization of nutrients already taken up or a combination of both. Incidentally, in conventional hybrids the enhanced yield was primarily due to a higher uptake efficiency (Venugopalan *et al.*, 2007). In northern transitional zone of Karnataka, to obtain a targeted SCY of 3 t/ha in MRC-6322 Bt cotton, 217:59:148 kg N:P:K/ha was found optimum (Patil *et al.*, 2009).

Fertigation studies in Bt cotton indicated that the application of RDF (NPK) and 125% RDF through drip were at par and were superior to 75% RDF in all the 3 cotton growing zones. Thus, if fertilizers are applied through drip (fertigation), additional dose above the recommended (soil test based) may not be necessary to sustain Bt cotton production (TMC, 2008).

In North China plains, the transgenic cultivars were more sensitive to K deficiency than the conventional cultivars and Zhang *et al.* (2007) attributed this as a reason for the premature senescence of Bt cotton on K deficient fields. On farmers' fields in Mansa, Bathinda, Muktasar, Faridkot and Moga districts of Punjab, irrigated Bt cotton hybrids 'RCH 134 and RCH 317' responded to soil application of K up to 41.6 kg/ha on soils testing low or medium in available K and there was no response on soils with high available K (Brar *et al.*, 2008b). Further, foliar application of 2% KNO_3 during boll development phase increased the seed cotton yield irrespective of the soil K status and K fertilizer applied.

For Bt hybrid (Bunny) grown under rainfed conditions on Vertisols of Agro-eco sub-region 10.2, split application of K along with N did not offer any yield advantage over splitting of N alone and hence the entire recommended quantity of K may be applied as basal dose. For high yield and high N utilization efficiency (27 kg seed cotton/kg N uptake), N may be applied in 3 equal splits at 10, 45 and 75 days after sowing (DAS) in a year of normal rainfall and at 10, 30 and 60 DAS in a drought year (CICR, 2009). Late application of N and K may delay the senescence (Dong *et al.*, 2005) and reduce yield of Bt cotton.

Studies on the effect of secondary and micronutrients on Bt cotton are few and it is likely that the results from

non-Bt versions will be valid on Bt cotton also. Ca and Mg do not constrain cotton productivity since cotton is grown on soils having pH 6.5 to 8.5. However, an excess of exchangeable Ca leads to Mg deficiency resulting in leaf reddening. Foliar spray of $MgSO_4$ (1%) is often recommended as a corrective measure. In the intensively cultivated North zone, S is becoming a major yield limiting factor and in recent years response to S application is commonly observed. On alluvial soils there was a response to direct application of 30 kg S/ha in cotton-wheat (Singh *et al.*, 2004), cotton-sunflower (Singh and Kairon, 2001) and cotton-mustard (Singh *et al.*, 2004) systems.

Positive response to soil application of 15-25 kg $ZnSO_4$ or foliar spray of 0.5% $ZnSO_4$ was reported from Hisar in Haryana, Faridkot and Ferozpur in Punjab (Rana *et al.*, 1984) and Delhi (Prasad and Prasad, 1994). Multi-location trials conducted under the Technology Mission on Cotton indicated SCY increases ranging between 73-322 kg and 54-210 kg/ha with the application of Zn and B respectively (Blaise 2006a). Application of Zn and B also increased the recovery and use efficiency of primary nutrients (Blaise 2006a). Boron plays a significant role in the fertilization, flowering and fibre development and its deficiency increased boll shedding. Earlier, there were some reports of response to foliar spray of 0.1 to 0.2% borax on coarse textured soils of Punjab (Brar *et al.*, 1983) with non-Bt cotton varieties. A field study conducted at Bathinda during *kharif* 2005-06 on Bt cotton in a zinc deficient soil (0.35 mg/kg soil) indicated that zinc sulphate was superior to zinc oxide (Brar *et al.*, 2008a). Further, drill method was significantly superior to broadcast application of Zn and zinc @ 10 kg/ha increased the yield by 47.6 and 17.6% in 2005 and 11.8 and 7.2% in 2006 over 0 and 5 kg Zn/ha, respectively.

Water and Soil moisture management

The consumptive use of water for cotton ranges from 650 to 1,100 mm for different places / different varieties, depending on the duration, soil and climatic conditions *e.g.* North India 700 to 750 mm, Gujarat 900 to 1,100 mm, Madhya Pradesh 660 to 685 mm, Karnataka 800 to 900 mm and Tamil Nadu 650 to 750 mm etc. (Sivanappan, 2004). Cotton is irrigated 2 to 13 times depending upon the soil, season, climate and crop duration etc. The number of irrigations in the North zone (sandy loam soil) range between 2 and 5, whereas in Tamil Nadu farmers give irrigation up to 13 times. Depending upon the number of irrigations, the irrigation requirements vary between 140 to 330 mm in North zone and 200 to 730 mm in Central zone and 500-700 mm in South zone. Crop requires about one-third of seasonal water use of 70-120 cm during initial growth till flowering and the rest during

flower and boll development. The break up of water use/day at different phases of the crop under normal condition is 3.8 mm water/day up to 1st flower, 8.9 mm water/day up to peak bloom and 5.1 mm water/day from the last bloom up to harvest (Kairon *et al.*, 2002). The crop water requirement is 20% till 1st flower, 40% during 1st flower to peak flower, 30% during peak flower to bursting of bolls and the balance 10% till maturity. Early maturity of Bt cotton may reduce its water requirement leading to saving of at least 1 irrigation. Trials conducted under the TMC with Bt hybrids indicated that drip irrigation at 0.8 or 0.6 ETc in semi-arid and sub-humid eco-regions of Parbhani and Nagpur (Maharashtra), Dharwar (Karnataka) and Surat (Gujarat) and at 1.0 ETc in arid to semi-arid eco-regions of Abohar (Punjab), Sirsa (Haryana) and Akola (Maharashtra) was optimum for obtaining high SCY, water use efficiency (WUE) and fertilizer N UE (TMC, 2008). On a vertic Ustropept at Coimbatore for winter irrigated cotton (RCH 2 Bt), Bandhopadhyay *et al.* (2009) observed that a protective irrigation at planting and 7 and 45 DAS provided maximum WUE and water productivity (WP) and the SCY was similar to that obtained with irrigation at 0.6, 0.8 or 1.0 IW/CPE. In the North zone (Delhi), Bt cotton receiving irrigation at 0.6 IW/CPE ratio proved promising from productivity and economics point of view (Ahlawat and Gangaiyah, 2007). Moreover, both WUE and WP decreased significantly with increase in the level of irrigation.

Effective management of soil moisture would be crucial in consolidating the productivity gains offered by the introduction of Bt cotton in rainfed areas. Contour bunding is an effective soil and water management system to reduce run off and soil erosion, while increasing infiltration of rainwater. Other soil moisture conservation practices include graded, narrow or broad ridges or beds separated by furrows. Forming beds (120 to 180 cm wide) and furrows on a grade for *in situ* water harvesting is found to be efficient in deep black soils with a rainfall of 700 to 850 mm (Venkateswarlu, 1980). Ridge and furrow method of water harvesting is a proven method to increase cotton yield under rainfed condition by improving the soil moisture availability. Among other techniques, there was a significant increase in SCY with black polythene mulch (25 micron) when compared with non-mulched cotton (Nalayini *et al.*, 2004). Opening of furrows after every row of cotton between 30 and 45 DAS and spreading of crop residue mulch were found to be promising in Maharashtra (Giri *et al.*, 2008). Among the *in situ* soil moisture conservation techniques tested in sole cotton, opening of furrows in every row after the last interculture recorded highest WUE of 3.15 kg/ha-mm (Shinde *et al.*, 2009). In Bt hybrids, straw mulching and bio-mulching

with sunnhemp were superior to opening furrows in alternate row in improving WUE at Akola and Nagpur (Maharashtra), Khandwa (Madhya Pradesh) and Dharwar (Karnataka) (TMC, 2008).

Cotton crop management canopy manipulation

The objective of crop management is to provide the desired plant morpho-frame and protection from biotic and abiotic stress necessary for the crop to attain its genetic potential. Introduction of Bt cotton changed the vegetative and reproductive characteristics of the plant which in turn affected its yield potential and fibre quality. The introduction of Bt gene made some changes in the physiological and metabolic process for growth and reproductive organs (Tian *et al.*, 2000).

On a whole plant basis and especially on a canopy basis, any modification that can increase the rate of photosynthesis, efficiency of carbohydrate utilization or the portioning ratio has the potential to increase yield. Mechanical (nipping, square removal) or chemical (growth promoters or retardants) techniques modify plant architecture and growth pattern and improve the synthesis and reallocation of carbohydrates. Manipulation of the morpho-frame of Bt plants through foliar application of ethylene (5.7 milli molar) at square initiation stage significantly improved yield. This increase was attributed to a higher number of bolls and harvest index. Application of ethylene enhanced root activity, increased shoot length and leaf area, helped in overcoming apical dominance and encouraged sympodial branching. There was a sudden abscission in the young squares immediately following the application of ethrel resulting in an enhanced source activity and a temporal shift in the emergence of new flush of squares i.e. sink activity (TMC, 2008).

Weed management

Cotton crop is highly susceptible to competition from weeds from sowing to about 60 days, when the canopy covers the inter-row space. Cotton yields were reduced by 50 to 85% with unchecked weed growth or ineffective weed control (Rajendran and Jain, 2004). Often, incessant rains in spells make the mechanical weeding impossible particularly in black soil regions. Under such circumstances, chemical weed control is a better option. Herbicides like alachlor, fluchloralin, pendimethalin and fenuron at pre-planting, pre-emergence and post-emergence were evaluated all over the country and no single herbicide has been found uniformly effective under all situations *vis-a-vis* manual weeding and hoeings (Rajendran and Jain, 2004). Glyphosate at 1.0 kg/ha as directed spray at 20 DAS followed by one-hand weeding at 45 DAS recorded the lowest weed dry matter and nutrient uptake by

weeds (Nalayani *et al.*, 1999 a,b). Fluchoralin at 1.0 kg a.i./ha or pendimethalin @ 1.5 kg a.i./ha as pre-planting application along with one inter-culture at 35 DAS consistently performed better in the control of weeds and is currently recommended (Rajendran and Jain, 2004).

Herbicide tolerant (genetically modified) cotton (HRC) offer broad spectrum weed control which may encourage farmers to adopt reduced tillage practices. The glyphosate resistance weed management system is an effective alternative to the conventional methods, requiring less herbicide and fewer applications to produce the same yield and net economic return (Culpepper and York, 1998). The Roundup Ready (RR) Flex cotton that provides increased tolerance to glyphosate is accepted in many countries and this technology is being tested in India by Monsanto India Ltd. in its cultivars MRC 7351 II Bt and MRC 7347 II Bt. However, there are apprehensions that large-scale cultivation of HRCs and indiscriminate use of the herbicide may lead to the development of herbicide resistant weeds, especially if wild relatives of crop plants are growing in the vicinity. The wild relatives of cotton that have been reported are *Gossypium tomentosum* in Hawaii and *Gossypium stocksii* in India. Moreover, resistance of weeds to glyphosate has already been reported (Van Gessel, 2001). The relevance of HRCs on small and fragmented farm holdings of India is, however, contentious. The supporters advocate that the new technology is scale-neutral and its benefits should be made available to Indian farmers. Others believe that HRCs are not suitable to Indian conditions and pose serious threat to the employment and livelihood opportunities of farm labourers, and will also adversely impact environment, ecology and biodiversity.

Effect of soil, climate and agronomic manipulation on Cry protein expression

The expression of Bt gene is influenced by environmental conditions and variation between places reported (Sachs *et al.*, 1998). Insecticidal protein was significantly lowered when crops were exposed to high temperature (Chen *et al.*, 2005), salinity (Jiang *et al.*, 2006) and nutrient deficiencies *viz.*, nitrogen (Coviella *et al.*, 2002 and Rochester, 2006). *Cry* toxin expression was more in Bt cotton hybrids grown on deep Vertisols because of their high plant available soil water than the shallow soils (CICR, 2007). Rochester (2006) reported significant decline in *Cry* toxin when the crop was exposed to a single 4-day episode of drought. But waterlogged conditions adversely affected *Cry* toxin expression to a greater extent compared to moisture stress. Adamczyk *et al.* (2001) found that *Cry I Ac* toxin concentration in 2 Bt cottons declined as the season progressed and there were consistent and significant differences in the toxin levels between the two. In China, the

effect of Bt cotton toxins was found at a higher level in the early season (Zhao *et al.*, 2000 and Zhang *et al.*, 2001). The toxin content in Bt cotton changed significantly over time and that depends on the structure, growth stage, and variety (Wan *et al.*, 2005). There exists a temporal and spatial variation in *CryIAc* expression (Kranthi *et al.*, 2005) and its expression ranged between 0.01 and 19 µg/g in various plant parts. The highest Bt expression was in leaves at 75 DAS and declined during later growth periods. The proportion varied with different hybrids. The expression levels were also highly variable in different plant parts with the highest concentration in young leaves and the least in boll rind, buds and flowers. Yet, pest control efficacy was not affected by variability in expression up to 100-115 DAS. In seed, there was no significant reduction in bioactivity of toxin stored in room temperature for 2 years (Kranthi *et al.*, 2005).

Hallikeri (2008) reported higher *Cry* toxin expression with early planting (June) than delayed planting (July and August). Rochester (2006) observed higher toxin expression with higher plant density (20 plants/m²) than the commercial planting density (8 plants/m²) in Australia. Higher toxin expression in soils well supplied with nutrients was observed in India and elsewhere. In Australia, application of fertilizer N significantly increased *Cry* toxin content (Rochester, 2006). Bruns and Abel (2003) observed a positive correlation of *Cry* toxin content with whole plant N concentration in Bt maize crop. It is conferred that increased available N likely increases Bt α-endotoxin- synthesizing proteins and thus increase the Bt α-endotoxin concentration. Pettigrew and Adamczyk (2006) reported that split application of 112 kg N/ha exhibited 14% greater *Cry I Ac* concentration than a single basal application. Similarly, N applied in 7 splits (5,043 ng/g) had higher *Cry* toxin concentration than 4 splits (4,066 ng/g) and the recommended method (3,583 ng/g) of application (Hallikeri, 2008). Under rainfed conditions of Nagpur, Maharashtra, 3 splits of N along with 2 or 3 foliar-N sprays increased *Cry* toxin concentration when compared with the farmers' practice and N applied in 2 splits (CICR, 2008). Direct effect of P application in toxin expression is not known. Rochester (2006) did not observe any change in toxin expression with K application. An integrated nutrient management (INM) strategy involving organic manure and recommended dose of fertilizer (RDF) recorded highest levels of *Cry I Ac* protein (1.9µg/g of seed) followed by farmyard manure alone (1.75µg/g of seed). Vermicompost (VC) application resulted in 1.14 µg/g of seed *Cry I Ac* protein while RDF + VC recorded reasonably higher level of *Cry I Ac* protein of 1.66 µg/g of seed (Hosmath *et al.*, 2004).

Bt cotton-fibre quality

The increase in productivity alone could not benefit the cotton growers as quality of cotton fibre is the primary concern for fetching higher price (Sreenivasan, 2004). Jenkins *et al.*, 1991) in the first field test of transgenic cotton lines reported that fibre properties were in the range of the adapted non-Bt cultivar. The quality parameters *viz.*, 2.5% span length, maturity ratio, uniformity ratio, micronaire, fibre elongation and fibre quality index were not different in Bt hybrids compared to their non-Bt counterparts (Sankaranarayanan *et al.*, 2008). Similarly, Ethridge and Hequet (2000) could not find any differences in micronaire, uniformity ratio, strength and elongation measured in high volume instrument as a result of transgenic technology. From Dharwad under protective irrigated condition, Hallikeri *et al.* (2004) reported that quality parameters were not influenced by Bt gene (Table 6). Similar results were reported by Halemani *et al.* (2004), Shankaranarayanan *et al.* (2004b) and Deosarkar (2004). There were no major differences in micronaire, yellowness, uniformity ratio, strength and elongation due to transgenic technology (Ethridge and Hequet, 2000).

In cotton about 80% of the variation on fibre length is governed by genetic factors. On the other hand, 60% and 80% of the variability in micronaire and colour grades respectively are controlled by environmental factors (Bradow, and Davidonis, 2000). With respect to fibre quality, effects of tillage have been inconsistent. Constable *et al.* (1992) and Blaise (2006b) reported no changes in fibre quality under different tillage treatments. On the other hand, Boquet *et al.* (2004) reported small but significant improvements in the fibre quality of the no-till compared to the conventional tilled cotton. N application increased fibre length and strength (Constable and Hearn, 1981) but decreased micronaire (Ebelhar *et al.*, 1996). But, Pettigrew (1996) reported that N application had no effect on fibre length or uniformity. K deficiency reduces the photosynthate available for the reproductive sinks and fibre quality reductions are associated with K deficiency and reduced leaf K levels (Read *et al.*, 2006). K application increased fibre length and

micronaire (Cassman *et al.*, 1990) and fibre strength. Fibre micronaire and its components *viz.*, fibre maturity and fibre perimeter were lower in K-deficient plants (Pettigrew, 1999) and fibre maturity index and micronaire were increased with K application (Pettigrew *et al.*, 1996). Application of two-third of the recommended K dose through soil and the remaining as foliar spray improved yield and fibre quality parameters (Bhatt, 1996) compared to soil application alone. Similar responses to foliar application of KNO_3 was observed with Bt hybrids at Surat and Junagarh, in Gujarat (AICCI, 2009).

Ansingkar *et al.* (2005) observed no difference between Bt and non-Bt hybrids with regard to ginning out turn and halo length. But Mayee *et al.* (2004) reported that Bt hybrids exhibited higher ginning% over their non-Bt counterparts. Thus, fibre quality parameters of Bt cotton hybrid may in general be similar to those of non-Bt cotton hybrids with few exceptions. Bandhopadhyay *et al.* (2009) did not observe any significant influence of N application or irrigation on fibre quality index of winter irrigated 'RCH 2 Bt' cotton on Vertic Ustropepts of Coimbatore. However, Singh *et al.* (2008) observed a marginal improvement in the fibre quality of Bt hybrids on rainfed vertisols when micro-nutrients (Zn and B) were supplemented to the recommended NPK.

Around 80 to 85% of the cotton area is now under Bt hybrids and this acreage has perhaps saturated. The morphological and physiological changes in these introgressed Bt cultivars offer an excellent opportunity for agronomic manipulation. Further improvement in the production and productivity of cotton and cotton-based production systems can only be expected by fine tuning its agronomic practices. Agronomic recommendations are also needed to redress source-sink mismatch related disorders like leaf reddening, pre-mature senescence and para-wilt which have re-emerged in pockets following the large scale adoption of Bt cotton. The evaluation of herbicide resistant cotton also needs to be taken up on priority. New sources of resistance to bollworm need to be explored and incorporated. Transgenics with tolerance to sucking pests

Table 6. Seed cotton yield (kg/ha) and quality parameters in Bt and non-Bt hybrids

Parameter	Yield	2.5% span length (mm)	Uniformity ratio	Micronaire value	Maturity (%)	Strength (g/tex)	Elongation (%)
MECH 184 Bt	2,183	29.13	46.33	3.85	66.93	24.17	5.58
MECH 184 non Bt	715	29.30	45.83	3.72	65.48	23.07	5.60
MECH 162 Bt	1,912	25.16	47.83	3.67	66.17	19.18	5.87
MECH 162 non Bt	1,077	24.50	48.50	3.82	66.43	18.75	5.83
MECH 12 Bt	1,935	27.53	48.17	3.53	65.07	23.95	5.13
MECH 12 non Bt	634	27.95	48.17	3.68	65.77	22.97	5.67
CD (P=0.05)	647	1.38	1.36	NS	NS	0.20	0.34

Source: Hallikeri *et al.* (2004)

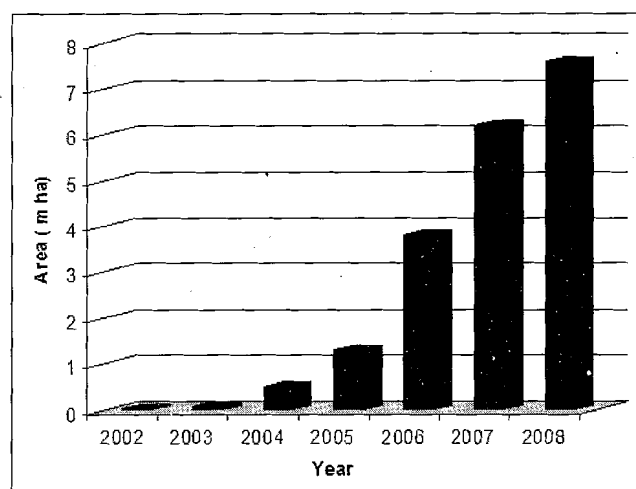


Fig 1. Adoption of Bt cotton in India.

and abiotic stress (drought and salinity) with improved fibre traits are likely to come up in future. Development and promotion Bt varieties instead of hybrids may reduce prohibitive seed costs. The spread of Bt cotton may limit the scope of organic production systems. Several opportunities for enhancing yields with Bt cotton have been documented but some more intensive studies followed by adaptive trials are needed before popularizing these agro-techniques.

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