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Review/Overview

Introduction of Bt cotton hybrids in India: Did it change the agronomy?

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ABSTRACT

The introduction and subsequent rapid adoption of Bt. transgenic cotton hybrids (*Gossypium* species) have undoubtedly been the most significant event in the history of cotton in India. Besides providing resistance against lepidopteron pests, the Bt. hybrids matured earlier, were more determinate, had a rapid leaf area development, retained more early set fruiting forms and perhaps have a shallower root system. Both researchers and farmers during the last decade have been fine-tuning the agronomy to maximize the benefits from Bt cotton. Some prominent changes accompanying this technology have been, compulsory seed treatment with imidachloprid, advancement in sowing wherever supplemental irrigation was available, a delay in sowing in the traditional rainfed till the soil profile absorbs sufficient moisture, application of atleast 25% higher fertilizer dose, shift towards balanced fertilization, foliar application of K and micronutrient mixtures. Adoption of drip irrigation and fertigation, more widespread use of booth pre-emergence (pendimethalin) and post-emergence herbicides (quizalofop ethyl and pyrithiobac sodium), practice of stale seed bed technique for weed management, pruning and extension of crop duration are some other agro techniques which are being adopted by Bt. cotton farmers.

***Key words**:* Asiatic cotton, *Bacillus thuringiensis*, *Gossypium* species, Transgenic, Upland cotton

Cotton belongs to the genus Gossypium of family Malvaceae. Of the 50 species, only 4 are cultivated, namely *G. arboretum* L., *G. herbaceum* L., *G. hirsutum* L. and *G. barbadense* L. *Gossypium arboreum* and *G. herbaceum* are diploids (2n = 26) and are popularly known as the *desi* cottons. Both *G. hirsutum* and *G. barbadense* (2n = 4x = 52; AD genome species), evolved in the New World and are referred to as allelotetraploids or amphidiploids and are popularly known as American or upland (*G. hirsutum*) and Egyptian or Pima (*G. barbadense*) cottons. India is the only country in the world where all the four cultivated species of cotton are grown on a commercial scale besides hybrids (both inter and intra specific).

Historically, the Asiatic *desi* cottons were cultivated with minimal external inputs. In the fifties, the *G. hirsutum* cotton, popularly known as the American cottons, varieties were being promoted. The first hybrid was introduced in 1970 by C. T. Patel. The technology was a great success and it revolutionized cotton cultivation (Basu and Paroda, 1995). The biggest change in cotton cultivation was witnessed after the *Bacillus thuringiensis* (Bt) cotton hybrids were introduced in March 2002. The area planted with Bt cotton hybrids increased from a meagre 50,000 ha in 2003 to more than 11.2 million ha in 2011–12. At present it occupies more than 92% of the total cotton acreage (Fig. 1).

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Genetically modified (GM) cotton

The first genetically modified Bt cotton was developed by transferring the *cry1Ac* gene from the ubiquitous soil bacterium *Bacillus thuringiensis* (Perlak *et al.,* 1990). The

Fig. 1. All India cotton acreage (million hectares) and lint production (million bales) over 1950-51 to 2011-12

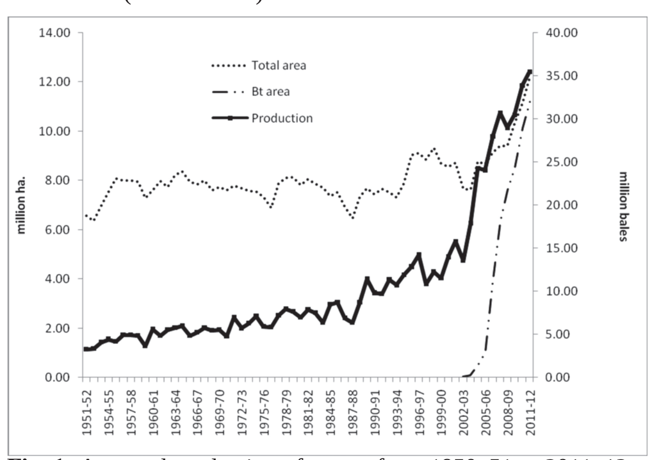

Fig. 1. Area and production of cotton from 1950–51 to 2011–12

insertion of these genes enables cotton (Gossypium sp.) plant cells to produce crystal insecticidal proteins, commonly termed cry proteins. The cry proteins are effective in killing the larvae of boll worms (*Helicoverpa armigera*) and tobacco budworms (*Heliothis virescens*). When the larva eats the cry proteins, its own digestive enzymes activate the toxic form of the protein. Toxic cry proteins then bind to specific receptors present on the intestinal walls and rupture midgut cells. Infected larvae stop feeding within a few hours after the first nibble, and, if they have consumed sufficient toxin, die within 48–72 hours. Bollgard–Bt cotton with *cry1Ac* was first cultivated in the US during 1996 and was released in China and Australia in 1997. Later, it was released in Mexico, Colombia, Indonesia, Argentina, South Africa, and India. Currently an estimated 18.8 million has are under Bt cotton in 13 countries. The *cry1Ac* gene (Bollgard ®) is available in cotton either alone or in combination (Bollgard II®) with a second gene, *Cry2Ab*.

Recently, several other genes such as protease inhibitors, *Vip3A*, *Cry1C*, *Cry2Ab* and *Cry1F* have been used for the development of GM cotton and are being tested used for the control of cotton bollworms and other leaf-feeding caterpillars. At present, GM cotton containing Bt toxin either *Cry1Ac* gene alone or in combination with *Cry2Ab* are commercially available in India. The first approval for commercial cultivation of Bt cotton in India was granted in 2002 to 3 cotton hybrids, 'MECH 12' Bt, 'MECH 162' Bt and 'MECH 184' Bt, developed by Mahyco (Maharashtra Hybrid Seed Co.). In 2004, one more Bt hybrid, i.e. 'RCH 2' developed by Rasi Seeds was recommended for commercial cultivation. More than 1400 Bt cotton hybrids are now available in the market (Ramasundaram *et al*., 2013).

Many different Bt cotton hybrids are made with the same gene construct. Every cell that successfully incorporates the Bt gene represents a unique "event". Different events can have varied consequences, depending upon the number of times the gene construct was added to the host (cotton) cell's genome and the site of placement of the new genes in the host genome. The event names correspond to the identifiers commonly used by regulatory authorities. At present, six events are recognized (Table 1) in the commercially available hybrids**.**

Two major changes occurred after the introduction of the Bt cotton hybrids–firstly, change in species composition (Table 2) and secondly, quantity and quality of lint produced (Table 3). Area under the *desi* cotton cultivars declined drastically and is now grown on less than 5% of the total area. Till the dawn of this century, India produced sufficient quantity of all the 4 species as per the requirement of the textile mills.

Bt cotton and productivity

It is argued that cotton productivity started increasing following the introduction of the Bt cotton hybrids in the country (Fig. 2). But was this yield increase due to the introduction of Bt hybrids alone? Did the introduction of Bt hybrids bring about a change in the agronomic practices compared to the earlier hybrids and varieties? These are questions frequently raised. In this review, we attempt to answer these questions and highlight the changes wit-

Table 1. List of the Bt cotton events approved for cultivation in India

Event name	Event number	Source company/ institution	Genes	Year of approval
Bollgard I	MON 531	Monsanto	*cry1Ac*	2002
Bollgard II	MON 15985	Monsanto	*cry1Ac* and *cry2Ab*	2006
Event 1	Event 1	IIT, Kharagpur	Truncated *cry1Ac*	2006
GFM Cry1A	GFM Cry1A	Chinese Academy of Sciences	*cry1Ab+cry1Ac*	2006
BN Bt	BNLA 601	UAS, Dharwad; NRCPB, New Delhi	Truncated *cry1Ac*	2008
9,124	9,124	Metahelix	*cry1C*	2009

Source: Karihaloo and Kumar. 2009.

Table 2. Change in cotton (*Gossypium*) species composition

Species	Per cent of total cotton area						
	1947	1970	1980	1990	2000	2007	2012
G. arboreum	65	30	20	30	17	4	4
G. hirsutum	3	53	54	48	69	90	90
G. herbaceum	32	17	14	12	11	5	5
G. barbadense	-	-	11	10	3	1	1

Source: CICR. 2011.

Table 3. Production of lint (lakh bales) of the various quality groups over decades

Year	Short (<20 mm)	Medium/medium long (20.5–27.0 mm)	Long (27.5–32.0 mm)	Extra long (>32.5 mm)
2000–01	9.50	74.0	52.0	4.5
2001–02	9.50	82.5	61.0	5.0
2002–03	9.00	72.0	51.0	4.0
2003–04	7.60	75.9	89.65	5.55
2004–05	7.11	136.8	94.07	5.02
2005–06	6.8	34.0	165.4	4.8
2006–07	6.0	54.0	216.15	3.85
2007–08	4.0	63.0	243	5.0
2008–09	3.5	60.0	222.0	4.5
2009–10	4.0	58.0	238	4.5
2010–11	4.0	71.0	259	5.0
2011–12	4.0	72.0	272	5.0

Source: Office of the Textile Commissioner, Ministry of Textile, Government of India

nessed over the years in the agronomy of cotton.

Bt cotton was developed as a crop protection technology to offer protection against boll worms (*Helicoverpa armigera*). Yield advantages of Bt over non-Bt in a number of countries was lower than those reported in our country (Qaim *et al.,* 2006; Crost *et al.,* 2007). However, in our country, the credit of yield gains was attributed to Bt alone. Gruere and Sun (2012) reported that Bt cotton contributed significantly to cotton yield growth ranging from 0.29 to 0.39% annually. Seed cotton productivity was 308 kg lint/ha in 2001–02 and 302 kg lint/ha in 2002-03 the year Bt cotton was introduced in the country (Fig. 2). In 2003–04 and 2004–05, lint yield was 399 and 470 kg/ha when the area planted to Bt cotton hybrids was hardly 1.2 and 5% respectively. It is interesting to note that when the cotton area occupied by the Bt hybrids increased to more than 90%, the productivity ranged from 490 to 510 kg/ha. If Bt hybrids alone contributed to productivity increases, one would expect the productivity level to have increased at rate similar to what was observed in the first two years after the Bt cotton hybrids were introduced. At the time when the Bt hybrids were being introduced, some new molecules of insecticides were made available on the market that offered good protection against the bollworms (Dandale *et al.,* 2000; Patil *et al.,* 2010). Another factor for yield improvements, when the percentage of Bt area was low, owing due to effective dissemination of technologies because of the Technology Mission on Cotton and adoption of improved production practices such as balanced fertilizer application; other integrated crop production packages played a role in yield increases (Gruere and Sun, 2012; ICAC, 2012). Further, area under irrigation increased considerably during this period (Ramasundaram and Vennila, 2013). It is alarming that when the Bt cotton hybrids reached a level of saturation in the country, yield levels have plateaued off. One major reason is the multiplicity of hybrids available on the market that caused a mismatch of the hybrid and the soil type on which these are cultivated (Kranthi, 2012).

Fig. 2. All India average seed cotton productivity (kg/ha) and the acreage planted to Bt cotton hybrids (million hectares) during 1950-51 to 2011-12

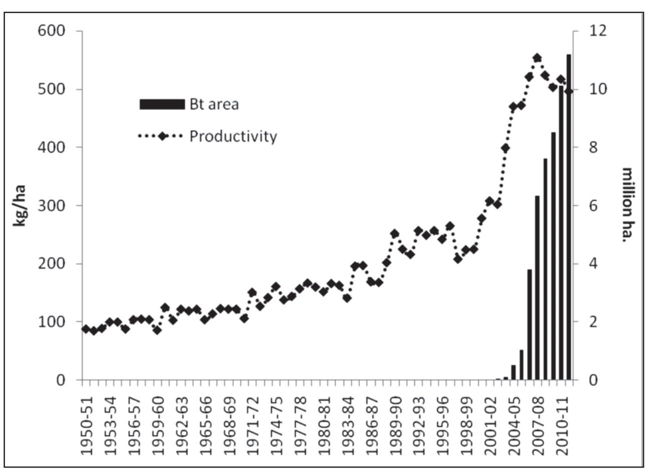

Fig. 2. Productivity before and after the introduction of Bt hybrids in India

Pre-Independence

Before the country gained Independence, the entire area of cotton belonged to our traditional *desi* cotton varieties. Most of these varieties were of long duration and were cultivated with minimal inputs because the manuring experiments did not show any significant yield improvement even to applications as low as 20 kg N/ha (Dastur and Asana, 1960). Further, high cost would not make application of inputs economical because of the low productivity. The crop was broadcast sown (Sawhney and Sikka, 1960).

After broadcasting the seeds, the fields were planked. High seed rate was used (>15 kg/ha) to ensure better germination.

Post Independence

Desi and American cotton varieties: There was great impetus to cotton research in the country after Independence. Breakthroughs were seen in the development of high-yielding *desi* cotton varieties. Further, the Agricultural Departments advocated line sowing to ensure uniform germination and facilitate inter-row cultivation. Farmers dropped the seed in shallow line furrows made by the *desi* plough (Sawhney and Sikka, 1960). Studies on the *desi* cottons indicated that they responded to low fertilizer-N dose (30 kg N/ha) (Bedeker *et al.,* 1957; Sharma, 1961). Later varieties responded to higher N application (Singh and Singh, 1971; Wankhede and Kharche, 1987). The improved *desi* cottons were found to be better responsive to fertilizers as high as 60–30–30 kg N, P and K/ha (Giri and Gore, 2006). Even the *desi* cottons grown with the use of mineral fertilizers alone over a long-term, resulted in the crop experiencing multiple nutrient deficiencies and low crop yields (Blaise *et al.,* 2007).

The crop was drill sown at a spacing of 60 cm between rows. The optimum seed rate was 8–12 kg/ha for *arboreum*s and *herbaceum*s. The improved *desi* cotton varieties also changed the planting pattern. Closer spacing was followed for 'PA 255' and 'PA 402' with planting at 45 cm between rows and 22.5 cm between plants (Giri and Gore, 2006).

Major focus of research was on developing varieties of the upland American cotton to make them adaptable to our situations. Major breakthroughs were seen with the advent of high-yielding varieties. This ushered in a new agronomy based on the type of the variety. Development of high yielding and short duration varieties such as 'Bikaneri Nerma' and 'H 777' made the introduction of the cotton–wheat [*Triticum aestivum* (L.) Emend. Fiori & Paol.] cropping system a reality in the north zone (Kairon *et al.,* 1996; Mayee *et al.,* 2008). Further, these were more responsive to inputs across cotton-growing zones and situations (Kairon and Venugopalan, 1999). Initially, more emphasis was given to fertilizer nitrogen and was fertilized at rates higher than those for the *desi* cottons. Before seventies, P fertilizer was not included as part of the recommendation as the preceding crops in rotation were preferentially fertilized. Cotton as a succeeding crop was found to benefit from this practice (Singh, 1966). Response to P started to be felt in the 70's (Ahlawat *et al.,* 1973). The optimum seed rate for *hirsutums* was 12–15 kg/ha. In general, a spacing of 60 cm × 30 cm with a plant population of 55,600 was recommended for the *G. hirsutum* varieties. Earlier varieties were considered to be more plastic and no significant differences were observed for the different plant spacing under irrigated conditions (Singh *et al.,* 1969a; Rao, 1982). However, development of compact, dwarf and early-maturing varieties made planting more amenable to closer row-to-row spacing of 60 cm × 20 cm (Prasad and Prasad, 1993). Higher plant densities were recommended under rainfed conditions, too, at Khandwa (Yadav *et al.,* 1991) and other locations. At present, plant population density as high as 1.5 to 2.2 lakh plants/ha was found to be an opportunity for increasing productivity on the shallow and marginal soils (Venugopalan *et al.,* 2011b; Singh *et al.,* 2012).

Cotton hybrids (1975-2000): C.T. Patel in 1970 was successful in developing the world's first cotton hybrid, 'H 4'. This was considered to improve and break the yield barriers as cotton production was stagnating. No doubt, the productivity potential of the hybrid H-4 was high and changed the concept of planting cotton totally.

From line planting, square planting of cotton done manually by dibbling seeds at intersections became a practice. A line marker is run at spacing as wide as 120 cm between rows and 60–120 cm between plants. This planting system became popular as it afforded criss-cross interculture mainly from an efficient weed control view point and also saved on the human labour involved for the sowing operations. Further, these were highly branched monopodial plant types that needed more space than the short, compact, non-branching sympodial plant types. However, the spacing varied based on the region, soil type and whether the crop was rainfed or irrigated (Kairon *et al.,* 2002).

Besides, changes in planting patterns, input use became more intensive. Since the hybrids were more vigorous in growth habit, they were also more responsive to fertilizers and amounts recommended were more than those for the *desi* and American cotton varieties as discussed in the previous section. Response ranged from 6 to 13 kg seed cotton/kg with a higher response under rainfed conditions (Venugopalan *et al.,* 2011a). In general, upland (*G. hirsutum*) varieties and hybrids responded better to higher doses of N than the Asiatic (*G. arboreum* and *G. herbaceum)* cultivars. Response up to 100–150 kg N/ha was observed for the irrigated cotton, whereas 60–100 kg/ha was optimum for cotton varieties grown in the assured rainfall areas.

Although the significance of balanced fertilizers in cotton was first pointed out by Qureshi (1962), it started to gain importance only after the area under hybrids started to increase. Farmers became more than willing to adopt the recommended practices. Thus, a change was seen moving from the single nutrient concept that was so common in the varietal era (Table 4). It was however, not sufficient in improving the productivity limits. Yield levels plateaued during the mid-80's and 90's due to an excessive use of synthetic pyrethroids which triggered in resistance of the insect-pests (Kranthi *et al.,* 2001). Consequently, several applications of pesticides were needed to control the bollworm. This led to the need for solutions and the genetically modified Bt cotton was developed.

Bt cotton hybrids (2002-03 onwards): A major question raised to agronomists is, did the introduction of Bt cotton hybrids bring about a change in the agronomy? However, the situation is different in our country where the Bt was introduced into the hybrids. 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 through backcrossing (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). In China, changes in morphological, phenological and physiological characteristics were reported in the Bt cottons (Chen *et al.,* 2002). Our own Bt hybrids were more compact (Mayee *et al.,* 2004), with lower leaf-area index (Rekha, 2007), as it produced smaller leaves (Sahai and Rahman, 2003). Root growth of the Bt hybrids was comparatively shallower than those of the *desi* and conventional hybrids (CICR, 2002). Hebbar *et al.* (2007) found that the Bt hybrids retained more bolls, especially the early formed ones at lower fruiting branches. This early and rapid development of bolls contributed to faster senescence and crop maturity. Because of an increased assimilate demand of early retained fruits, the growth reduces leading to early maturity and reduced yields (Bange *et al.,* 2008). Furthermore, because fruiting commences earlier in the Bt hybrids, translocation of photosynthates and assimilates to the root slows down. As a result of this, root growth ceases. This was not the case with the earlier varieties and hybrids, as (i) bollworm infestation reduced fruit load and (ii) a later fruiting habit. Thus both vegetative and reproductive growth continues simultaneously. Consequently, root growth was more vigorous. Especially, the *desi* cottons had a slow initial growth with more of the resources diverted to the root and were noted to be deep rooted (Kapur and Sekhon, 1985; Blaise 2006). In subsequent sections, the changes in agronomy are dealt with right from the sowing to harvest of the economic produce.

Seed treatment, seed rate, and sowing method

Seed treatment is a technology developed to offer protection of the emerging and young seedlings to diseases and insect-pests. The varieties grown earlier, especially of the *desi* cotton were immune to the diseases and insect-pests. Therefore, no seed treatment was followed. To a limited extent, seed treatment was adopted for the American cotton varieties and hybrids. But this was on a small scale. Treatment was usually done with Thiram. Farmers used to re-use the seed and followed some traditional treatment methods such as cowdung paste, ash etc (Sawhney and Sikka, 1960). This was also to make the seed free flowing after the lint was separated from the seed and free of insect-pest and diseases. Commercial and large scale seed treatment became popular with the introduction of Bt hybrids. Seed produced by the private sector was made available to the farmers as a treated seed. Years of research on seed treatment for protecting the crop against fungal and bacterial diseases and insect pests finally saw the light of day with the advent of the Bt cotton. This also changed the way other hybrids were marketed. Seed treatment with Imidacloprid (ca. 2.5 g/kg seed) became the most common

Table 4. Fertilizer schedules (NPK kg/ha) pre- and post introduction of hybrids

Cotton type	Rainfed/irrigated	N	P	K
Varietie				
Old *desi*	Rainfed	20-40	0	0
Improved *desi*	Rainfed	40-60	20	0
High yielding *desi*	Rainfed	40-60	20-30	20-30
American	Rainfed	60	30	30
American (old)	Irrigated	56	0	0
American (Improved varieties)	Irrigated	60	30	40
Hybrids				
American	Rainfed	80-90	40-45	40-45
American	Irrigated	120-150	60	60
Desi	Rainfed	80	40	40

Source: Ahlawat *et al.* 1973; Dastur and Gopani, 1952; Jain and Katti, 1980; Saxena, 1962; Singh and Singh, 1971; Singh *et al.,* 1966; Singh *et al*., 1969a, b.

practice. This insecticide was available by the Trade Name *Gaucho* and it became popularly known as '*Gaucho* seed treatment'.

Seed dibbling, a practice that was adopted and followed for the conventional hybrids was adopted for the Bt hybrids, too. Cost of a single Bt seed is approximately 15 paise (₹ 930/packet of 450 g seed). Therefore, a single seed is dibbled per hill compared to 2–3 seeds for the conventional varieties and non-Bt hybrids. Cost became a prohibitive factor and a reason for change in the way cotton was sown and planted. Although, seed cost was high, Bt cotton hybrids are still preferred mainly because of the ease of availability on the market and their effectiveness against bollworms (Tayade *et al.,* 2011).

Transplanting

The spacing adopted for the conventional non-Bt hybrids was adopted for the Bt cotton hybrids, too. Subsequently, agronomic research started to indicate that the Bt cotton hybrids are more compact. Therefore, closer spacing was recommended (discussed in subsequent section). This means more numbers of seed is required per hectare. Since a single seed is dibbled per hill, chances of mortality and poor plant stand are high, especially under the rainfed regions. Karve (2003) opined that transplanting is a technique for improving yields of Bt cotton under rainfed conditions, as the transplanted crop escapes heavy build up of pests compared to the hand-dibbled cotton. Earlier research with the cotton varieties indicated that crowbar method of planting and transplanting of seedlings raised in polybags to give significantly higher yields than the normal sowing with onset of monsoon (Pundarikakshudu *et al.,* 1992). This did not find favour with the farmers because either the availability or cost seed was not a limitation. Presently, farmers have taken up raising few seedlings in polybags. These were later transplanted wherever gaps were seen. Significantly higher seed cotton yield was obtained from transplanting seedlings (20–25 days old) than the farmers' practice of dibbling (Table 5). Further, under delayed sowing, transplanting could be an option as plants are better established (Salakinkop, 2011) and optimal plant stand is maintained.

Table 5. Seed cotton yield (tonnes/ha) of transplanted vis-à-vis the normal sown crop

Method	Spacing (cm)	Yield[1]	Yield[2]
Transplanting	90 × 45	3.16	
	90 × 30		3.84
	90 × 60	3.05	3.83
	90 × 90		4.26
Dibbling	90 × 45	2.61	
	90 × 60	2.55	3.27
CD (P=0.05)		0.21	0.18

Source: [1]Rao *et al.,* 2012; [2]Salakinkop 2011.

In the irrigated north zone, most often planting is delayed due to the non-availability of irrigation water. A delay in planting would adversely affect the seed cotton yield. At times, timely planting is done, but irrigated with poor quality irrigation water that is brackish. High salinity also affects the young seedlings. Therefore, transplanting was thought of as a solution to avoid delay in sowing. In Faridkot, Punjab, transplanting 20 days old seedlings raised in Farmyard manure (FYM) and soil mixture in 1:1 proportion produced seed cotton yield as good as those obtained with the normal sown crop (Singh *et al.,* 2013).

Planting time

Sowing earlier or later than the optimum period results in imbalanced apportioning of assimilates into vegetative and reproductive parts resulting in low yields. Moreover, the late-sown crop suffers due to higher incidence of early season-sucking pests and pink boll worm (*Pectinophora gossypiella*) during the boll formation. In the rainfed cotton proper time of sowing is crucial to make the full and efficient use of water available during the rainy season. In the north zone, a week's delay in sowing after the normal crop sown with the onset of rains would mean a yield loss of about 18–55% (Kairon, 1979). The sowing time for the Bt cotton hybrids remains the same as that for the conventional cotton varieties and hybrids (Venugopalan *et al.,* 2009). Due to the involvement of high seed cost for the Bt hybrids, the crop is usually planted after adequate rains are received.

Early sowing: Early sown crop has always been found to result in higher crop productivity than the delayed planting. Any delay in sowing reduces cotton yield drastically. In the rainfed areas, dry sowing was recommended for conventional varieties. But in the recent years, farmers are taking up an '*early sown*' crop in Maharashtra and Gujarat. This practice is slowly gaining ground wherever irrigation facilities exist or availability of adequate well water. Further, State Governments have embarked on a mission of rain water harvesting, soil and water conservation, and use of microiirgation systems making this practice feasible. The crop is sown in the month of May with microirrigation systems (Kumar *et al.,* 2011b). Farmers have also availed the benefits of subsidies offered by the Government. The advantage of an early-sown crop is that it escapes sucking pests that is high during July–August. Further, it is also possible to take up a timely winter season second crop (Ramamurthy and Venugopalan, 2009). Moreover, earliness was noticed in the Bt hybrids compared to the non-Bt hybrids (Singh *et al.,* 2003; Sudha *et al.,* 2011; Tayade *et al.,* 2012).

Extended crops: Novel practice such as taking an '*extended crop*' is now being followed. This practice became very popular in Chandrapur district where the trials were conducted by the IFFCO with yields as high as 9.7 tonnes/ha (IFFCO, 2013). Department of Extension Education, Rahuri, identified the practice of ratooning being followed in some areas such as Nandurbar, Dhule, Jalgaon and Ahmednagar districts of Maharashtra (Sabesh, 2012). An additional yield of 10–15 q/ha has been reported in addition to the previous harvest. However, these practices are adopted in a limited area wherever shortage of water is not faced. In the north zone, wheat is sown in the inter-row spaces of cotton. This is also called as relay cropping (DAC, 2013). Cotton is allowed to continue and not uprooted. The late set bolls are allowed to mature fully and open. By this method, farmers are able to take up timely sowing of wheat in addition to obtaining full yields of cotton. Availability of Bt technology has also spurred interest in double cropping cotton after wheat in Arkansas, USA. Earlier, this would not be recommended or even followed because late planted crop would succumb to the late season pest pressure (Barber *et al.,* 2011). Studies on the relay cropping of wheat into cotton were experimented in the Yellow river Valley of China (Zhang *et al.,* 2008). They observed an improvement in light interception, better resource-use efficiency and higher productivity. Such studies need to be planned for our situations in the cotton-wheat belt of north India.

Refugia

Another major change was the use of refugia. A Bt cotton seed packet contain a small quantity of the non-Bt seed (50 g). This is a mandatory practice and the Genetic Engineering Approval Committee has recommended sowing of 5 border rows of non-Bt cotton around the Bt cotton fields. Refugia is meant to ensure the maintenance of susceptible populations on the non-Bt crop to prevent bollworm-developing resistance to the Bt toxin (Kranthi, 2012). However, these seeds are discarded and not sown by farmers because of misconception that yield per unit area would decline and make the crop vulnerable to bollworms (Kranthi, 2012). Moreover, farmers are unaware of the benefits and the need for refugia (Sudha *et al.,* 2011). In view of this, alternate crops that could be fitted are being proposed that could serve as refugia. One such crop is pigeonpea [*Cajanus cajan* (L.) Millsp.] and it got wide acceptability because it is part of the cotton-based cropping systems in central India (Blaise *et al.,* 2005b). Likewise, other crops need to be decided for the other cotton-growing regions. Further, to enhance practicability, 5% refugia in bag (same non-Bt hybrid) may be recommended along with 5% area planted to pigeonpea (Kranthi, 2012).

Spacing and plant population

Crop geometry (spatial arrangement) and plant density significantly influence cotton yield. Considerable research work was done to determine the optimum plant population for maximum yield and quality. The population and crop geometry depend upon the plant type, soil conditions and moisture availability (Table 6). As compared to the non-Bt hybrids, closer spacing was found more suitable for realizing potential yields of the Bt cotton hybrids. This was mainly because in case of the Bt cotton hybrids, vegetative growth is restricted due to better and early retention of the fruiting forms. Thus closer spacing is ideal. Further, the Bt hybrids had compact growth habit (Mayee *et al.,* 2004; Sankaranarayanan *et al.,* 2011). Bt hybrids planted at a spacing recommended for the conventional non-Bt hybrids were found to yield less than the closely spaced crop. Thus, existing planting patterns were below optimum from the yield view point (Sankaranarayanan *et al.,* 2011). This is reiterated through field experiments at vari-

Table 6. Recommended spacing of Bt cotton hybrids across locations compared to the old conventional hybrids

Location	Bt hybrid	Spacing (cm)		Reference
		Conventional	Bt hybrid	
Bhatinda, Punjab	'Ankur 651', 'Ankur 2534'	105 × 90	90 × 67.5	Buttar *et al.* (2010)
Hisar, Haryana	'RCH 134'	100 × 60	67.5 × 60	Devraj *et al.* (2011)
Sirsa, Haryana	'RCH 134'	100 × 60	67.5 × 60	Devraj *et al.* (2011)
Hisar, Haryana	'JKCH 1050', 'JKCH 1945'	100 × 60	67.5 × 60	Kumar *et al.* (2011a)
Sri Ganganagar, Rajasthan	'RCH 134'	108 × 60	108 × 60	Nehra and Yadav (2011)
Akola, Maharashtra	'RCH 2'	90 × 90	90 × 45	Bhalerao and Gaikwad (2010)
Nagpur, Maharashtra	'Bunny'	90 × 60	75 × 60	Chavan *et al.* (2011)
Parbhani, Maharashtra	'Bunny'	90 × 90, 90 × 60	60 × 60	Pawar *et al.* (2010)
Parbhani,	'RCH 2', 'Bunny'	90 × 60		Pendharkar *et al.* (2010)
Nandyal, Andhra Pradesh	'Bunny '	90 x 60, 90 x 90	90 x 45	Aruna and Reddy (2009)
Warangal, Andhra Pradesh	'Bunny'	90 x 90	90 x 30	Reddy and Gopinath (2008)
Coimbatore, Tamil Nadu	'Bunny'	90 x 60	75 x 60	Sankaranarayanan *et al.* (2011)

ous locations in the country and is summarized in Table 6.

Spacing of the Bt hybrid is also governed by the plant architecture and type. Kalaichelvi (2009) in studies conducted with various Bt cotton hybrids in Coimbatore observed that the okra leaf type hybrid 'MECH 184' was more compact and performed better with closer spacing (90 cm × 45 cm) than those of the spreading types 'MECH 162' and 'RCH 2'. The latter hybrids performed better at a spacing of 90 cm × 60 cm. The usual recommended spacing for the conventional hybrids under irrigated conditions was 120 cm × 60 cm. Singh *et al*. (2011), in a study at Meerut, Uttar Pradesh under irrigated conditions, reported that the Bt hybrid performed better at closer spacing (67.5 x 60 cm) than its near isoline. The non-Bt hybrid required a spacing of 100 cm × 60 cm. Varied spacing is recommended across regions and hybrids as also evident from the Table 6. With a closer spacing, more bolls are produced per unit area (Venugopalan and Blaise, 2001; Blaise *et al.,* 2005b). Since yield is a function of number of bolls per unit area, seed cotton yield was greater at closer spacing than the wide row spacing recommended for the non Bt hybrids.

Tillage and crop residue management

With the introduction of Bt hybrids, there was no change in the type of tillage practices followed compared to the traditional non-Bt hybrids and varieties. In the North zone, immediately after the wheat is harvested, seedbed is prepared by two discings, and two cultivator passes followed by planking (Jalota *et al.,* 2008). All the operations are tractor based. However, in the Central zone, cultivation is still done by the bullock-drawn plough. Tillage in this zone starts with the odd pre-monsoon shower and most often with the onset of rains. The soils are deep ploughed once in three years. Before planting the soils are given light harrowing and planked (Blaise and Ravindran, 2003). In the southern red soil region, field is given 2–3 light ploughings after harvest of the previous crop. Before planting the field is prepared and levelled.

In general, clean cultivation is practiced in the cotton fields, wherein all the crop residues are removed off the field and are disposed-off by burning. This also happens to be an IPM recommendation as crop residues harbour insect-pests. Conservation tillage systems are yet to catch up in the cotton-based systems. In the irrigated north zone, reduced tillage systems for cotton (cultivar: 'LH 1556') and minimum tillage system for wheat was found to enhance remuneration, as present tillage operations involve nearly 50% of the total production costs (Jalota *et al.,* 2008). Field studies at the Central Institute for Cotton Research, Nagpur, showed the promise of conservation tillage systems for Bt cotton hybrids (Blaise, 2011). Further, cotton crop provides very little residue and it is difficult to maintain a 30% cover in monocrop situations prevalent in the rainfed areas (Blaise and Ravindran, 2003; Blaise *et al.,* 2005a). In such a situation, it would be ideal to take up a green-manure or cover crop between crop rows and place it as mulch (Blaise, 2011). Moreover, there were concerns whether the Bt hybrids could be recycled as the leaves would contain cry toxin. Research conducted at the CICR indicated no adverse effects of cultivating the Bt cotton hybrid on soil microflora and fauna (Usha *et al.,* 2011; Velmourougane and Sahu, 2013). Results of laboratory studies with soil amended with Bt cotton biomass indicated no persistence of the cry proteins (Sims and Ream, 1997).

Weed management

Weed-management practices in the North zone remained almost the same as those that were recommended for the conventional hybrids (Nehra *et al.,* 2006). Changes became more apparent in the Central and South zone. Stale seedbed method of planting Bt cotton was identified as a technology for the irrigated areas (Nalayini and Raju, 2010). Farmers adopted this technology to a certain extent because of the availability of low-priced and effective herbicides. This is not suitable to the rainfed tracts because sowing would get delayed (Nalayini and Raju, 2010). Use of a mixture of herbicides (1 kg each of Glyphosate and Pendimethalin) was found to give the highest weed- control efficiency (Narayana *et al.,* 2011). Staple (pyrithiobac-sodium) is an over the top post-emergence herbicide and was reported to be effective both in case of transgenic and non-transgenic cotton (Swann and Wilson, 2001). Recent studies at Guntur, Andhra Pradesh indicated a mixture of Pyrithiobac (32 g/ha) and Quizalofop-ethyl (25 g/ha) had the lowest weed dry weights and highest seed-cotton yields (Rao, 2011). Timely and effective weed control can be achieved with the use of pre-emergence herbicides offering residual control and a post-emergence herbicide for control of emerged weeds. Prabhu *et al*. (2012) recommended use of a pre-emergence herbicide (Pendimethalin ca. 0.68 kg a.i./ha) followed by a post-emergence application of Quizalofop-ethyl (50 g a.i./ha) along with 1 inter-row cultivation and a hand-weeding 60 days after sowing for irrigated Bt cotton hybrids. Use of herbicides has reduced the number of inter-row cultivations done compared to those for the varieties and conventional hybrids. In the past, inter-row cultivations were done 4 to 6 times besides hand-weeding for obtaining an effective weed control (Wankhede, 1970; Blaise and Ravindran, 2003). An innovative method of weed control evolved that is practiced by the farmers growing Bt hybrids. Farmers are using non-selective herbicides such as Glyphosate in the inter-row spaces with a protective hood to protect the crop. Farmers have understood the benefits of herbicides, as they are low-priced and solve problems of labour that is in short supply. Thus, weed-management strategies recommending the use of herbicides are now becoming acceptable.

Nutrient management

Compared to *desi*, American cotton varieties and hybrids, nutrient removal is greater with the Bt cotton hybrids. In general, a rainfed crop removes about 6–7 kg N, 2–2.5 kg P, 7–8 kg K (Venugopalan and Blaise, 2001) and 1.2-2.0 Kg S/100 kg seed cotton produced. The removal is slightly higher for irrigated cotton: 9–10 kg N, 3–4 kg P, 10–12 kg K and 2.5–3.0 kg S/100 kg seed cotton (Palaniappan and Annadurai, 1995). Nutrient removal is the highest in intensive cropping systems such as the cotton–wheat system (Blaise and Prasad, 2005). At a productivity levels of 1.5 tonnes/ha of seed cotton and 4.5 tonnes/ha of wheat, about 261 kg of N, 59 kg of P_2O_5, 450 kg of K_2O, 3302 g of Fe, 318 g of Mn, 290 g of B, 295 g of Zn and 50 g of Cu are removed annually (Venugopalan *et al.,* 2011a). Widespread cultivation of high-yielding Bt transgenics enhanced nutrient removal further. This possibly depleted soil-nutrient reserves. Therefore, replenishing the soil would be a key factor to achieve potential yield levels.

Nutrient response in Bt cotton: Most of our soils are growing infertile due to continuous mining of the soil (Blaise and Prasad, 2005). Thus an efficient nutrient management plan is the key in the light of the negative nutrient balances. Systematic trials were also conducted under the All India Coordinated Cotton Improvement Programme (AICCIP) at 17 centres across the 3 cotton-growing zones in the country. These studies were conducted to establish whether the fertilizer recommendations need to be modified. Based on the results emerging from the field experiments, State Agricultural Universities (SAU's) have modified their existing fertilizer recommendations.

Among the fertilizer nutrients, nitrogen (N) is critical because it is a component of proteins, enzymes, nucleic acids and chlorophyll. A deficiency has negative effects on the number of fruiting parts produced and ultimately the yield. Very few studies have seen the effects of N alone, mainly because of adopting the balanced fertilizer application policy. In general, Bt cotton hybrids are more responsive to N application. However, at some locations, amount of fertilizer N recommended for the conventional hybrids was found sufficient (Buttar *et al.,* 2010). Almost all the studies fall short of suitable controls. The Bt hybrids are compared with a popular local check rather than a near isogenic non-Bt hybrid.

Timing of N application: For the *desi* cottons, application of N in a single dose, entire at sowing was found to be the best option under rainfed conditions of Madhya Pradesh (Singh and Singh, 1971). Application at later stages was found to adversely affect the cotton growth and seed cotton yields, especially if the crop faced moisture-stress conditions. With regard to the American cottons, N in 2 split doses was recommended (Srinivasan, 2003). With the advent of hybrids, that had a much longer duration of fruiting, 3 split applications (Sree Rekha and Pradeep, 2012) were recommended. However, with the Bt cotton hybrids, a shift in the time of fertilizer N application became evident. Application of N in 3 to 5 equal splits; sowing, 20, 45 and 60–90 DAS significantly improved cotton yields. A summary of the results for the Bt cotton hybrids obtained from various locations is presented in Table 7 indicating the optimum and critical time of N application. In general, an early application was found better because the Bt hybrids were early maturing. Bhosle *et al.* (2012) found besides the number of split application, the amount of N supplied in each split is also important. They found that 3 splits was sufficient provided, the optimum amount is given at sowing (20%), 30 DAS (40%) and 60 DAS (40%).

Cry toxin expression a function of N supply and timing of application: Cry protein, that is toxic to the bollworm, is dependent on N supply. In a deficient soil, the expression is low (Bruns and Abel, 2003). Maintaining an optimal N supply would therefore be critical for cry toxin expression. Studies in other cotton-growing regions of the world such as Australia (Rochester, 2006), USA (Bruns and Abel, 2003; Pettigrew and Adamczyk, 2006) indicated that cry protein content could be enhanced with fertilizer-N. Recent studies in our country indicated improvement in the cry toxin content in the irrigated cotton grown on Vertisols of Karnataka (Hallikeri *et al.,* 2011). Further, it

Table 7. Timing of fertilizer-N application for Bt cotton hybrids grown on Vertisols under rainfed conditions across locations in India

Location	Split fertilizer-N (days after sowing)	Reference
Nandyal, Andhra Pradesh	10, 30, 45 and 75	Aruna (2011)
Adilabad, Andhra Pradesh	25, 50, 75, 100 and 125	Sree Rekha and Pradeep (2012)
Parbhani, Maharashtra	10, 30, 45 and 60	Gokhale *et al.* (2012)
Akola, Maharashtra	Basal, 15, 30, 45, 60 and 75	Gawade and Bhalerao (2012)

is known that the efficacy of bollworm is dependent on cry toxin expression. Moreover, toxin expression declines with age (Blaise and Kranthi, 2011; Kranthi *et al.,* 2005). Nitrogen supply at a later growth stage through split or foliar application could possibly enhance the toxin expression. Some studies indicated that the toxin expression could be enhanced with increasing number of splits (Hallikeri *et al.,* 2011) or foliar supplementation of nutrients. On the irrigated Vertisols, Hallikeri *et al.* (2011) reported that cry toxin expression was significantly greater with 7 split applications (5,043 ng/g) compared to 4 splits (4,066 ng/g) or the recommended method of 3 splits (3,583 ng/g). However, this did not result in any significant yield increases. Considering the fact that the effectiveness of the Bt cotton depends on the cry toxin expression, increasing the number of splits would be in the best interest of sustaining the Bt technology. This may not be a practical approach for the rainfed conditions, where not more than 3 splits are recommended. However, it could be taken up in the drip irrigated systems.

Phosphorus: With regard to P, response was not observed in the earlier studies resulting in removal of P application from the fertilizer packages (Kairon and Venugopalan, 1999; Blaise and Prasad, 2005). This could have been due to the low P requirement of the earlier varieties (Mannikar, 1993). Further, the Asiatic and American cotton varieties with deep root systems explored the subsoil layers (Kapur and Sekhon, 1985). Later improved varieties of American cotton started to show significant response to P application (Pundarikashudu, 1989). However, requirement of P for these cotton varieties was 30 kg P_2O_5/ha (Blaise *et al*., 2006). Present-day high yielding cultivars, more importantly, the Bt cotton hybrids have responded to P application across locations (Venugopalan *et al*., 2009; Venugopalan *et al.,* 2011a). At present P is recommended @ 45 to 60 kg P_2O_5/ha for the Bt cotton hybrids depending on whether the crop is rainfed or irrigated.

Potassium: Among fertilizer nutrients, potassium application has increased. Earlier, use of potash fertilizers was negligible, although the SAU's recommended application for the American cotton varieties and hybrids. This was because most of the cotton-growing soils had medium to high available K and response to K application was either low or inconsistent, and this changed with the large-scale cultivation of the Bt cotton hybrids. Cotton-grown in irrigated as well as under rainfed conditions responded positively to K application (Table 8). In north China, transgenic cotton cultivars were more sensitive to K deficiency than the conventional cultivars (Zhang *et al.,* 2007). This was attributed as a cause for premature senescence (Wright, 1999). Brar *et al.* (2008b) reported the irrigated Bt cotton hybrids ('RCH 134' and 'RCH 317') in Punjab responded up to 41.6 kg K/ha on soils testing low to medium exchangeable K. No response was observed on soils with high available K content. Increase in seed cotton yields of Bt cotton hybrids to an extent of 13–20% was observed in the rainfed and irrigated conditions in Karnataka (Biradar *et al.,* 2011). On the rainfed Vertisols of central India, response to K application was noticed with the Bt transgenic hybrids on the farmer field trials having low exchangeable K content. These soils also had low non-exchangeable K content (Blaise, 2012). More recently, Bt hybrid cotton (Mallika) grown on Vertisols in Adilabad, Andhra Pradesh, was found to respond to K as high as 90 kg/ha (Das *et al.,* 2013).This is because K requirement is high during boll-formation stage and the uptake is limited during this phase, particularly under rainfed conditions. Such responses were not observed in the past with the old varieties and hybrids (Mannikar, 1993). Due

Table 8. Effect of soil application of K on seed cotton yield (tonnes/ha) of Bt hybrids at various locations

Locations	Soil type	Available K (kg/ha)	Seed cotton		Reference
			NP	NPK	
Irrigated					
Mansa, Punjab	Entisols	230–370	2,900	3,010	Brar *et al*. (2008b)
Bhatinda, Punjab	Entisols	129–347	3,150	3,300	Brar *et al.* (2008b)
Moga, Punjab	Entisols	185–207	1,840	2,030	Brar *et al.* (2008b)
Muktsar, Punjab	Inceptisols	405–750	2,970	2,950	Brar *et al.* (2008b)
Faridkot, Punjab	Inceptisols	360–750	2,280	2,280	Brar *et al.* (2008b)
New Delhi	Typic Ustochrepts	287	2,890	3,330	Hussain *et al.* (2013)
Siriguppa, Karnataka	Vertisols	430	2,085	2,383	Biradar *et al.* (2011)
Rainfed					
Nagpur, Maharashtra	Lithic Ustepts	40–260	796	960	Blaise (2012)
Nagpur, Maharashtra	Typic Haplusterts	>500	960	997	Blaise (2012)
Adilabad,Andhra Pradesh	Vertisols	240	2,095	2,555	Das *et al*. (2013)
Dharwad, Karnataka	Vertisols	333	2,727	3,392	Biradar *et al.* (2011)

to such significant responses, farmers have begun to apply potash fertilizers to their Bt cotton crop.

Balanced fertilization: Balanced fertilization is a dynamic and site and situation-specific concept. Balanced dose of N, P and K is usually applied to the soil in the ratio of 2:1:1 ($N:P_2O_5:K_2O$) for obtaining greater efficiency. Instead of these blanket recommendations, soil test based site specific nutrient-management practices are now recommended for productivity, profitability, sustainability and environmental safety (Srinivasa Rao *et al.,* 2012; Blaise *et al.*, 2013). Site-specific nutrient management advocates need-based supply of nutrients to ensure application at the right time in desired quantities for obtaining target yields. Site-specific nutrient management (SSNM) has the potential to improve energy returns to fertilizer. The fertilizer nutrient recommendations for the different locations are given in Table 9. It is evident that the present recommended dose of nutrients are sufficient at some locations (Srinivasulu *et al.,* 2007; Reddy and Gopinath, 2008; Buttar *et al.* 2010; Kaur *et al.,* 2010; Kumar *et al.,* 2011a; Nehra and Yadav, 2011). On the other hand at many locations 25 to 50% higher than the recommended dose was found to maximize seed cotton yields (Devraj *et al.,* 2011; Ravikiran *et al.,* 2012; Sree Rekha and Pradeep, 2012). This has lead to a revision of fertilizer recommendations in many states such as Maharashtra and Karnataka from 80–40–40 to 100–50–50 kg N, P and K/ha. Thus, response varies according to the soil type and more importantly the hybrids grown (Venugopalan *et al.,* 2009). This is clear from the experiments conducted at Parbhani from 2004–05 to 2008–09. In a study during 2004–05 and 2005–06, the present recommended rate was found sufficient for 'MECH 162' Bt (Tayade *et al.,* 2012). But in a separate study at the same location from 2005–06 to 2008–09, Bunny and RCH-2 Bt hybrids responded to 25% more than the recommended dose (Pawar *et al.,* 2010).

Foliar nutrition: In general, crop demand for the nutrients is the highest during the boll-development stage more so in the Bt hybrids compared to the traditional varieties and hybrids. It is evident from Figure 3; K demand is greater than the conventional hybrid during the boll-filling phase (Fig. 3). Further, accelerated uptake begins earlier than the conventional hybrids. A high proportion of nutrients taken up by the crop are eventually translocated to the bolls. As the bolls fill, there is an enormous drain on the plants nutrient reserves and the plants' ability to take up nutrients may not meet the demand (Rochester *et al.,* 2006). Further, the nutrient absorption is poor because of the cessation of root growth after flowering, foliar feeding with essential nutrients is an efficient means of supplying the crop when the need is the greatest (Brar and Brar, 2004). About 50% of the K accumulates in the boll. Since most of the applied K remains in the top soil, cotton root systems fail to adequately exploit it. Foliar application of K (2% KCl) at weekly or 10 day interval is often employed to meet the additional K requirement especially late in the season (Blaise *et al.,* 2009). Although foliar feeding of nutrients was recommended earlier (Brar and Brar, 2004; Mathur *et al.,* 1968), this technology did not catch up with the farmers. Foliar supplementation increased af-

Table 9. Recommended dose of fertilizers (RDF) for Bt cotton hybrids across locations in India

Location	Bt hybrid	RDF (N-P-K kg/ha)	Reference	Comment
Bhatinda, Punjab	'RCH 134'	150–30–0	Brar *et al.* (2008a)	No change
Ludhiana, Punjab	'Ankur 3028', 'NCS 855', 'MRC 7017'	150–30–0	AICCIP (2012)	No change
Faridkot, Punjab	'Bioseed 6488', 'MRC 7361', 'RCH 134'	150–30–0	AICCIP (2012)	No change
Hisar, Haryana	'JKCH 1050', 'JKCH 1945'	150–60–60	Kumar *et al.* (2011a)	No change
Hisar, Haryana	'RCH 134'	187.5–75–75	Devraj *et al.* (2011)	25% >RDF
Sriganganagar, Rajasthan	'RCH 134'	150–40–0	Nehra and Yadav (2011)	No change
Akola, Maharashtra	'RCH 2'	50–25–25	Bhalerao and Gaikwad (2010)	No change
Nagpur, Maharashtra	'Bunny'	100–50–50	Chavan *et al.* (2011)	50% >RDF
Parbhani, Maharashtra	'MECH 184'	80–40–40	Tayade *et al.* (2012)	No change
Parbhani, Maharashtra	'RCH 2', 'Bunny'	100–50–50	Pawar *et al.* (2010)	25% >RDF
Warangal, Andhra Pradesh	'Bunny'	150–75–75	Reddy and Gopinath (2008)	No change
Guntur, Andhra Pradesh	'Maillika'	120–60–60	Srinivasulu *et al.* (2007)	No change
Nandyal, Andhra Pradesh	'Bunny'	150–75–75	Aruna and Reddy (2009)	25% >RDF
Raichur, Karnataka	NA	187.5–93.5–93.5	Ravikiran *et al.* (2012)	25% >RDF
Coimbatore, Tamil Nadu	'Bunny'	112.5–56–56	Sankaranarayanan *et al.* (2011)	25% >RDF

NA: Not available

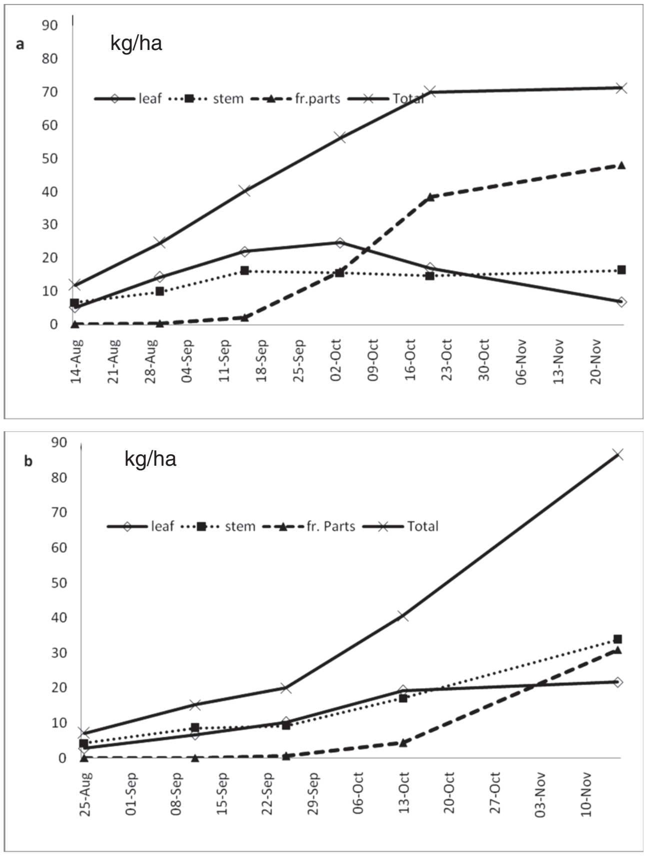

Fig. 3. K uptake pattern in (a) Bt hybrid and (b) conventional non-Bt hybrid during crop growth

ter the Bt cotton hybrids were introduced. One major factor responsible for this rapid growth in adoption of the technology was the problem of leaf reddening.

Leaf reddening

Leaf reddening is a physiological disorder as a response of various stress stimuli (Dixon and Paiva, 1995). Abnormal red colouring in the leaves is due to accumulation of red pigments from the flavonoid group, namely anthocyanins and a degradation of chlorophyll (Edreva *et al.,* 2002). It was first reported in the country on the newly introduced American cottons (Burt and Haider, 1919). All the American cotton varieties introduced in the country were prone to red leaf (Dastur *et al.,* 1952; Dastur and Asana, 1960). Introduction of hybrids accentuated the problem further (Bhatt *et al.,* 1982). All these were related to greater boll loads (Chimmad, 1989). The *desi* cottons were not reported so far to be afflicted by leaf reddening.

After the introduction and widespread cultivation of the Bt cotton hybrids, the problem of leaf reddening became prominent (Hosmath *et al.,* 2012). It was to the extent that desperate cotton cultivators went all the way to Agriculture Departments, research institutions and SAU's to know possible remedial measures. This did not happen earlier because the bollworm infestation would keep the number of fruiting forms at a lower level than the potential a plant could sustain. All this changed with the widespread cultivation of Bt cotton.

Several hypothesis are put forward for the cause of leaf reddening in Bt cotton, such as (i) synchronous boll development (Hebbar *et al.,* 2007), (ii) use of some insecticides such as methomyl, lanate (Kranthi, 2012), (iii) deficiency of Mg and some micronutrients (Upperi and Kuligoud, 2011; Gade *et al.,* 2013), and (iv) selection of hybrids (Hosmath *et al.,* 2012). Red leaves before onset of winter was caused by jassids and thrips attack while nutrient deficiency was limited to 8–10% only. Red leaf in early winter is caused due to senescence or nutrient deficiency and contributes to yield reductions (Raju and Thakre, 2012). Shallow and marginal soils are deficient in both water and nutrients, reducing seed cotton yields to an extent of 25% compared to that of medium and deep soils (Raju and Thakre, 2012). Soil application of $MgSO_4$ (25 kg/ha every third year) significantly reduced formation of red leaves (Raju and Thakre, 2012). Enhanced nutrition and supply of Mg was found to decrease anthocyanin content (Upperi and Kuligoud, 2011). For the control of reddening, nearly 50% of the farmers resort to spray of $MgSO_4$ (5%) and 1–2% urea (Sudha *et al.,* 2011). Demonstrations conducted through the All India Coordinated Cotton Improvement Project have indicated the benefits of foliar nutrient supplementation. The results of these trials are summarized in Table 10. However, these studies did not indicate clearly the extent to which reddening was mitigated with sprays of either the macro- or micro-nutrients. A recent study at different locations in Maharshtra indicated that spray of 1% $MgSO_4$ three times (pre-flowering, flowering and boll-development stages) was effective in reducing the intensity of reddening (Gade *et al.,* 2013). Red leaf intensity in the $MgSO_4$ sprayed plots was 32.2, 46.4 and 44.1% at 60, 90 and 120 days respectively, compared to 48.5, 54.7 and 59.8% in the control plots. Studies are needed to address the cause and effect of reddening Bt cotton hybrid. Factors predisposing the hybrids to reddening are well understood but whether these factors operate singly or in combination and the extent to which these factors contribute to reddening are not clear from the studies conducted, thus far.

Spray of multinutrient mixtures: Several remedial measures are suggested by local vendors for the products they stock such as Greengold B.T. cotton special (Goldfarms, 2010), Bt-Biozyme (Biostadt, 2013) to name a few. This has stimulated research on the effectiveness of such multinutrient mixtures available on the market (Ravikiran *et al.,* 2012; Hosmani *et al.,* 2013). These studies indicated

Table 10. Effect of recommended dose of fertilizer (RDF) with or without foliar nutrients on Bt cotton hybrids at various locations

Location	Components of foliar spray	Yield (kg/ha)		Reference
		With	Without	
Punjab	KNO_3 spray			Brar *et al.* (2008b)
Rahuri, Maharashtra	2 sprays of urea and DAP, alternatively	2,978	3,861	AICCIP (2010, 2011)
Junagadh, Gujarat	2 sprays of urea and DAP, alternatively	2,020	2,422	AICCIP (2010, 2011)
Khandwa, Madhya Pradesh	2 sprays of 2% KNO_3 + 2% DAP	919	1,061	AICCIP (2010, 2011)
Indore, Madhya Pradesh	2 sprays of 2% KNO_3 + 2% DAP	1,104	1,529	AICCIP (2010, 2011)
Nanded, Maharashtra	2 sprays of 2% KNO_3 + 2% DAP	2,124	2,718	AICCIP (2010, 2011)
Akola, Maharashtra	2 sprays of urea or DAP	664	766	AICCIP (2010, 2011)
Surat, Gujarat	1 spray each of urea, DAP and $MgSO_4$	1,935	2,599	AICCIP (2010, 2011)
Raichur, Karnataka	3 sprays of 0.5% Tracel	1,212	1,988	Ravikiran *et al.* (2012)
Siruguppa, Karnataka	1% $MgSO_4$ at flowering and boll development	1,620	2,031	Basavennappa *et al.* (2011)

positive effects of spraying the multinutrient mixtures. Department of Agriculture, Tamil Nadu has recommended application of TNAU MN mixture (ca. 7.5 kg/ha) mixed with sand or enriched with FYM to control reddening in Bt cotton hybrids (DoA, 2013). Such spray of multinutrient mixes are reported to be effective mainly for correcting micronutrient deficiencies for cotton grown in calcareous soils of Punjab, Pakistan (Yaseen *et al.*, 2013). In their study, the formulation of multinutrient mixture supplied 705 mg Zn/ha, 150 mg B/ha, 300 mg Fe/ha, 300 mg Mn/ha and 45 mg Cu/ha. No such information is available in the studies conducted in our country, thus far. In general, the products available on the market do not disclose the contents and composition of the mixture. Furthermore, systematic scientific studies have not resulted in any conclusive recommendations except for a few situations such as Tamil Nadu. In Tamil Nadu, the recommendation is made for the product developed by the public sector. However, the dealers recommend these products for application to cotton. Nevertheless, farmers are spraying these mixtures anticipating positive benefits. Leaf reddening did bring about a change in the way Bt cotton crop was managed.

Micronutrients: Increasing cultivation of the high-demanding crops, intensive cultivation and limited use of organic manures has contributed to widespread micronutrient deficiencies (Singh, 2004; Shukla *et al.,* 2012; Srinivasa Rao *et al.,* 2012). Furthermore, over decades farmers relied only on N or to a limited extent use of N and P fertilizers. Use of micronutrients was nonexistent before the arrival of hybrids. Even after the introduction of hybrids, micronutrient applications were not required mainly because only a single crop of cotton was grown followed by a fallow. However, long-term application of single nutrients leads to multiple nutrient deficiencies. This was observed in the intensive cropping systems (Rattan *et al.,* 1999) as well as the cotton-based systems (Blaise *et al.,* 2007). The first signs of micronutrient deficiencies and their use as a corrective measure in cotton were seen in the irrigated north zone where cotton-wheat cropping system was extensively followed (Kairon and Venugopalan, 1999) following the introduction of short-duration cotton varieties. After the advent of the Bt hybrids, use of micronutrients increased. Research studies also demonstrated the benefits of micronutrient application at various locations (Table 11). Foliar sprays of micronutrients in combination with recommended dose of fertilizers was found to improve productivity in irrigated conditions compared to application of fertilizers alone (discussed in the previous section).

Table 11. Effect of micronutrient on seed cotton yield of Bt hybrids across locations in India

Location	Soil type	Deficient nutrient and status (mg/kg soil)	Bt hybrid	RDF	RDF + micronutrients	References
Sri Ganganagar, Rajasthan	Sandy loams	-[a]	'RCH 134'	3,088	3,359	Nehra and Yadav (2013)
Bhatinda, Punjab	Sandy loams	Zn (0.45)	'RCH 134'	2,970	3,390	Brar *et al.* (2008a)
Parbhani, Maharashtra	Vertisols	-	'Bunny'	1,446	2,270	Gokhale *et al.* (2011)
Dharwad, Karnataka	Vertisols	-	'Bunny'	2,245	2,635	AICCIP (2011)
Vadodara, Gujarat	Vertisols	Zn (0.32)	NA	2,598	3,505	Srinivasa Rao *et al.* (2012)

[a]Soil sample status not mentioned

Water management

In the irrigated cotton-growing zones in north India, the first irrigation after sowing is critical. Delay of 1 to 2 weeks had adverse effect on seed-cotton yield (Singh *et al.,* 1993). Water-management practices remained almost the same and did not change to a great extent for the Bt cotton hybrids compared to the non-Bt hybrids or varieties. Flood or check basin method of irrigation is the common practice. Recent studies at Bhatinda, Punjab, on Ustochreptic Camborthid soil type showed that the drip method of irrigation resulted in a saving of 50% irrigation water compared to the check basin method (Thind *et al.,* 2012). Further, 25% saving of fertilizer was also observed as the yields of the drip irrigated plots with 75% of fertilizer was equivalent to the check basin with 100% recommended dose of fertilizer. With minor modifications to existing cotton planters and other machinery, the paired row planting could be adopted in the irrigated North zone. Productivity of the paired row planting system could be further increased by taking up dense paired row planting (Thind *et al.,* 2012). With the dense paired row, 50% more plants were accommodated. The dense paired row planting was done at a spacing of 35 cm between the rows and 55 cm between the plants. Plant-to-plant distance remained the same as the normal paired row or the normal spacing (75 cm).

The Central zone is predominantly rain dependent. But with the cultivation of Bt cotton hybrids, area under irrigation increased, especially the western Maharashtra (Pawar *et al.,* 2013). Wherever, possible a protective irrigation was also provided. Timing of the first irrigation is an important management consideration where less rainfall is received. In high rainfall areas of south Gujarat, the first irrigation at flowering and the second at boll-development stage at 0.8 IW:CPE were sufficient (Patel *et al.,* 2008). In the drier areas of Maharashtra, Bt cotton hybrids needed 3 irrigations at square, flower and boll-development stages (Shinde *et al.,* 2009). Micro irrigation system (drip irrigation) can bring about a considerable saving in water ranging from 20 to 76% in Gujarat, up to 50% in Maharashtra and elsewhere (Kumar *et al.,* 2011b). Field level survey data also clearly pointed out the benefits of drip irrigation in Bt cotton (Narayanamoorthy, 2008). Seed cotton yield was 4.65 tonnes/ha with the drip systems compared to 2.16 tonnes/ha with flood irrigation. This also led to increases in water productivity (kg/HP-hour of water) (7.99 in the drip vs 2.05 in normal). The reduced consumption of water obviously curtails working hours of pump sets, thus, reducing the required quantum of electricity (Narayanamoorthy, 2008). This has an important bearing in the areas where there is a huge shortfall in electricity supply. Because of these advantages, the drip irrigation systems are becoming popular and the State Governments are providing incentives.

Drip irrigation systems also opened up an avenue of providing fertilizer nutrients, too. Fertigation with water soluble speciality fertilizers of N-P and K are now available on the market most commonly used in vegetable crops and orchards. Results of the combined application of water soluble fertilizers with drip irrigation systems were found to significantly improve seed cotton yields than the use of drip irrigation alone (Pawar *et al.,* 2013). Further, water use efficiency, water productivity and the nutrient use efficiency also improved compared to the traditional flat bed irrigation systems. In Australia, Roth (2007) found that the Bollgard II cotton varieties were more efficient and required 10% less water than the conventional varieties. Such information is lacking for our conditions.

Pest management

With the introduction of the Bt hybrids for commercial cultivation, right practices for pest control evolved such as restricting the use of chemicals to seed. With a single seed treatment, approximately 2–3 field applications were dispensed with. This led to an improvement in biodiversity with a conservation of natural enemies and savings on labour and fuel.

Cultivation of Bt cotton on a large scale led to reduction in insecticide use as the Bt technology offered effective control of the American boll-worm (*Helicoverpa armigera*), spotted boll worm (*Earias vitella* and *E. insulana*) and pink boll worm (*Pectinophora gossypiella*). Farmers adopting Bt cotton have experienced remarkable savings in pesticide use in the developed as well as the developing countries (Pray *et al.,* 2002; Qaim and Zilberman, 2003; Bennett *et al.,* 2004). India was no exception (Kouser and Qaim, 2011; Kranthi, 2012). Qaim et al. (2006) reported insecticide use to decline from 4.17 kg/0.4 ha to 2.07 kg/0.4 ha. Insecticide sprayings dropped by 55%, although predation by non-target pests was rising (Stone, 2011). However, most of the Bt cotton hybrids being cultivated are susceptible to sucking pests: jassids (*Empoasca devastans*), aphids (*Aphis gossypii*) and whitefly (*Bemisia tabaci*) and are now the major pests (Kranthi *et al.,* 2011). Dhillon and Sharma (2013) reported significantly more white flies on Bt than on the non-Bt. Although initially, a sharp reduction of pesticide use against bollworms was registered, an increase in insecticide use against the sucking pests increased. Consequently, the volume of insecticide use started to grow (Kranthi, 2012).

Harvesting/picking of cotton

Cotton is entirely hand-picked in our country and is considered as the cleanest cotton produced (Prasad and

Majumdar, 1999). However, manual picking involves human drudgery. The earlier varieties and hybrids were picked and as many as 5 to 6 times. The cultivation of Bt hybrids brought in a synchrony in cotton maturity. Thus, it created a shortage of hired female cotton pickers and more than doubled the picking cost (Subramanian and Qaim, 2010; Stone, 2011). Manually operated small hand-picking machines were evaluated. Majumdar *et al.* (2011) reported these machines to be significantly inferior to conventional female manual picking with only 70% efficiency. Operational difficulties were noticed besides difficulty in walking due to front loaded picking bag compared to manual picking which was only light to moderate work (Majumdar *et al.,* 2011). Additional harvests increased labour opportunities and farm employment (Subramanian and Qaim, 2009). In the North zone, excessive vegetative growth and dense foliage hinders opening of bolls. Further, picking either manually or with machine would also be hindered. Use of growth regulators are being explored to make picking easier with uniform boll opening, (Rajni *et al.,* 2011).

Based on the review following conclusion are drawn:

1. Bt cotton hybrid is the fastest adopted technology in the history of cotton in India. With its introduction area under hybrids increased from 40% of the cotton growing area in 2002-03 to 90-95% at present.
2. Introduction of Bt hybrids changed the species composition in favour of American cotton (*G. hirsutum*) and marginalized the area under the *desi* cottons (*G. arboreum* and *G. herbaceum*) and skewed the fibre quality profile towards long staple fibre at the expense of short and medium staple categories.
3. Dibbling of a single cotton seed become a rule with the introduction of Bt hybrids because of the prohibitive seed cost (approximately 15 paise/seed). Transplanting of seedlings reused in poly-bags is now being practiced as an option of gap filling.
4. Bt hybrids are planted only after adequate rains are received and the soil profile is sufficiently moist. Thus, the practice of dry sowing before the onset of monsoon, a popular technology in the rainfed central zone, is no longer in vogue because of the risks associated with poor germination. Pruning and extension of the crop beyond the winter period is also becoming popular particularly in mono-cropped areas whenever there is supplemental irrigation. The threat of pink boll worm (*Pectinophora gossypiella*) damage is greatly reduced with the introduction of Bt hybrids.
5. Sowing of the subsequent wheat crop in cotton-wheat double cropping sequence is delayed after the introduction of Bt hybrids in North India.
6. Several short duration compact hybrids are now becoming popular which respond to closer planting. Closer planting of Bt hybrids at 90 × 60 cm and 90 × 45 cm compared to the traditional 90 × 90 cm recommended for non-Bt hybrids is becoming popular.
7. Adoption of stale seed bed technology for early season weed control, use of post emergence herbicides like pyrthiobac-Na and quizalofop-ethyl are other technological changes witnessed in during the decade under Bt hybrids but this cannot be seen as a fallout of Bt technology.
8. Foliar spray of urea, DAP, KNO_3 and micronutrient mixtures has become more widespread with the adoption of Bt hybrids mainly as a prophylactic measure against leaf reddening.

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