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Bt Crops Past Their Sell-By Date: A Failing Technology Searching for New Markets?

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TWN
Third World Network

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Chapter 1

Introduction

GENETICALLY modified (GM) crops were initially heralded by proponents as the coming of the second Green Revolution, set to enhance agricultural "productivity" and thereby address issues of hunger and improve farmer incomes. However, GM crop adoption reached a plateau over a decade ago, less than 20 years after the first commercial planting in 1996. While certain crops, namely soybean and maize, have reached market saturation in a handful of high-GM-adopting nations, wider global adoption has been more restricted. Two traits still dominate the GM crop market, the first being herbicide tolerance, and the second most common being insecticidal "Bt" crops. Both are heavily designed for industrialised farming systems.

Bt crops are genetically engineered to use sequences of genes from the soil bacterium *Bacillus thuringiensis* (Bt) to express one or more crystal proteins (known as "Cry toxins" or "Bt toxins") which are toxic to some pests.

In countries where Bt crops are currently grown, the technology is facing challenges to its durability, with rising pest resistance, and other problems already having significant economic impacts on farmers. Such problems are exemplified by recent experiences in India's Punjab region, where pest infestations have left farmers reeling from 2021 crop losses and new seed price hikes of ~10% are compounding the economic suffering (Singh, 2022). In the US, the Environmental Protection Agency is to start a "phasedown" of Bt varieties that are no longer effective due to pest resistance, focusing on single-toxin cotton and maize crops (United States Environmental Protection Agency, 2021). While numerous Bt toxins have been added to the market, prolonging efficacy to some degree, the number of commercially available toxins that remain effective is declining (see the section on "Pest resistance" in Chapter 3).

Bt toxins are only able to target a narrow range of pests, further limiting the adaptability of the technology going forward. Development of novel Bt toxins remains an active field, with companies such as Bayer and BASF recently announcing the identification of novel versions (Chen et al., 2021; Kahn et al., 2021). However, those aimed at resistant target pests may yet again suffer from cross-resistance with existing toxins that can undermine their efficacy.

Furthermore, it remains questionable whether such developments are indeed designed to rescue a technology long-term. Indeed, the technology has recently been described as possessing a built-in "sociobiological obsolescence" that dispossesses marginalised or resource-poor farmers and households when crops fail, reproducing hegemonic structures that further facilitate the redistribution of wealth from the bottom to the top of the agricultural sector (Najork et al., 2022). Going forward, resistance problems are set to continue as pests likely evolve to adapt to the latest varieties on the market.

Adding to efficacy and suitability challenges is the bearing out of longstanding biosafety concerns that further challenge any new rollouts of Bt technologies. While this paper focuses on efficacy and suitability considerations of Bt crops, extensive reviews of both environmental and health effects have been published. These reveal adverse environmental impacts such as the spread of Bt cotton in Mexico (Vázquez-Barrios et al., 2021) and widespread contamination of traditional maize in Brazil (Fernandes et al., 2022).

In addition, potential human health risks have been raised (Latham et al., 2017; Then et al., 2020, 2022; Wilson, 2021) including allergenicity (Santos-Vigil et al., 2018). These risks have long been dismissed by Bt crop developers, despite lack of routine empirical testing in risk assessments to vanquish concerns. Many open questions remain regarding the mode of action of Bt toxins, combinatorial effects of different toxins, persistence in the pest gut, as well as impacts on non-target species, such as levels of susceptibility to Bt toxicity.

Amidst this backdrop of declining performances in existing, saturated markets, the GM industry appears to be eyeing up new avenues for Bt crop sales. Projects funded by the US Agency for International Development (USAID) to develop Bt brinjal for Bangladesh and the Philippines are ongoing and Bangladesh has started cultivating this crop. Other nations, including Nigeria and Burkina Faso, have recently approved Bt cowpea (HOMEF & ACB, 2022), while Ghana is involved in research but is yet to approve field trials. Bt cotton has also been planted in Kenya since 2020.

The Green Revolution has been described as effectively converting farming and agriculture to industrialised systems with the extensive adoption of proprietary "high-yielding" seeds, fertilisers, pesticides, and intensive mechanisation, amongst other practices (Maingi, 2020). This was accompanied by significant costs to crop and wider biodiversity and traditional farmer knowledge, as well as changes to dietary consumption patterns and increased chemical-induced environmental damage. The expansion of Bt crops into new countries thus raises important implications for further adoption of the so-called protracted "second Green Revolution", and the suitability of Bt crops outside of the industrialised systems for which they were originally envisaged.

This paper summarises the state of play with regard to Bt crops, their declining efficacy, durability, and considerations regarding lack of suitability within and beyond the monocultures of industrialised farms, particularly in the context of developing countries, which appear to be renewed targets for Bt crop developers.

Chapter 2

Bt Crop Cultivation: State of Play

GM crop adoption has been stalling in recent years, leaving developers in search of new markets. According to the International Service for the Acquisition of Agri-biotech Applications (ISAAA), which promotes crop biotechnology, from 1996 to 2002, 16 countries were cultivating GM crops; this figure rose to 25 countries by 2008, and 29 by 2011. Numbers, however, appear to have dropped to 26 countries by 2021 (Turnbull et al., 2021). Total land dedicated to GM crops has also plateaued and was on a slight decline in 2019, the latest year ISAAA reports were published, with countries like the US and Argentina having reached market saturation for soybean, cotton and maize.

Traits to date have been dominated by herbicide tolerance, with the second most common being insecticidal Bt crop traits. The vast majority of land dedicated to GM crops is also concentrated in only five countries – the US, Brazil, Argentina, Canada, and India – which in 2019 reportedly grew 91% of all GM crops globally (ISAAA, 2019). In 2019, Bt crops reportedly made up 12% of GM crops planted globally, and a further 45% were "stacked" with other traits, most commonly herbicide tolerance, in attempts to maximise profits.

Moreover, many Bt crops are "pyramided", carrying multiple Bt toxins in order to delay the development of resistant pests for as long as possible. Bt crops remain largely concentrated in the US, Canada, Brazil and Argentina, while India grows Bt cotton but not Bt food crops. India has transitioned from growing Bt cotton with one toxin that is no longer effective, to varieties with multiple toxins. China reportedly grew 100,000 hectares of Bt cotton in 2018, representing 2% of global GM cultivation (ISAAA, 2018). Bt rice and maize varieties were developed but were never commercialised in China, at least in part due to low consumer acceptance for such staple food products (Liu et al., 2016; Wang, 2015).

In the US, faced with increasing resistance, there has been a steady trend against the use of Bt traits alone. Adoption rates for Bt maize without other traits were 2%, in contrast to 87% for stacked herbicide tolerance/Bt traits in 2018, representing a slight decrease from 2017. Similarly, for Bt cotton, there was a 2-percentage-point drop in Bt-only crops planted in 2018 compared with 2017, from 5% to 3%. Instead, the trend has been to approve Bt crops stacked with multiple toxins and/or traits.

For example, Smartstax® Pro from Bayer was released for 2022, combining glyphosate and dicamba tolerance, multiple Bt toxins and a more novel RNA interference technology. The additional use of soil insecticides to address resistance problems has also been recommended to farmers (Pucci, 2021). Crucially, in 2020 the Environmental Protection Agency launched a proposal to phase out many Bt maize and cotton varieties over the next 3-5 years (Progressive Farmer, 2020; United States Environmental Protection Agency, 2021). These include all Bt crops that carry only one Bt toxin, as well as all pyramided products that do not carry the Vip toxin, which is the only toxin to which pests have yet to develop resistance.

In Burkina Faso, Bt cotton was widely adopted, making up an estimated three-quarters of all cotton grown by 2015. However, the crop was phased out in 2016 after it emerged that the agronomic quality was significantly impacted due to a substantial decline in staple length and ginning ratio. The unintended changes limited the quality and quantity of cotton that could be obtained from the plant. Burkina Faso's cotton industry, renowned for its high-quality cotton, suffered market losses that prompted farmers to seek $280 million in compensation from Monsanto for losses incurred since 2010 (Dowd-Uribe & Schnurr, 2016). After the phaseout, the country experienced a 20% rise in cotton output the following year (Gongo, 2017).

Bt cotton was also introduced into South Africa but was rejected after a few years by the majority of smallholder farmers due to the higher seed costs that compounded existing debt problems. Bt maize, however, has been more widely adopted in South Africa, the only country in the world to cultivate a GM staple food crop for consumption. (The vast majority of GM crops grown in the Americas are dedicated towards processed food ingredients, animal feed and biofuels.) As is the case with the US, South African farmers face resistance challenges that have also resulted in a move to double-toxin crops as of the 2012/2013 season (Tabashnik & Carrière, 2015).

Bangladesh is one of a few countries that have approved Bt toxins for an indigenous crop, in this case brinjal (aubergine), or *begun* as it is called in Bangla. Brinjal, a culturally important crop, was genetically engineered by Mahyco, an Indian seed company that has been licensed to use one of Bayer's (formerly Monsanto) Bt traits. The introduction of Bt brinjal has been aided by funding from USAID for the Feed the Future South Asia Eggplant Improvement Project, which was recently extended in 2022 (McCandless, 2016). While the Cornell Alliance for Science's website reports successes in the country, adoption rates appear to be low, growing from 1% in the year it was first planted, to 6% in 2018. According to ISAAA, there was also a decline in adoption from 2018 to 2019, with a drop in hectares planted from 2,975 to 1,931 hectares (ISAAA, 2018). A 2020 survey by civil society organisations of Dhaka food markets was unable to find any presence of Bt brinjals, despite an abundance of other locally grown varieties (Akhter, 2020).

Nigeria, Ghana and Burkina Faso have also been conducting field trials on the indigenous cowpea bean variety, in a project by the African Agricultural Technology Foundation (AATF) (heavily funded by the Bill and Melinda Gates Foundation), the US-based Donald Danforth Plant Science Center, the Institute of Agricultural Research, and the Commonwealth Scientific and Industrial Research Organisation (CSIRO), an Australian government agency. The AATF negotiated a royalty-free transfer of a Bt gene (Cry1Ab) from Monsanto (now Bayer). Nigeria has reportedly started planting Bt cowpea, though cultivation does not appear to have commenced in neighbouring countries.

Kenya, after instituting a ban on GM food imports in 2012, has now allowed the planting of Bt cotton varieties beginning in 2020. However, seed production by the Indian firm Mahyco, contracted to supply the plant materials, has hit problems and the company stopped seed distribution. This was recently described as a major blow for the crop, while raising concerns regarding the lack of self-sufficiency with regard to cotton seed production (Andae, 2022). Kenya has also been trialling Bt maize, and may imminently approve its cultivation.

Meanwhile, Nigeria is evaluating TELA GM maize, a Bayer variety being sold as a means to combat the fall armyworm as well as to purportedly provide drought tolerance. This drought-resistance trait has already hit hurdles in South Africa, where a stacked variety performed no better, and for some parameters worse, than conventional varieties in field trials (ACB, 2019).

Chapter 3

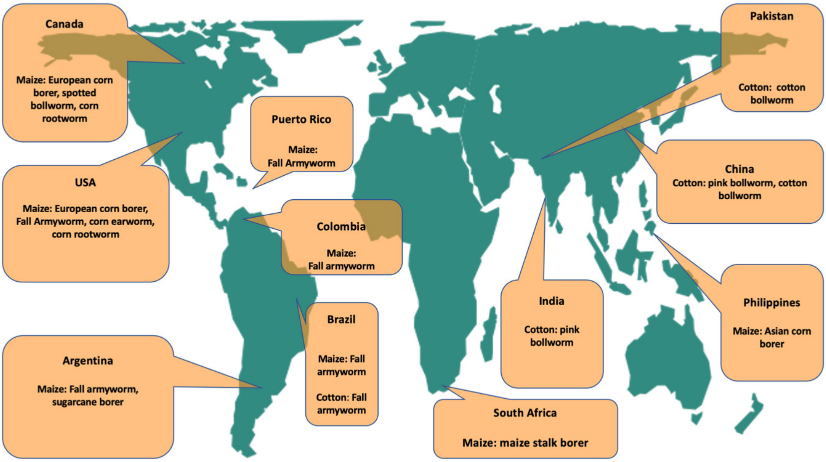
Efficacy Problems Are Undermining Bt Durability

Pest resistance

ONE of the major threats to the long-term sustainability of Bt crops has always been the potential for target pests to become resistant to the insecticidal toxins inside the crop. Management strategies such as the planting of non-GM "refuges" were expected to reduce the pressure on pests to evolve resistance, but such policies have either not been sufficient or have been unimplemented in many cases (see the section on "Reality of farmer refuge (non-) compliance" below).

As summarised in Figure 1, major pests have developed resistance, including corn rootworm (*Diabrotica virgifera virgifera*) (Gassmann, 2021; Gassmann, 2016; Gassmann et al., 2011), cotton bollworm (*Helicoverpa armigera*) in the US and Pakistan (Alvi et al., 2012; Gunning et al., 2005; Tabashnik, 2008), pink bollworm (*Pectinophora gossypiella*) in India and China (Dhurua & Gujar, 2011; Wan et al., 2012; Wang et al., 2022), spotted bollworm (*Earias vittella*) (Ahmad et al., 2021), European corn borer (*Ostrinia nubilalis*) in Canada (Field Crop News, 2019), fall armyworm (*Spodoptera frugiperda*) in the mainland US, Puerto Rico, Colombia and Brazil (Fatoretto et al., 2017; Gutierrez-Moreno et al., 2020; Zhu et al., 2015), sugarcane borer (*Diatraea saccharalis*) in Argentina (Signorini et al., 2018), and Asian corn borer (*Ostrinia furnacalis*) in the Philippines (Alviar et al., 2021). Major pink bollworm attacks returned to India last year across several cotton-growing states, resulting in severe setbacks for smallholder farmers (Najork et al., 2021).

Figure 1. A global summary of documented pest resistance to Bt toxins



The first cases of resistance were documented in 2002, and resistance has been accelerating over the last two decades. By 2013, reduced efficacy of Bt crops caused by field-evolved resistance had been reported for some populations of five of 13 major pest species examined (Jin et al., 2015; Tabashnik et al., 2013; Van den Berg et al., 2013). Resistance associated with crop damage is increasing, with one study reporting three cases in 2005, but 16 cases in 2016 (Tabashnik & Carrière, 2017).

While initial cases took an average of eight years to develop, later cases took only four years, suggesting an acceleration of resistance development over time. Authors attributed this acceleration to the development of cross-resistance to different Bt toxins, as well as the increased planting of Bt crops that reduces the land dedicated to non-GM crops, which can act as a refuge that delays resistance. Indeed, cross-resistance has been reported in many field populations (Bernardi et al., 2015; Gassmann, 2021; Jakka et al., 2016; Ludwick et al., 2017; Machado et al., 2020; Zukoff et al., 2016).

In the US, the issue has become such a problem that all single-Bt-toxin products and all pyramided toxins that do not carry the Vip3Aa Bt toxin were recently proposed to be phased out (Progressive Farmer, 2020; United States Environmental Protection Agency, 2021), with crop failures occurring in many states over recent years (Gassmann et al., 2011; Ludwick et al., 2017; Wangila et al., 2015). Resistance of American corn earworm (*Helicoverpa zea*), for example, has been detected, with 80% of the field populations 13- to more than 150-fold resistant to the Cry1Ab Bt toxin (Niu et al., 2021).

Farmers report a significant decline in performance of the GM varieties, and are now left with one single Bt toxin, Vip3Aa, to carry the technology. Vip3Aa is the only toxin left to which pests have not developed widespread resistance. Any widespread resistance to this toxin would be a potential negative game changer for the survival of the technology. Indeed, signs that Vip3Aa may be losing hold are now emerging. The first cases of field resistance have now been documented in the US (Yang et al., 2019, 2020, 2021) in corn earworm, a major maize pest, with frequencies of resistance increasing from 2016 to 2020 (Yang et al., 2019).

Critical factors assumed to delay resistance include: (1) a high-dose refuge strategy; which further relies on (2) resistance mutations to be recessive; (3) low initial frequency of resistance mutations in the pest population; as well as additional factors including (4) incomplete resistance; and (5) fitness costs (Gould et al., 1997; Tabashnik et al., 2013). These strategies are clearly not foolproof. First, a high-dose refuge strategy relies on the hope that any resistance mutation will be delayed by sufficiently high doses of Bt toxins to kill pests where the mutation is recessive. The aim is that mutations will not rapidly spread to future generations as long as they can breed with susceptible pests that should, in theory, be abundantly present within refuge areas. High doses of Bt crops are supposed to be sufficiently lethal to kill any pests carrying only one copy of a resistant mutation. However, low doses of Bt toxins in some of the first Bt products were linked to resistance development, compromising the fundamental rationale of the high-dose refuge strategy (Tabashnik & Carrière, 2015). Moreover, expression of the transgenes can vary with environmental conditions, growth stages, plant organ, and crop variety, such that it is difficult to ensure such variables are controlled to optimise efficacy. In cases where unapproved varieties are bred with unregistered varieties, this could exacerbate the situation.

Second, the high-dose refuge strategy also relies on resistance mutations being recessive. That is, for resistance to be passed down to offspring, it requires a copy of a resistance mutation from both parents rather than just one (a dominant mutation), thus spreading through the population slower. However, dominant mutations have been documented in the field (Campagne et al., 2013; Tabashnik et al., 2009).

Third, low initial frequency of resistant mutations in a pest population is sought after to delay its spread. However, this cannot be predicted or guaranteed prior to approval of a Bt crop, requiring detailed molecular field testing, and is not always shown to be present at low frequency (e.g., Gould et al., 1997).

Fourth, incomplete resistance, where insects can still complete development on a Bt crop but suffer a disadvantage that impedes survival, is not guaranteed. Evidence of complete resistance evolving in the field has also been documented (Gassmann et al., 2020).

Fifth, a lack of fitness costs has also been documented in target pests (Garlet et al., 2022; Kruger et al., 2014). Moreover, fitness costs are mediated by a range of factors including host plant species, allelochemicals, pathogens and parameters at the individual level or population level. This adds complexity and unpredictability such that fitness costs cannot actually be relied upon as a mediating factor in delaying resistance (Bird & Akhurst, 2007; Chen et al., 2019; Gassmann et al., 2006; Raymond et al., 2005; Wang et al., 2016). Such complexities challenge claims that farmers have a successful set of tools to manage resistance in Bt crops. External factors are outside the control of farmers, mediating the issue to a high degree.

The issue of fall armyworm resistance is particularly pertinent, considering the possible rollout of Bt crops to combat infestations in Africa and potentially Asia, if the pest becomes established there in the future. Resistance has been detected to all but one Bt toxin, with resistant populations arising in the mainland US, Puerto Rico, Brazil and Argentina, including cross-resistance to multiple toxins (Bernardi et al., 2015). Significant levels of resistance in US crop fields were reported at rates of between 10-29% across different regions by 2014 (Huang et al., 2014; Vélez et al., 2013). Field-evolved resistance to Cry1F (Farias et al., 2014) and Cry1Ab (Omoto et al., 2016) Bt toxins in Brazil resulted in high survival rates on maize and cotton plants expressing pyramided Bt proteins (Bernardi et al., 2015; Santos-Amaya et al., 2016).

Moreover, a new study has found that resistance to two Bt crops carrying multiple Bt toxins (Cry1F/Cry1A.105/Cry2Ab2 and Cry1A.105/Cry2Ab2) incurred a complex range of fitness effects, with fitness benefits when fed on non-Bt maize and cotton, and some fitness costs when on some Bt hosts (Garlet et al., 2022). The authors concluded that resistance in the fall armyworm is thus not linked to substantial fitness costs, and thus such populations may persist once present in the field.

Resistance is therefore a major threat to the longevity of Bt technologies, and a limitation that undermines the rationale for further expansion into new crop species or new countries for cultivation. While there is an active field of research to understand resistance mechanisms in order to design strategies to combat the problem, how exactly Bt toxins exert their toxicity in the first place, and how resistance develops, both remain incompletely understood (Liu et al., 2021).

Moreover, the tendency to focus solely on mutations as a mechanism of resistance development omits other complexities that mediate it. A new study, for example, has found that the rapid spread of a virus in pink bollworm increases the bollworm's survival on Bt cotton (expressing the Cry1Ac toxin). The virus, which can spread vertically to offspring, or horizontally to neighbouring pests, reduces the fitness costs associated with resistance mutations (Xiao et al., 2021). The lack of understanding around resistance mechanisms is also likely to have consequences for how resistance is detected and monitored, leading to potential under-detection.

Reality of farmer refuge (non-)compliance

The use of refuges has been a central component in Bt crop cultivation as a required practice to delay resistance development. The refuge area is planted with non-Bt crops so that the pests in the refuge area do not develop resistance. The aim is for these susceptible pests to mate with resistant pests in the Bt-planted area, thus slowing the development of pests that are resistant to the Bt toxins in the GM plants.

However, refuge strategies have been critiqued as being unable to give a one-size-fits-all solution. Over-enthusiastic modelling of efficacy under ideal conditions has been one factor that has promoted the reduction in refuge requirements in the US, but the claimed efficacy has not been reflected in real-world conditions. Complexities have not been accurately factored in. For example, natural refuges, i.e., nearby areas with wild weeds, or non-GM crops that can serve as a source refuge for pests, have shown a lower-than-expected ability to delay resistance. In addition, the reductions in durability of double-toxin crops when pests are already resistant to one of the toxins, have prevented lofty claims reaching reality in many cases (Tabashnik & Carrière, 2015).

Total areas dedicated to refuges vary, with some countries requiring or recommending the practice, and requirements differing for certain crops and pests. South Africa, for example, has 5% minimum refuge requirements, India has 20% requirements, while the US rules vary depending on the crop and if the crop is a single or stacked variety. GM companies and scientists have disagreed over the years over refuge requirements, with companies in the past having petitioned for the removal of refuge requirements that undermine total sales of GM seeds, promoting the use of natural refuges instead (Charles, 2020; Farm Progress, 2006).

Moreover, adhering to refuges can be challenging for a number of reasons, particularly on smallholdings with limited growing space. Lack of compliance has been a general problem across countries including the US, India, South Africa and Brazil, and this is linked to the subsequent development of resistant pests (Dhurua & Gujar, 2011; Mohan et al., 2016; Monnerat et al., 2015; Naik et al., 2018; Storer et al., 2010).

Brazilian farmers who sought compensation in 2014 for failed protection against target pests complained of a lack of availability of non-GM seeds for refuge planting (Stauffer, 2014). In Pakistan (Alvi et al., 2012) and India (Kukanur et al., 2018), it appears common for smallholder farmers to not plant refuges. When seed prices are high, cotton may be planted all year round, giving pest populations a greater chance to develop resistance and pass it down to future generations.

As Van den Berg (2016) notes, due to non-compliance in South Africa: "*To delay resistance evolution, novel IRM [insect resistance management] strategies that are appropriate for use in small-scale agriculture are needed*", including strategies that are economically viable, socially acceptable and easy to implement.

As resistance develops, recommendations or requirements have moved to increase refuge sizes. South African scientists have recently recommended the planting of 50% refuges for GM maize as a means to delay resistance to the newly invasive fall armyworm for crops expressing a single Bt toxin, and 20% for stacked varieties (Van den Berg et al., 2021). The authors warn that the 5% refuge strategy proposed in Kenya for future maize cultivation will likely be inadequate. Moreover, proposals to use wild plants as refuges for Bt maize in Africa to combat the African stem borer have been described as inadequate and a recent study notes that "*Current IRM strategies and reliance on wild host plants as refuge in most of the* *developing world [are] not appropriate to small farming systems"* (Van den Berg, 2016).

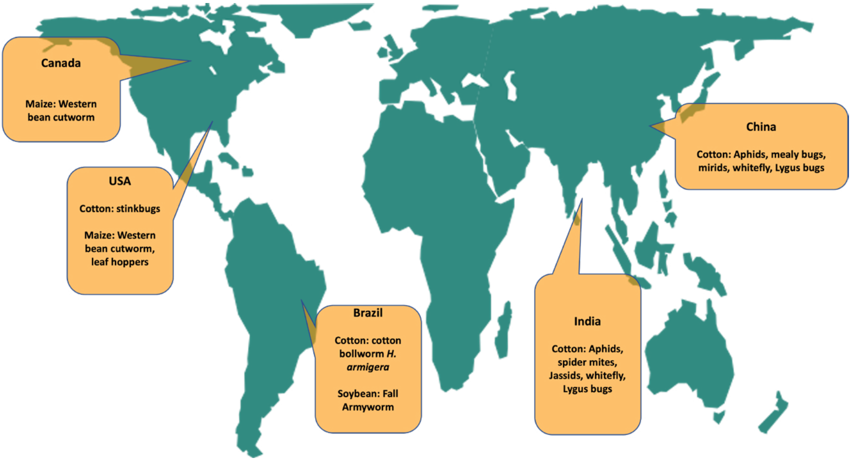
While robust and large-scale use of non-Bt refuges may provide a partial theoretical solution to the delaying of resistance, experience to date suggests that in reality, such strategies are either inappropriate or often out of reach of the farmers on the ground, particularly smallholder farmers. With smallholder farming systems typically adopting more self-organising practices such as seed saving, as well as other practices such as small plots being located in the vicinity of neighbouring fields, the likelihood of resistance is further increased as a result of gene flow from GM to non-GM maize. This has been documented in Bt maize farms in Zambia (Bøhn et al., 2016), diluting the Bt toxins and thus potentially exacerbating resistance development.

Such key determinants of Bt efficacy cannot simply be ignored, or expected to be transferred over from industrialised systems such as in the US, where even there farmers face challenges to their efficacy and adherence.

Rise of secondary pests

Along with the rise in resistance, other issues are plaguing the long-term efficacy of Bt crop technologies. Secondary pest attacks are now a well-recognised issue associated with Bt crop adoption, requiring the use of synthetic pesticides and thus increasing farmers' costs (see Figure 2). Secondary pest infestations are the indirect effect of eliminating the primary crop pests, a predictable problem already experienced with synthetic pesticides such as DDT decades ago (Castle et al., 1996; Eveleens et al., 1973).

Figure 2. A global summary of documented secondary pest infestations in Bt crop fields



Bt toxins only target a limited number of pests, leaving crops susceptible to many other potential pest species. Despite the importance of this issue that can determine the success or failure of a crop harvest, it has received only limited attention. There have been numerous farmer reports of problems over the years. The rise of secondary pests has been attributed to a number of problems associated with the technology, including an initial reduction in broad spectrum pesticides, a reduction in natural enemy populations and a decrease in interspecific competition between target pests (Catarino et al., 2015).

In China and India, where cotton is a major cash crop, secondary pest infestations have been repeatedly documented for over a decade, with a rise in pests such as mirids (*Lygus* spp., *Neurocolpus nubilus*), aphids (e.g., *Aphis gossypii*), thrips (*Thrips tabaci*), mealybugs (e.g., *Pseudococcus corymbatus*, *Pulvinaria maxima* and *Saissetia nigra*), jassids (*Amrasca biguttula biguttula*), lygus bugs (*Adelphocoris saturalis*, *A. fasciaticollis*, *Lygus lucorum*, etc.) and whiteflies (e.g., *Trialeurodes vaporariorum* Westwood and *Bemisia tabaci* Genn), including novel species that were previously not reported in the region, such as mealybug infestations in India (Hagenbucher et al., 2013; Kranthi, 2014; Lu et al., 2010; Nagrare et al., 2009; Nair & Bhardwaj, 2015; Wang et al., 2008; Yang et al., 2005).

Secondary pest infestations have eroded claims that Bt technologies result in reduced pesticide inputs and thus reduced farmer costs, with farmers reporting a lack of reduction in pesticide application (Men et al., 2005). A 2011 survey of 1,000 Chinese farmers across five provinces found a rise of numerous secondary pests such as aphids (*Aphis gossypii*), spider mites (*Tetranychus cinnabarinus*), and lygus bugs (*Adelphocoris saturalis*, *A. fasciaticollis*, *Lygus lucorum*, etc.) (Zhao et al., 2011). Similarly, in India, evidence gathered more than a decade ago showed no reduction in pesticide use, consistent with farmers attributing pest damage to aphids and other sucking insects not targeted by Bt toxins (Ramaswami et al., 2012). Secondary pests and resistance problems linked to a lack of resistance management, particularly in smallholder systems where there is lack of space for refuge planting, and less infrastructure for coordination and regulation, have meant that an initial dip in insecticide use with Bt crops was not sustained (PAN UK, 2017).

In the US, Bt cotton adoption has resulted in a rise of the damaging stink bug pests (e.g., *Euschistus servus* and *Nezara viridula*), leafhoppers (*Dalbulus maidi*) and mirid bugs (*Lygus* spp., *Neurocolpus nubilus*) (Naranjo, 2011; Zeilinger et al., 2016). In both the US and Canada, the western bean cutworm (*Striacosta albicosta*) has also become an increasingly important pest on Bt maize (Catangui & Berg, 2006; Dorhout & Rice, 2010; Lindroth et al., 2012; Smith et al., 2018). Brazil has suffered infestations of cotton bollworm (*Helicoverpa armigera*) in cotton, a pest previously not associated with the Americas (Tay et al., 2013). The country is also now seeing a rise of the fall armyworm on soybean crops, a species that was not considered a soybean pest until the early 2000s. This situation likely arose as a result of changing cultivation systems associated with a decline in insect pest management practices alongside the widespread adoption of GM crops (Horikoshi et al., 2021).

Other challenges

The dawn of Bt crops was sold as an environmentally progressive move that would reduce pesticide use. Nonetheless, this fallacious argument ignores the fundamental fact that rather than reducing pesticide use, Bt crops instead alter the mode of pesticide application from external applications to internal production inside the crop. Crops thus express Bt toxins throughout the growing season, regardless of whether pests are present, leading to chronic exposure of all organisms feeding on these plants (Hilbeck et al., 2020). Even the claim of reductions in external pesticide use is not supported by the latest evidence. Overall applied pesticide toxicity in the US has increased, with no reduction in insecticide use (mass) applied to Bt maize versus non-Bt maize from 2000-2016 (Schulz et al., 2021).

Seed treatments are also expanding globally, but are not included in pesticide application surveys in the US (Douglas & Tooker, 2015). Approximately 43% of the total mass of insecticides applied to maize were in the form of neonicotinoid seed application. As noted by Douglas and Tooker (2015): "*Several analyses on the influence of Bt crops on pesticide-use patterns do not seem to have considered seed treatments, and so may have overstated reductions in insecticide use (especially 'area treated') associated with this technology*."

According to Mullin et al. (2005), seed treatments indeed increasingly focus on genetically modified seeds. Leslie et al. (2009) also note that: "*All commercially available rootworm-directed Bt field corn varieties contain neonicotinoid seed treatments*", describing it as a "*coupled technology*". As with Bt toxins that are expressed by the Bt crops irrespective of pest pressure, treated seeds are also a prophylactic measure, running the risk of resistance development from the increased pressure of constant exposure.

Bt crops are also associated with other "coupled" inputs and practices, such as fertiliser use and irrigation. For resource-poor farmers, such inputs are often not available. So, for example, the planting of Bt crops in non-irrigated farms has led to crop failures (Kranthi & Stone, 2020a). Claims of Bt cotton successes have instead been attributed to farms that are able to fund wider deployment of labour, irrigation and chemical inputs (Kranthi, 2016), rather than the Bt crop itself.

As elaborated by Kranthi and Stone (2020a), the increased use of fertiliser in cotton-growing regions in India has added to the financial pressure on already marginalised and resource-poor farmers. These farmers, rather than becoming beneficiaries of agronomic improvements, are now being entrenched further into an intensive agricultural model that is pushing many farmers into more cycles of debt and distress.

Chapter 4

Bt Crops: An Assault on Smallholder Farming Systems?

THE limitations associated with Bt crop technologies, from resistance development, secondary pest infestation and lack of refuge compliance to the subsequent increased input costs associated with Bt crops, have had well-documented effects on smallholder farmers in developing countries.

India's transition to Bt cotton came after the Green Revolution that had already drastically altered agricultural practices and introduced new technologies and inputs, with costs borne by the small and marginal farmers (Kannuri & Jadhav, 2021). Cultivation of Bt crops has become an additional toxic element contributing to farmer indebtedness amidst a broader agrarian crisis in India. Crop failures still plague cotton farmers (Kumar, 2008; Nair & Bhardwaj, 2015; Singh, 2021; Singh, 2022), and yields have stagnated after 20 years of cultivation, accompanied by increased pesticide and fertiliser use, farmer distress and indebtedness (Gutierrez et al., 2015, 2020; Kranthi & Stone, 2020a, 2020b; Najork et al., 2021).

Farmer suicides have been linked directly to crop failures in non-irrigated farms (Gutierrez et al., 2015), with the technology ill-suited to rain-fed areas in comparison to native non-Bt varieties. Reports from families of those who have taken their lives reveal the financial debt suffered by farmers attempting to recover from pest infestations and crop failures (Kannuri & Jadhav, 2021). This incurs greater risk to farmers, though they have little choice but to purchase Bt hybrid cotton, which has completely taken over the market (Siddiqi, 2020).

The political economy of Bt cotton in India was recently described by Najork et al. (2021) as a form of “sociobiological obsolescence” that systematically dispossesses farmers and concentrates wealth further up the agricultural sector. Inherent limitations as a result of the resistance problems prevent the technology from being a sustainable option for farmers. Nonetheless, the products are introduced to smallholder farmers as a means to increase profits.

The introduction of Bt cotton was also promoted as a panacea for the problems facing smallholder farmers in South Africa, providing “crucial ammunition” for promoting GM crops on the African continent (Schnurr, 2012). The USAID-backed project, promising to propel farmers out of poverty, turned out to be shortlived, with a majority of smallholder farmers halting adoption of the crop due to the inability to pay back debts. A five-year study by civil society in South Africa reported losses in farmer incomes (GRAIN, 2005). With seed prices double those of conventional varieties, further compounded by droughts and low cotton prices, Bt crops exacerbated rather than reversed the debt problems facing farmers in the Makhathini Flats region.

Burkina Faso is another country that has experienced adverse agronomic and economic consequences from cultivating Bt cotton. Developers shaped a narrative of success around the release, which was the first entry point for GM crops into West Africa. However, conflicts of interests, data integrity issues, and methodological problems led to reports of inflated yields, and large variability in yields that was not properly reported. Yield issues were compounded for poorer farmers who were unable to buy fertiliser; they also had additional issues of having to repurchase seeds when they failed to germinate. Such local dynamics were not factored into the developers’ evaluations of purported successes. As Luna and Dowd-Uribe (2020) describe, the power dynamics meant that transnational GM developers got to shape early narratives around Bt cotton in Burkina Faso, which ultimately served their bottom line, and whose lofty projections supported high royalty prices on Bt seeds.

In reality, the technology reduced the agronomic quality of the crop, which suffered a serious decline in staple length and ginning ratio. Burkina Faso's cotton industry, well known for its high-quality cotton, suffered serious economic consequences from market losses. Despite the failures resting with the technology development process, the burden of economic costs was placed on smallholder farmers instead of the developers (Luna & Dowd-Uribe, 2020).

The latest Bt cowpea crop development raises additional concerns with regard to the engineering of indigenous crop plants, particularly in a centre of diversity. The possible approval of Bt cowpea is being challenged in a legal case in Ghana by civil society organisations (Food Sovereignty Ghana, 2022) on the basis that these approvals are a threat to indigenous crop systems (ACB, 2015; HOMEF & ACB, 2022). Cowpea is a crop whose economic and cultural significance extends to diasporic communities in the Americas/Caribbean and Europe.

Potential approvals have also sparked biosafety concerns surrounding a lack of safety data, as well as findings published by developers that reveal a range of biosafety issues. These include unintended effects at the molecular level (e.g., transgene instability) that may go on to impact non-target organisms, reduction in soil fertility, potential health impacts including increased immune responses, as well as contamination of non-GM indigenous and wild-relative varieties via gene flow (Then et al., 2022).

The introduction of Bt crops (and GM crops more broadly) raises important implications for smallholder farmer systems. As highlighted by the examples of pest resistance and crop failures above, Western claims of successes are by no means an accurate reflection of lived experiences. Serious questions remain about the suitability of a technology designed for Western systems, for smallholder farmers (Schnurr & Dowd-Uribe, 2021).

Aside from efficacy problems associated with the technology, questions also surround its appropriateness, with the technology designed without sufficient knowledge of the farming systems it is destined for. For example, as noted by Schnurr and Dowd-Uribe (2021), Bt cowpea is designed to ward off the legume pod borer, but this pest is most prevalent in a region of Burkina Faso that does not widely cultivate cowpea, challenging the benefit and thus profitability of the crop's adoption. Moreover, other pests not targeted by the Bt toxins are viewed as a more generalised threat to cowpea across the country. Nonetheless, unrealistic projections of yield gains are being presented (Schnurr & Dowd-Uribe, 2021).

The most common GM crops, including Bt varieties, remain commodity crops designed for industrialised systems. While new Bt crops include some indigenous crop varieties, it raises concerns that such projects, while promoted as catering to the needs of smallholder farmers, are instead a mechanism for gaining wider acceptance of commodity crops and further industrialisation of agriculture.

Experiences to date with Bt crops are raising serious questions about the durability of the technology, particularly in developing-country contexts where additional farm inputs, refuge requirements and other intensive practices such as irrigation have not always been realistic or feasible. The compatibility of Bt crops with the realities of agriculture in developing countries, where there can be difficulties in complying with refuge obligations due to the size of smallholdings, is in question.

Moreover, farmer seed systems are characterised by the ability of farmers to freely save, exchange and sell farm-saved seed, practices that supply the majority of seed in developing countries. Criminalisation of seed saving is accompanying the push for GM crop cultivation, threatening these practices required for self-determination within the agricultural sphere. Any entry of Bt crops requires a curtailment of such practices in order to avoid resistance development. Not acknowledging the seed-saving reality may also undermine the efficacy of Bt traits, which may be altered upon breeding.

Chapter 5

Concluding Remarks

BT crop systems were designed for industrial agricultural systems where they have, in part, provided a degree of short-term success in certain settings. However, even within industrialised systems, the technology is succumbing to serious efficacy problems that threaten its survivability. This has led agricultural experts to scramble for solutions for countries that are now saturated with Bt crop varieties, creating an unhealthy dependency on this type of short-term techno-fix solution for timeless issues of pest management.

With a dearth of crops for the industry to present to smallholder farmers, it appears that Bt crops are now being served up as a profitable solution. This is despite the experiences in developing countries thus far showing markedly less success and, in repeated cases, serious failures that have had knock-on economic consequences for farmers, particularly smallholder farmers who do not have the additional inputs that are required to support Bt crop cultivation.

While this latest offer to new markets across the world may present new opportunities for the GM industry, smallholder farmers are at risk of having to once again shoulder the liability of any future failures if Bt crops are more widely adopted (Glover et al., 2020). Experiences to date serve as a clear forewarning of how Bt crops, and GM crops more generally, have best served transnational corporations, which may only continue with the “dumping” of old technologies anywhere opportunity allows.

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CROPS genetically modified to contain toxins from the bacterium *Bacillus thuringiensis* have been touted as having inbuilt capacity to ward off pests. These so-called Bt crops are now increasingly being promoted in developing countries despite growing concerns surrounding their efficacy and suitability.

Development of resistance among target pests to the Bt toxins is reported to be accelerating, while the plants are also coming under attack from non-target secondary pests. On top of this, the cultivation of Bt crops often requires additional agricultural inputs and practices, which throws into doubt its viability for resource-poor farmers in the Global South.

This paper flags the potential pitfalls associated with the push by Bt crop backers to make market inroads into developing countries for a technology of questionable effectiveness and durability.

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