Journal of Genetic Engineering and Biotechnology (2011) 9, 83–95

Academy of Scientific Research & Technology and
National Research Center, Egypt

Journal of Genetic Engineering and Biotechnology

www.elsevier.com/locate/jgeb

Global capture of crop biotechnology in developing world over a decade

Ademola A. Adenle [a,b,*]

[a] *United Nations University-Institute of Advanced Studies (UNU-IAS), Japan*
[b] *National Graduate Institute for Policy Studies (GRIPS), 7-22-1 Roppongi, Minato-ku, Tokyo 106-8677, Japan*

Received 13 June 2011; accepted 27 August 2011
Available online 1 October 2011

KEYWORDS

GM technology;
Sustainable agriculture;
Hunger;
Food security;
Developing countries;
Policy Implication

Abstract There is an urgent need for the advancement of agricultural technology (e.g. crop biotechnology or genetic modification (GM) technology), particularly, to address food security problem, to fight against hunger and poverty crisis and to ensure sustainable agricultural production in developing countries. Over the past decade, the adoption of GM technology on a commercial basis has increased steadily around the world with a significant impact in terms of socio-economic, environment and human health benefits. However, GM technology is still surrounded by controversial debates with several factors hindering the adoption of GM crops. This paper reviews current literatures on commercial production of GM crops, and assesses the benefits and constraints associated with adoption of GM crops in developing countries in the last 15 years. This article provides policy implication towards advancing the development and adoption of GM technology in developing countries and concludes with summary of key points discussed.

* Address: United Nations University-Institute of Advanced Studies (UNU-IAS), 6F International Organisations Centre, Pacifico Yokohama, 1-1-1 Minato Mirai, Nishi-ku, 220-8502, Yokohama, Japan. Tel.: +81 45 221 2367, +81 03 6439 6000; fax: +81 45 221 2303, +81 03 6439 6010.
E-mail addresses: adenle@ias.unu.edu, aadenle@gmail.com.

Peer review under National Research Center, Egypt.
doi:10.1016/j.jgeb.2011.08.003

ELSEVIER Production and hosting by Elsevier

Contents

1. Introduction . . . 84
2. Commercial production of GM crops in developing countries . . . 84
3. Global impact of GM crops . . . 87
 3.1. Benefits of GM crops . . . 87
  3.1.1. Yield impact . . . 87
  3.1.2. Farm level impact . . . 87
  3.1.3. Profitability impact . . . 87
  3.1.4. Environmental impact . . . 88
  3.1.5. Human health impact . . . 88
 3.2. Potential role of GM crops in food security and poverty reduction in developing countries . . . 88
4. Challenges and the way forward . . . 89
 4.1. Constraints in adopting GM crops . . . 89
 4.2. Policy Implications for the development and adoption of GM crops . . . 91
  4.2.1. Provision of functional and appropriate international regulatory capacity . . . 91
  4.2.2. Educational policies for the interpretation of biosafety regulation . . . 91
  4.2.3. Transfer of technological innovation . . . 92
  4.2.4. Investment in technological innovation and agricultural research . . . 92
  4.2.5. Increase access to information resources . . . 92
5. Conclusion . . . 92
 Acknowledgment . . . 93
 References . . . 93

1. Introduction

GM crops otherwise known as biotech or transgenic crops have captured the minds of various people and organizations around the globe, particularly in terms of its potential benefits and risks associated with it. Over the past decade, GM crop productions have gradually increased and captured strategic places both in developed and developing countries. At the same time intense public debate continues as to whether GM products are safe due to potential long-term effects on human health and environments. But no environmental or human health problems resulting from GM crops have been documented so far [8,21,28,44,105,107]. Contrary to this debate, evidence-based reports on health and environment benefits have been documented [13,34,46,75,92,98,118]. Apart from potential risks, control of food supply as a result of concentration of industry power is another major concern among the critics [17]. Given the growing world population with majority living in developing countries and suffering from hunger and poverty, critics have the right to express their concerns.

This brings about Green Revolution that benefited mostly Asian and Latin America country in 1960s through the 1980s while African countries were by passed, perhaps the biggest failure of Green Revolution. The Green Revolution was successful to some extent in Asia due to high-yielding varieties of rice and wheat, chemical inputs, irrigation and improved crop systems, saving almost 1 billion people from hunger. It was noticeable in terms of food security, poverty reduction and increased per capital income [23,104]. After many years of continuous use of agro-chemicals and irrigation under Green Revolution regime, serious environmental changes of soils started, water bodies' quality was affected, and agricultural yields declined. It was indicated that increased agricultural production from Green Revolution has reached its limits, thus the need for newer technologies to increase the food production for rising world population [23]. The application of GM technology was acclaimed as Doubly Green Revolution that has a great potential to improve and increase crop yields [22].

In this review, a wide range of relevant papers that focus on current issues of GM crops in developing countries were analysed, and latest information were obtained from the first year of commercialization till date. The data used for the analysis of commercialization of GM crops between 1996 and 2010 were obtained from the International Service for the Acquisition of Agri-Biotech Applications (ISAAA), published annually by James Clive. ISAAA provides up-to-date database information on global cultivation of GM crops since 1996, and however it does not necessarily represent high quality information but provides reliable data on GM crops (Personal communication). This paper is divided into three parts. First part provides reviewed background to the commercialization of GM crops production in developing countries while corroborating it with some evidence in developed countries. Second part discusses the global impact of GM crops that covers the benefits and potential roles of GM crops in global food security and poverty reduction in developing countries. Third part examines some of the constraints obstructing the progress of GM technology in developing countries, with policy implications that highlight and discuss vital points which can facilitate the development and adoption of GM technology in developing countries. Finally, this paper ends with concluding remarks about the observations noticed during the review and how GM technology can progress for sustainable human development in developing countries.

2. Commercial production of GM crops in developing countries

The first commercial production of GM crops started officially in 1996. Prior to 1996, only China (GM tobacco) and USA

Table 1 The area of GM crops produced globally between 1996 and 2010, by country (million ha).

Country	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
USA	1.5	8.1	20.5	28.7	30.3	35.7	39.0	42.8	47.6	49.8	54.6	57.7	62.5	64.0	66.8
∗Argentina	0.1	1.4	4.3	6.7	10.0	11.8	13.5	13.9	16.2	17.1	18.0	19.1	21.0	21.3	22.9
∗Brazil	–	–	–	–	–	–	–	3.0	5.0	9.4	11.5	15.0	15.8	21.4	25.4
∗India	–	–	–	–	–	–	–/+	0.1	0.5	1.3	3.8	6.2	7.6	8.4	9.4
Canada	0.1	1.3	2.8	4.0	3.0	3.2	3.5	4.4	5.4	5.8	6.1	7.0	7.6	8.2	8.8
∗China	1.1	1.8	–/+	0.3	0.5	1.5	2.1	2.8	3.7	3.3	3.5	3.8	3.8	3.7	3.5
∗Paraguay	–	–	–	–	–	–	–	–	1.2	1.8	2.0	2.6	2.7	2.2	2.6
∗Pakistan	–	–	–	–	–	–	–	–	–	–	–	–	–	–	2.4
∗South Africa	–	–	–/+	0.1	0.2	0.2	0.3	0.4	0.5	0.5	1.4	1.8	1.8	2.1	2.2
∗Uruguay	–	–	–	–	–/+	–/+	–/+	–/+	0.3	0.3	0.4	0.5	0.7	0.8	1.1
∗Bolivia	–	–	–	–	–	–	–	–	–	–	–	–	0.6	0.8	0.9
Australia	–/+	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.2	0.3	0.2	0.1	0.2	0.2	0.7
∗Phillippines	–	–	–	–	–	–	–	–	0.1	0.1	0.2	0.3	0.4	0.5	0.5
∗Myanmar	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.3
∗BurkinaFaso	–	–	–	–	–	–	–	–	–	–	–	–	–/+	0.1	0.3
Spain	–	–	–/+	–/+	–/+	–/+	–/+	–/+	0.1	0.1	0.1	0.1	0.1	0.1	0.1
∗Mexico	–/+	–/+	–/+	–/+	–/+	–/+	–/+	–/+	0.1	0.1	0.1	0.1	0.1	0.1	0.1
∗Romania	–	–	–	–/+	–/+	–/+	–/+	–/+	0.1	0.1	0.1	–/+	–/+	–/+	–/+
Total	1.7	12.7	27.8	39.9	44.2	52.6	58.5	67.5	81.0	90.0	102.0	114.3	125.0	134.0	148.2

Note: Countries represented in the table are the ones that produced at least more than 50,000 hectares of GM crops in a single year between 1996 and 2010. Minus sign (–) in the table shows that country did not grow GM crops in that particular year. Minus and plus sign (–/+) show that the country grew less than 0.1 million hectares in that particular year. The countries that were not represented in the table are the ones that did not grow up to 50,000 hectares in a single year between 1996 and 2010 with the years of commercial GM crop production stated as follows; Colombia (2002–2010), Chile (2007–2010), Honduras (2002–2010), Portugal (1999, 2005–2010), Czech Republic (2005–2010), Poland (2007–2010), Egypt (2008–2010), Ukraine (1999), France (1998–2000, 2005–2007) Bulgaria (2000–2003), Indonesia (2001–2003), Slovakia (2006–2010), Costa Rica (2009–2010), Iran (2005–2006) Sweden (2010) and Germany (2000–2002, 2005–2008, 2010). The data shown in the table does not necessarily represent accurate information on commercial production of GM crops between 1996 and 2010 but shows reliable data in the last 15 years of commercialisation. Developing countries according to World Bank list 2010 are represented with symbol (∗).

Source: adapted from Refs. [54–67].

(GM tomato) are widely known to have planted GM crops for commercial purposes in 1992 and 1994, respectively [101,117]. Since the commercial production of GM crops started 1996, steady growth has mostly taken place in developing countries. Current commercial productions of GM crops are more in Asia and Latin America countries with few countries in Africa. There are also few commercial GM crops in North America but the United States, being the major player has the highest adoption, and arguably the only country with most advanced biotechnology research and development (R&D). The European attitude towards GM crops has led to scanty adoption, while Japan one of the few developed Asian countries has shown little or no interest. Apart from developed countries, both Asia and Latin America have relatively high level of capacity building including functional biosafety regulations for growing commercial GM crops. These literatures [43,103] provide some relevant information on status of biotechnology programs in Asia and Latin America, respectively. Some countries like India and China in Asia, Argentina and Brazil in Latin America have enacted biosafety regulations, while other countries are working on it. Only few African countries like South Africa, Egypt and Burkina Faso have functional biosafety regulations and capable of producing commercial GM crops, while majority are at different stages of developing national biosafety frameworks [71,76].

The year 2010 marked 15th anniversary of commercial production of GM crops. 29 countries produced commercial GM crops with a remarkable record of total global area of 148 million hectares since commercialization started in 1996, and majority of the cultivations took place in developing countries [67]. Between 1996 and 2010, when 1.7 million hectares and 148 million hectares of GM crops were planted, respectively, an unprecedented growth of 8, 606% was achieved. This was a significant achievement with 87-fold increase, making it the fastest crop technology in the history of commercial agriculture [67]. During the 15 years, the number of GM growing countries increased from 6 in 1996 to 29 in 2010. Of 29 countries that planted GM crops in 2010, 19 are from developing countries. Two developing countries like Pakistan and Myanmar and the first Scandinavian country, Sweden planted GM crops commercially for the first time in 2010.

China and India are the most advanced and dominant GM crop producers in Asia. Of global total area of 148 million hectares planted in 2010 (Table 1), China (3.5 million hectares) and India (9.4 million hectares) planted a combined total area of 12.9 million hectares. In Asia, China and India represent 45% (34.3 million hectares) and 49% (37.3 million hectares) respectively of total area of 76.4 million hectares of GM crops (mostly *Bt* cotton) planted in 15 years of commercialization (Table 1). Australia is the only Asia-Pacific country that planted 0.7 million hectares of GM crops in 2010. Australia has planted a total area of 2.6 million hectares since commercialization started in 1996 with focus on *Bt* cotton and *HT* canola.

Argentina and Brazil are the most advanced and dominant GM crop producers in Latin America. Of global total area of 148 million hectares planted in 2010 (Table 1), Argentina (22.9 million hectares) and Brazil (25.4 million hectares) planted a combined total area of 48.3 million hectares. In Latin America, Argentina and Brazil represent 61% (197.3 million hectares) and 33% (106.5 million hectares) respectively of total area of 326 million hectares of GM crops planted in 15 years of commercialization with focus on *Bt* cotton, *Bt* maize and *Bt* soybean (Table 1). Argentina is the second highest GM crop adopter in the world 18% (197.3 million hectares) after United States 55% (609.6 million hectares) of total global area of 1.1 billion hectares produced between 1996 and 2010.

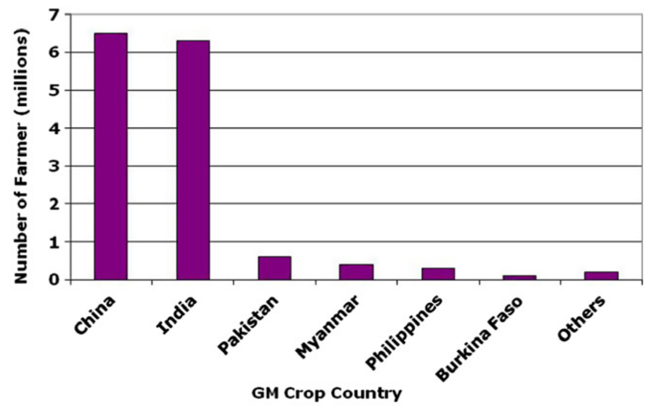

Figure 1 Distribution of resource-poor farmers that planted GM crops in 2010. The figure represents the distribution of resource-poor farmers in developing countries. Of 14.4 million farmers that cultivated GM crops in 2010, 6.5 million farmers are from China with an average of 0.6 hectares for GM cotton, and 6.3 million farmers from India cultivated mainly GM cotton. More than 350,000 farmers cultivated GM cotton for the first time in Pakistan and Myanmar in 2010. Over 250,000 farmers cultivated GM maize in Philippines, while nearly 100,000 farmers in Burkina Faso cultivated GM cotton. The remaining 13 developing countries with 200,000 farmers growing GM crops like GM maize, GM soybean, GM cotton and GM canola. *Source:* adapted from [67].

Of three African countries that grow GM crops commercially, South Africa is the largest producer of GM crops such as *Bt* maize, *Bt* soybean and *Bt* cotton followed by Burkina Faso that produces *Bt* cotton. Of global total area of 148 million hectares planted in 2010, South Africa (2.2 million hectares) and Burkina Faso (0.3 million hectares) planted a combined total area of 2.5 million hectares (Table 1). Egypt produced less than 50,000 hectares of GM maize since the country joined GM crops producing countries.

The United States (US) and Canada are the two top producers of GM crops in North America. Of global total area of 148 million hectares planted in 2010, the US (66.8 million hectares) and Canada (8.8 million hectares) planted a combined total area of 75.6 million hectare (Table 1). The US alone represents 45% of global total area of 148 million hectares in 2010 and has been the largest adopter in the world since 1996. Spain is the only European country that has been growing GM crops for over a decade but only became visible in 2004 when the country planted 0.1 million hectares up till 2010 (Table 1), as opposed to 20,000 hectares planted in 1998 the first year of commercialisation [55]. A total of 0.7 million hectares of GM maize have been grown in Spain over the past decade, making it the highest adopter in Europe. Other few European countries planted less than 0.1 million hectare as described in the Table 1.

The global area of four main GM crops that were grown in 2010 include; 50% *Bt* soybean (73.3 million hectares), 31% *Bt* maize (46.8 million hectares), 14% *Bt* cotton (21 million hectares) and 5% *Bt* canola (7 million hectares). In terms of crop grown by traits globally, herbicide tolerance of four main GM crops (*Bt* soybean, *Bt* maize, *Bt* canola and *Bt* cotton) plus sugar beet and alfalfa remains the dominant trait at 63% (89.3 million hectares), followed by insect resistant traits at 17% (26.3 million hectares). About 15.4 million farmers planted commercial GM crops around the world in 2010, 94% (14.4 million farmers) are mainly resource poor-farmers from developing countries with majority of farmers coming from China (6.5 million farmers) and India (6.3 million farmers) Fig. 1.

3. Global impact of GM crops

3.1. Benefits of GM crops

The global benefit of GM crops since commercialization began in 1996 has been outstanding, delivering socio-economic, environmental and human health benefits to both small and large-scale farmers in developing and developed countries, respectively. At the same time, benefits of GM crops have been criticised. The literatures on the benefit of GM crops are vast, but this section of the article has discussed some of the relevant papers while mentioning others' data that criticised with mixed situations.

3.1.1. Yield impact

The yield impact of GM crops varies from country to country with different literature reports and some of the GM crops producing countries have been reported. For example, *Bt* cotton, yield increase is reported as follows; 0% in Australia [31], 7–15% in China [49], 9–11% in USA [11], 20% in Mexico [113], 32–34% in Argentina [95], 40–70% in South Africa [53,80] and 43–87% in India [98]. The United States, South Africa and Spain represent 5–8% [111], 11% [37] and 4.7% [36], respectively, for yield increase in *Bt* maize. In USA, Argentina and Romania, the yield increase for *Bt* soybean represent −2% to 2% [7,11], 0% [97] and 31% [9], respectively. The literature report on *Bt* soybean shows little or no yield gains but significant yield increase in Romania may be due to poor control of weed with introduction of HT soybean resulting to less damage on crop [9]. According to the literature evidence as described above, most developing countries have been shown to have increased yields in *Bt* cotton compared to developed countries. While relative increase in yields have been recorded for GM crops particularly in developing countries [14,47,94,98], others' data [38,45,106] have argued that potential of GM crops in developing countries have too little substantial yield effects especially in regions with rapid growth population.

3.1.2. Farm level impact

Some of detailed assessment carried out by Brookes and Barfoot [10] for the first 13 years of commercialization (1996–2008) is based on farm level economic effects and the production effects. According to Brookes and Barfoot assessment [10], adoption of GM technology for commercialization has dramatically improved agricultural production with a positive impact on farm income, accounting for an increase of US$ 52 billion since 1996. Based on their estimate, increase in farm income benefit for the GM crops such as *Bt* soybean, *Bt* maize, *Bt* cotton, *Bt* canola and others represent 5.7% added to the total value of global production in GM adopting countries in 2008. Also, in the year 2008, the division of economic benefits in developing countries relative to developed countries as obtained by the farmers was estimated. As shown in Table 2, the result showed that the developing countries farmers (predominantly from all countries in South America, Mexico, Honduras, Burkina Faso, India, China, Philippines and South Africa) obtained 50.5% of income farm benefits and the cumulative farm income gain was estimated to be 50% (US$ 26.2 billion). In terms of production impact, the use of GM technology has contributed considerably to global production of corn (79.7 million tonnes), soybean (74.0 million tonnes), cotton (8.6 million tonnes) and canola (4.8 million tonnes) since 1996.

In contrast, Glover [111] argues that benefits of GM crops are not uniform and inconsistent due to obvious variability in farmer income in India; for example, his report suggests that only few small-scale farmers benefited from *Bt* cotton as reflected in their incomes. Also, a two years survey of small-holder farmer in South Africa by Thirstle et al. [112] claim that the amount of labour required to grow *Bt* cotton is exaggerated and that time and labour to grow *Bt* cotton did not change. Qayum and Sakkhari [99] report that social and economic forces will influence the GM technology, and as a result little or no resource-poor farmers will benefit from *Bt* cotton adoption in India. As stated by Herring [45] that: ''*Bt* cottons have been in the field too short a time for definitive assessment of either biological or economics success across so varied an agro-ecology as India; results vary with seasonal variations of pests, weather and local agronomics''.

3.1.3. Profitability impact

GM crops have enhanced increase in yield and profitability. Carpenter [14] analysed 80 examples of GM crops profitability, 59 showed an increase with GM crops with a decrease of 14 and 7 showed no difference. In terms of yields, increase in profitability was higher in developing countries than developed countries, especially in GM cotton. For example, the United States and Australia have an average increase in gross margin, representing US$ 58/ha and US$ 66/ha, respectively, whereas China, Mexico, India, South Africa and Argentina have an average increase in gross margin, representing US$ 470/ha, US$ 295/ha, US$ 135/ha, US$ 91/ha and US$ 23/ha, respectively.

Qaim [94] also analysed the difference between developed and developing countries in term of increase in profitability for GM maize. The result showed an increase in gross margin

Table 2 Global farm income benefits of GM crops in developed and developing countries (million US$, 2008).

GM crops	Developed	Developing
GM HT soybeans	1232.1	1693.6
GM IR maize	2, 380.5	265.0
GM HT maize	357.4	76.1
GM IR cotton	213.8	2690.8
GM HT cotton	5.5	9.1
GM HT canola	391.8	0
GM virus resistant papaya and squash and GM HT sugar beet	51.5	0
Total	4632.6	4734.6

Source: [13].

that represents US$ 12/ha in the United States, whereas an increase in gross margin in Philippine, South Africa and Argentina represents US$ 53/ha, US$ 42/ha and US$ 20/ha, respectively, for GM maize. The authors, Carpenter and Qiam conclude that data only represent the benefit of GM crops which are greater in developing countries but not the statistical significance of average increases in yield and profitability for GM crops.

By contrast, Gouse et al. [38] argue that increased yield of GM varieties was not as a result of GM technology in the case of *Bt* and herbicide-tolerant maize in the KwaZulu Natal region of South Africa. But tillage system was a key factor for determining the efficiency levels, therefore GM technology only had a minor effect on efficiency. In fact the authors, corroborated with statement like ''the results mostly serve to show how dangerous it is to make any interferences from small sample surveys in one production season''.

3.1.4. Environmental impact

The cultivation of GM crops has contributed to reduced pesticide and fuel use, controlling water erosion, preserving soil structure, lowering tillage operations and green house gas emission. Reduction in chemical use also lead to reduced cost that is associated with spraying of pesticide [77]. A study of environmental impact was examined by Brookes and Barfoot [10] to assess the amount of pesticide and herbicide applied on GM crops between 1996 and 2008 using Environmental Impact Quotient (EIQ) indicator. The result showed that the adoption of GM traits (e.g. GM cotton) have led to reduction (8.4%) in pesticide application by 352 million kg of active ingredient with 16.3% drop of environmental impact resulting from pesticide and herbicide application on crops. This result suggests that the use of GM crops have had a significant positive impact on the environment, thereby lowering the greenhouse gases emission. Moreover, Brookes and Barfoot also examined the contribution of GM technology in terms of carbon sequestration impact; saving of carbon emission due to reduction in the use of fuel. The report shows that the use of fuel was reduced for planting GM crops (e.g. GM herbicide tolerant-HT crops), thereby saving carbon dioxide emission. For example, 3137 million litres of fuel to equivalent to 8632 million kg was used between 1996 and 2008, compared to 1205 million kg of car equivalent for carbon dioxide saving. Also, a remarkable figure of 101,613 million tonnes of carbon dioxide that could have been released into the atmosphere was prevented due to carbon saving. Other than Brookes and Barfoot data, reductions in pesticide use and costs have been reported in developed countries such as United States, Australia and Spain [16,94] and developing countries like India, Mexico, Argentina, China and South Africa [50,94,96,100]. In addition, a detailed review on positive impact of GM crops on biodiversity in the past 15 years in different countries has been reported [15].

3.1.5. Human health impact

Human health benefits due to reduction in pesticide use have been recorded from the adoption of GM technology, particularly among the farmers without adequate training who are growing *Bt* cotton in China [48,92]. In South Africa, introduction of *Bt* cotton has led to reduced number of illnesses that is associated with pesticide applications [5,80]. Moreover, other findings have shown that cultivation of GM maize can lead to health benefits. For examples, GM maize contains low amount of mycotoxins that can cause human disease such as cancer [115]. And cases like lowering mycotoxins in *Bt* maize have also been reported in USA [42,114] and Europe [10,32]. These are cases where low pesticide uses have resulted in reduced level of toxicity, thereby reducing the number of poisonings among the farmers. In developing countries, mcyotoxins inspection is poorly controlled when compared to developed countries, the use of *Bt* maize can contribute to greater health benefit among less trained farmers.

3.2. Potential role of GM crops in food security and poverty reduction in developing countries

GM crops have potential roles towards solving food security problems and poverty crisis in developing countries, particularly in Africa continent and South East Asia. Global food demand is projected to at least double, and likely to triple, by the year 2050 when the world population growth is expected to reach 10 billion people with majority living in developing countries [30,35]. According to recent statistics estimate by FAO [29], 925 million people (13%) of 6.3 billion estimated world population are hungry and undernourished notably in Asia pacific 9% (578 million) and Africa 4% (239 million). This evidence suggests that there is still overwhelming shortage of food production to feed world poor people or perhaps people cannot afford the food prices due to high poverty level.

As stated in the new book, the New Harvest in Africa published by Juma, that ''global agriculture over the past 40 years has been characterized by per capita food production growth of 17 percent and total production up 145 percent'' [70], which is not enough for world rapidly growing population particularly in developing countries. And this problem has been mostly attributed to neglect of agriculture relevant to poor people by governments and international agencies [29]. Therefore, food production will have to expand to meet the demand of growing populations by increasing the agricultural production. World food and feed grain production will need to increase by 40% including roots and tubers to increase by 58% so as to meet the projected global food demand in 2020 [89]. GM technology as one of agricultural technologies will play an important role.

Food security and poverty reduction can be achieved through GM technology by creating job opportunities, increasing crop productivity, improving nutritional contents, lowering production costs and food prices [66]. Improving the livelihood and incomes of people in rural and urban areas is also fundamental to food security, since people's access to food depend on income. Apart from population growth that may likely affect food security in years to come, problems resulting from abiotic stresses such as drought, salinity, water-logging, toxic levels or deficiencies of nutrients and biotic stresses due to weeds, insects and diseases and climate change will take a heavy toll of the 5 billion tons of food currently produced annually, hence a serious need to tackle these problems.

GM technology can play an important role to achieve economic and productivity gains, introduce resistance to pests, insects and diseases for biotic stress, reduce pesticide use, improve crop tolerance for abiotic stress and enhance the durability of products during harvesting and shipping [22,40,110,116]. For example, since commercialization of GM crops started in 1996, economic gains of US$ 51.9 billion has been achieved during period 1996–2008, 50.6% accounts for a reduction in production cost and 49.6% for substantial yield gains [66]. While increase in yields and reduction in production costs are important, food security will be improved much more effectively by reducing poverty, for example by increasing the employment rate and household incomes.

In the year 2008, if not for GM crops, 29.6 million metric tons of increased crop production from four principal GM crops (10.1 million tons of soybean, 17.1 million tons of maize, 0.6 millions of canola and 1.8 million tons of cotton) would have required 10.5 million hectares [12,13]. The result suggests that 29.6 millions metric tons of crop production is a reasonable contribution towards 5 billion tons of food produced annually. Therefore, adoption of GM technology for growing these crops has already contributed largely to global crop productivity and reduced cost productions.

Increasing the income of poor farmers which constitute 50% of world population will go a long way towards reducing poverty of 70% world poorest people that depend largely on agriculture for survival. GM crops production has increased the income for more than 90% (13 million) small scale and resource-poor farmers from developing countries which have contributed to poverty alleviation in 2008 [66]. James [66] argues that the production of GM cotton in China, India and South Africa and GM maize in Philippines and South Africa have already improved livelihood of 12 million resource-poor farmers and contributed significantly to their incomes. In future, production of GM rice has potentials to feed and increase the income of 250 million people in Asia where some of poorest people live in the world with income less than US$ 1 a day.

GM technology can provide cost-effective solution to vitamins and mineral deficiencies by developing rice varieties that can contain vitamin A and minerals which can solve the problem of malnutrition in developing countries. For example, the genetically enriched rice called "Golden Rice" is the vitamin A improved rice that could alleviate vitamin A deficiency in developing countries [83,90], particularly in South-East Asia and Africa where vitamin A and malnutrition problem are endemic among the children. GM cassava can also provide essential micronutrients for the young children and pregnant women as well as improving farmer's productivity and livelihoods in sub-Saharan Africa. Other orphan crops such as rice, tropical maize, wheat, sorghum, millet, banana, potato, sweet potato and oil seed can also benefit from GM technology in developing countries.

In the context of Millennium Development Goal (MDG-1) to halve poverty by 2015, improving agricultural productivity and food security is fundamental to achieve MDG-1. A growing body of literatures already showed that GM technology has great potentials to improve agricultural productivity and it will be one of vital agricultural technologies to reduce poverty in developing countries. GM crops are expected to contribute towards reducing poverty by 50% by 2015 [66]. There is always need to emphasise that GM technology alone cannot offer complete solution or a magic bullet for food security problem, but when combined with a mix of regulated policies, effective-appropriate institutions, political commitments, public and private investments in rural areas, and other agricultural technologies, it could be a powerful tool against fighting poverty and food insecurity [88].

4. Challenges and the way forward

4.1. Constraints in adopting GM crops

Despite the benefits of GM crops over the past decade since the commercialization started, there are still many challenges or constraints associated with the adoption of GM technology across the globe, particularly in developing countries that are expected to benefit most from this technology (Table 3).

Most developing countries are yet to grow GM crops on commercial scales due to a number of factors. One of the most prominent factors is biosafety regulations as most countries have not fully satisfied the requirements for the release of GMO products, and due to "go-slow" approach toward GM technology by individual counry government, thus delaying the commercialization of GM crops. There is lack of proper coordination and harmonization for developing biosafety regulation in developing countries and this can been seen as slowing down the growth in international adoption of GM crop innovations [91]. This challenge appears to be the most formidable and biggest limitation in adoption and growth of GM crops in developing world including Africa countries. For example, a change of administration, political lobbying and lack of priority can delay approval of biosafety regulation in Africa [2].

Africa is arguably one of the most affected continents due to a considerable number of factors hindering the development of GM technology. This is clearly evident as only three African countries are growing GM crops when compared with other developing countries. However, different constraints are associated with different continents around the world when it comes to adoption of GM technology, but Africa seems to have a lot more. It is difficult to argue and attribute a particular constraint to the adoption of GM technology in Africa but there are several factors that may be responsible. Africa is poverty stricken continent where problems like poor governance, political crisis, inadequate infrastructures, weak markets, human immunodeficiency virus/acquired immunodeficiency syndromes (HIV/AIDs), malaria and civil war can be taken into account in adopting GM technology. Moreover, Asia are not exempted from attributes commonly associated with Africa, South-East Asia have similar problems that affects the adoption of GM technology.

The adoption of GM crops between global North and global South is not evenly distributed geographically, with most adoption coming from global South. As a result, data resulting from global production of commercial GM crops are sometimes difficult to analyse. Only few developed countries such as US and Canada are the dominant producers of GM crops in North America with outstanding capacity building to support agricultural development. Unlike European countries that are expected to be among top adopters, only Spain has been consistently producing GM crops for over a decade with total production less than 1 million hectare since the country joined GM producing countries in 1998, suggesting the influence of other European countries on production level. Without a doubt, most European countries have strong capacity building with a big financial investment to support agricultural development. But, however, European concerns about the food safety and lack of support for relevant GM crop policies, particularly based on precautionary principle are one of main reasons why adoption of GM crop has been slow [3,26,69].

Table 3 Constraints in the adoption of GM technology in developing countries.

Constraints	Country	Complex issues arising from adopting GM crops
Regulatory cost	India	High cost for regulatory process in India (e.g. GM cotton) [93]
	Philippine	Regulatory delay of GM rice may lead to high cost [4]
Trade concerns	Egypt and South Africa	Fear of European ban on GM products is a major factor for delaying an approval of GM potato [24,86]
	Brazil	Fear of losing market in Europe may affect the approval of GM soybeans [72,85]
	Argentina and China	Commodity export losses to Europe and Japan stopped the approval of new GM crops by Chinese and Argentina governments in 1998 and 2001, respectively, [20]
	India	Planting GM rice may lead to European ban, [109] and mandatory labelling of GM food due to rice import from India to Qatar [73]
Intellectual property rights (IPR)	China	Local piracy of GM cotton due to weak IPR and lack of access to large commercial seed market in China [20]
	Brazil	Black market seeds and smuggling of GM soybean seeds to Brazil from the border of Argentina due to GM levy as farmers cannot afford high seed price [97]
	Argentina	Resource-poor farmers are unwilling to pay for high seed price of GM cotton despite reduction in pesticide application and increase in yield [95]
	India	Proposed introduction of IPR form of Variety Genetic Use Restriction Technologies (V-GURTs) otherwise called terminator genes for seed sterility was disqualified in India [87] and was rejected by the Rockefeller Foundation [102] and by the Consultative Group on International Agricultural Research (CGIAR) [18]
Safety concerns	India	Moratorium was placed on the first GM eggplant to be commercially produced due to health reason [4], and alleged complaints were made over GM cotton due to allergic reactions among GM cotton workers [41]
	Brazil	Allergic reaction due to the presence of brazil nut gene in GM soybean led to the research to be stopped on this crop [82]
	Mexico	GM maize was stopped due to alleged discovery of transgenic DNA in indigenous maize in 1998 [74]
	European countries	A group of five European countries which include France, Austria, Germany, Greece and Luxembourg banned Mosanto's GM maize (MON810) due to potential environmental hazard [25]
Anti-GMO (Genetically Modified Organism)	India	GM rice test plots were burnt down by Indian farmers and The All India Rice Exporter Association (AIREA) were trying to convince governments to stop GM rice field trials in basmati rice growing states [52]
	Europe	GMO products are prohibited in many places in Europe with GMO-Free Zone declared in Ireland [84]. A well organised group and leading European NGO like Greenpeace campaigns vigorously against GM in developing countries [24,39], including many other NGOs in Europe and around the world

Source: information in the table was compiled from different sources as shown in the references above.

Notably, large percentage of the GM crops was cultivated in top five lead developing countries such as Argentina, India, China, Brazil and South Africa. Several factors underpin high adoption rate among those five developing countries. And some have to do with the fact that the institution building to promote biotechnology activities are effective and reliable to a large extent in the five countries. In addition to that, a lot of financial investment has been made. For example, in Latin America, Argentina alone is the top producer of GM crops with 229-fold increase between 1996 and 2010 (Table 1), with the exception of US. Argentina is known to have invested close to $US 10 billion on agriculture between 1996 and 1998 to improve crop biotechnology capacity [55]. China and India have stood out in Asia for leading commercial GM crops production and these two countries have invested more than $US 4 billion annually on agricultural development [47,68].

While few countries with considerable scientific infrastructure and clear programmes on cutting-edge biotechnology have translated R&D into significant adoption of GM crops and commercialized some of their products, many countries in Asia, Latin America and Africa are far from adopting GM crops that have potential to improve livelihood and increase income of resource-poor farmers. And this is simply because they lag behind in terms of capacity to produce, regulate and apply biotechnology in crop productions [6,81]. African country seems to be the worse among all the countries with very few institutions dedicated to biotechnology R&D development. Juma [70] reports that reduction in agricultural production was as a result of decrease in R&D investment, hence Africa must invest in agricultural R&D, particularly agricultural biotechnology.

Another major constraint hindering the development of GM technology in developing countries is lack of financial resources to support biotechnology R&D which requires huge capital to develop and sustain. Genetic engineering research is very expensive relative to conventional or traditional biotechnology. For example a genetically modified potato research cost an average of US$ 2 million when compared to tissue-culture and marker technology project at an average of US$ 300,000 [79].

The absence of a well established and enabling policy that encourage intellectual property rights (IPR) system is also depriving most developing countries of a proper functioning commercial market for improved seed varieties. It may be one of the reasons why biotech industries are not investing in developing countries due to non-existing IPR and poorly structured market system. While lack of legal protection for IPR system is more common in Africa [79], some countries in Asia (e.g. China) have weak IPR protection [20]. In spite of benefits that may come from IPR systems, there are concerns that strong IPRs will dominate global food production by a small biotech industries (e.g. Monsanto) [17,79]. Also, IPR placing restriction on resource-poor farmers in terms of their existing rights to store and exchange seed through terminator technology in developing countries, if implemented can constrain innovations germane to developing countries (Table 3).

The role of media in the likelihood of adopting GM technology for agricultural production is very important. But most media coverage in developing countries have been disappointing on the issue of GM crops due to lack of analytical reporting, lack of balance of views and poor informed debate. For example, complete rejection of GM food aid from United States by Zambian Government may have been influenced by media involvement, and this can potentially affect government decision and policy. Moreover, recent report showed that much of the media coverage revealed a lack of adequate investigative reporting on GM debate as most announcements were based on unreliable sources in developing countries [78]. This report suggests some weaknesses in the way journalists investigate some science-related issues in most developing countries.

Trade concern is another issue that may delay adoption of GM technology in developing countries. Perhaps, the influence of European Union may be a contributing factor as African, some Asia and Latin America countries would not like to compromise their trade partnership with European countries (Table 3). It was reported that Eastern and Southern African countries showed low interest of GM export market due to possibility of being rejected by European Union [86]. Cohen and Paarlberg [20] report that slow adoption of GM technology in developing countries can be attributed to commercial fear, particularly in partnership with European countries and East Asia. The authors showed the examples of Argentina and China where approvals for growing some certain GM crops were delayed in 1998 and 2001, respectively. They conclude that fear of losing their export sales to European countries and East Asia coupled with political matter can seriously affect the approval of biosafety regulation in developing countries. The adoption of GM technology in developing countries is affected by other factors such as low level of education, lack of public awareness, acceptance, international regulations and many others.

4.2. Policy Implications for the development and adoption of GM crops

The constraints discussed above are formidable but not invincible. From the collection of summarised activities and information on the commercialization of GM crops since 1996, it possible to synthesize and mention vital policy implications that will help towards the development of modern biotechnology in developing countries as described below.

4.2.1. Provision of functional and appropriate international regulatory capacity

If adoption of GM technology will mostly and truly benefit developing countries as being said frequently, something therefore must be done about international regulatory capacity. The lack of an international regulatory capacity is affecting the development and adoption of GM technology in developing countries. Moreover, resource-poor farmers are still deprived of this technology and prevented from achieving innovative agricultural success [108]. One of the points to reckon with is the limited adoption of GM crops by small land holders in most of developing countries. A serious but convincing effort to help developing countries should be rendered to establish effective regulatory frame work capacity. In fact, a combined effort from credible international bodies or agencies is needed as this is beyond one country approach. The Food and Agriculture Organization (FAO), the Organisation for the Economic Cooperation and Development (OECD), World Bank and other relevant agencies can be involved to ensure the effort becomes a success.

Another point is the current trend to enact highly restrictive regulations which make it difficult for public institutions in developing countries to conduct GM field trials under local conditions, thereby affecting the product development. As time consuming and excessive compliance within the regulations may prevent public institutions from conducting the field tests. Therefore, the developing countries must given the opportunity to develop GM products to suit their needs while conducting field tests under local conditions.

4.2.2. Educational policies for the interpretation of biosafety regulation

Lack of educational policies for interpreting biosafety regulation for resource-poor farmers is affecting the adoption of GM technology in developing countries. Most small-scale farmers in developing countries have low level of education, and their inability to read or understand the official language in which biosafety law is written may lead to wrong application of GMO products. For example, commercial production of GM cotton employed 2–4 million farmers mostly illiterate in Burkina Faso. Because the level of education among these farmers is extremely low, particularly reading of Biosafety Law written in French is a big challenge [51]. To solve this problem, Biosafety Law was translated into three most commonly spoken languages (Moore, Jula and Gulmacema) in cotton growing areas to create awareness on Biosafety Law. The idea is to promote and enlighten the farmers and local people about the Biosafety Law. Given low level of education among resource-poor farmers in developing countries, individual country government should formulate educational policies that will facilitate the interpretation of national biosafety regulation in most commonly spoken languages for safe application of GMO products.

4.2.3. Transfer of technological innovation

Identifying more efficient ways and means of transferring technological innovation to developing nations by driving reliable bioeconomy will create wealth and economic benefits for the users. The developed countries clearly have important roles to play when transferring technological innovations (e.g. GM technology) by working in collaboration with international initiatives such as the International Service for Acquisition of Agric-biotech Applications (ISAAA), African Agricultural Technology Foundation (AATF) and relevant government initiatives in developing countries. Different agricultural research organisations and government departments such as Ministry of Science and Technology, Ministry of Agriculture in developed and developing countries can work together to establish a common goal on policy formulation and implementation that will facilitate and encourage international transfer of technology. All OECD countries have to make this a priority if modern biotechnology will truly have global economic impact as envisioned by early innovators.

4.2.4. Investment in technological innovation and agricultural research

Agricultural investment plans must be coherent and part of overall national plans that are clearly spelt out in the budget for economic development, food security and poverty reduction in any country. Many people are poor and hungry today in developing countries due to long-term under-investment in agriculture particularly in scientific research and technological innovation development which is synonymous to African countries [108]. The authors argue that funding agriculture research will yield profitable returns, and will serve as a powerful weapon in fighting against poverty and hunger. One key strategic approach to tackle this constraint in the area of scientific research and technological innovation is to invest in biotechnology R&D in developing countries.

Before it can be a viable biotechnology R&D through adequate investments as described by ADB [1], it will have to satisfy the following four attributes: (1) it must address both the problems of small farmers in rainfed areas where majority of poor live, and those of small farmers in irrigated areas that provide bulk of food grain in Africa and Asia; (2) Priority should be placed on orphan crops such as rice, tropical maize, wheat, sorghum, millet, banana, oilseed, potato and sweet potato. Biotechnology R&D should also focus on high value commodity crops such as cotton, soybean and vegetables that can increase resource-poor farmers income through crop diversification; (3) The development and provision of technology for resource-poor farmers must be simple, low cost with little or no risk to human health and environment; (4) Biotechnology development should be accompanied by welcoming policy environment that reflect transparent governance, rural infrastructural development, efficient agricultural extension services and reliable credit and marketing.

Although, lack of financial resources are hampering the development of biotechnology R&D in some of developing countries, in that situation, the governments should set a specific goal clearly underlined in biotechnology R&D, supported with reliable policy and some level of commitment that will attract some foreign donors to support and invest in their program.

4.2.5. Increase access to information resources

Adequate and free access to information resources on technology that still requires a lot to learn or know about it should not be confined to a small group. Many developing countries, particularly in public research institutions do not have access to vital information that could improve their understanding on GM technology. Some access problems relate to data collection, management and storage such as availability of systems for reliable sample and data tracking, or access to modern analytical methodologies and tools for accurate decision-making, amongst others. Even though, there is still much sharing for research purpose, but access to biotech research is restricted by one or more material-transfer agreements, which further restrict distribution and commercialization.

Also, restricting information from the data on the performance of biotechnical products by private sector is another concern, and this sometimes makes it difficult for the analysis of policy issues. This is in sharp contrast to previous epochs of technical change including the green revolution, in which publicly funded research led to public data availability. The most immediate policy need is perhaps, to provide transparent and efficient means of data dissemination that can facilitate quantitative assessment of the potential of biotechnology. More importantly, the developed country like US needs to take the lead as integral part of the sector in conjunction with international communities towards creating a welcoming policy environment that will encourage more access to information on biotechnology R&D in developing countries at little or no cost or through reformed public–private partnership.

5. Conclusion

In summary, steady growth of GM crops in the past 15 years have shown that GM technology has a great potential towards contributing to sustainable agriculture, particularly in developing countries. Moreover, the global benefit of GM crops have made significant difference in terms of cost savings, increases in yield and profitability, improving the quality of life and reducing the use of pesticide and herbicide. This in turn leads to a significant saving on fossil fuels and lowering carbon dioxide emissions, thereby mitigating climate change. According to James [66], more countries from different continents including Africa, Asia, Latin and Central America and Caribbean are expected to join GM producing countries on a commercial basis, and countries are expected to reach 40 or over by the year 2015 with about 20 million farmers cultivating GM crops across the globe. In the last few years supports for GM crops have come from different sections of life such as political leaders (e.g. G8 leaders), scientists, world reputed scholars, including policy makers and leaders from developing countries [19,33,66], suggesting that benefits of GM technology are being recognised.

The world needs fast and reliable solutions to fast growing population and the problems of hunger, malnutrition, ravaging diseases, poverty and global warming crisis. One of ideal technological innovations such as GM technology can be part of solutions to these problems. It is imperative to understand that GM technology cannot establish its ground if continuously faced with the baggage of constraints as discussed in Section 4.1 above. Moreover, it is not surprising to gather from a variety of literatures that most developing countries lack capacity building and still struggling with the establishment of biosafety system that can facilitate GM field trials and commercial release of GM products. Some of the challenges associated with the development of modern biotechnology still boil down to the fact that individual country government and international organisations have not clearly identified a coherent strategy and enabling policy instrument to deal with the problems. While some progress have been made on GM technology in terms of research and development, capacity building, and biosafety regulation in developed countries and a few developing countries, concerted effort is still needed to make it an accessible technology for every country.

Finally, the world of agricultural biotechnology should be appreciated while assessing its potentials and global impact in the last 15 years. More attention should be paid to the improvement of GM technology to harness its maximum potentials as well as taking case-by-case cautious regulatory approach [27], while considering future potential risks. All relevant institutions that include individual country government, private and public sector and international agencies should work together to ensure that everyone benefits from GM technology, particularly in developing countries. Therefore, the developing world if not entire world need GM technology and must not be ignored, marginalised or sidelined, because it has the weapons to fight poverty, reduce malnutrition and hunger, improve food security, create friendly environments, increase the income of poor farmers and benefit society as a whole.

Acknowledgment

The author acknowledges the support of the Japan Society for the Promotion of Sciences (JSPS). Special thanks to Janet E. Carpenter for corrections and insightful comments.

References

[1] ADB, Agricultural Biotechnology Poverty Reduction and Food Security, Asian Development Bank (ADB), Working Paper, 2001.
[2] A.A. Adenle, Nigeria must press ahead with GM crops: science and Innovation Policy, SciDev.Net April 27, 2011.
[3] I.S. Arvanitoyannis, P. Tserkezou, T. Varzakas, Int. J. Food Sci. Technol. 41 (2006) 130–159.
[4] J.C. Bayer, G.W. Norton, J.B. Falck-Zepeda, AgBioForum 13 (2010) 53–62.
[5] R. Bennett, S. Morse, Y. Ismael, Outlook Agric. 32 (2003) 123.
[6] T. Berg, M. Syed, H.G.O. Ferstad, B. Tsegaye, A. Waktola, Why are developing countries falling behind in biotechnology? Center for International Environment and Development Studies, Nairobi, Kenya, 2003.
[7] J.C. Bernard, J. Pesek, C. Fan, Agric. Resour. Econ. Rev. 33 (2004) 282–292.
[8] BMA, British Medical Association (BMA), Genetically Modified Foods and Health: A Second Interim Statement. British Medication Association, March 2004. Available from: <http://www.bma.org.uk/health_promotion_ethics/nutrition_exercise/GMFoods.jsp>.
[9] G. Brookes, AgBioForum 8 (2005) 235–241.
[10] G. Brookes, Int. J. Biotechnol. 10 (2008) 148–166.
[11] G. Brookes, P. Barfoot, AgBioForum 9 (2007) 139–151.
[12] G. Brookes, P. Barfoot, AgBioForum 13 (2010) 76–94.
[13] G. Brookes, P. Barfoot, GM Crops: Global Socio-Economic and Environmental Impacts 1996–2008, PG Economics Ltd., UK, 2010.
[14] J.E. Carpenter, Nat. Biotechnol. 28 (2010) 319–321.
[15] J.E. Carpenter, Landes Biosci. 2 (2011) 1–17.
[16] M. Cattaneo, C. Yafuso, C. Schimidt, C. Huang, M. Rahman, C. Olson, C. Ellers-Kirk, B. Orr, S. Marsh, L. Antilla, P. Dutilleul, Y. Carriere, Proc. Natl. Acad. Sci. USA 103 (2006) 7571–7576.
[17] J. Cayford, Issues Sci. Technol. (2004) 46–59.
[18] CGIAR, "Shaping the CGIAR's future: summary of proceedings and decisions" Consultative Group on International Agricultural Research (CGIAR) International Center Week, October 26–30, CGIAR Secretariat, Washington, DC, 1998.
[19] C. Clive, A time to sow? GM food could curb the cost of staples, Financial Times, July 10, 2008.
[20] J.I. Cohen, R. Paarlberg, AgBio-techNet 4 (2002).
[21] A.J. Connor, R.G. Travis, J.P. Nap, Plant J. 33 (2003) 19–46.
[22] G. Conway, The Doubly Green Revolution: Food for all in the 21st Century, Penguin Books, Cornell University Press, London, Ithaca, NY, 1999.
[23] G. Conway, G. Toenniessen, Nature 402 (1999) 55.
[24] J.G. Cooke, R. Downie, African Perspectives on Genetically Modified Crops: Assessing the Debate in Zambia, Kenya, and South Africa; A Report of the CSIS Global Food Security Project, Center for Strategic and International Studies (CSIS), 2010.
[25] S. Das, France's GM ban set to hurt Indian food exports, The Financial Express, 2009. Available from: <http://www.financialexpress.com/news/frances-gm-ban-set-to-hurt-indian-food-exports/535891/0>.
[26] EuropaBio, Eur. Assoc. Bioind. (2010).
[27] FAO, Food and Agriculture Organization of the United Nations, Statement on Biotechnology, March 2000. Available from: <http://www.fao.org/WAICENT/OIS/PRESS_NE/PRESSENG/2000/pren0017.htm>.
[28] FAO, Food and Agriculture Organization (FAO) of the United Nations. The State of Food and Agriculture 2003–04: Agricultural Biotechnology: Meeting the Needs of the Poor? FAO, 2004. Available from: <http://www.fao.org/docrep/006/Y5160E/Y5160E00.HTM>.
[29] FAO, World Hunger Educ. Serv. (2010).
[30] FAO, World agriculture: towards 2030/2050: Interim Report, 2006. Available from: <http://www.fao.org/docrep/009/a0607e/a0607e00.HTM>.
[31] G.P. Fitt, 'Implementation and impact of transgenic Bt cottons in Australia' The ICAC Recorded, vol. 21, 2003, pp.14–119.
[32] L. Folcher, M. Delos, E. Marengue, M. Jarry, A. Weissenberger, N. Eychenne, C. Regnault-Roger, Agron Sustainable Dev. 10 (2010) 1051.
[33] G8, Reporter's Notebook, G8 Leaders Call for Increased Global Access to Agricultural Biotechnology, Council for Biotechnology Information, July 2008. Available from: <http://www.whybiotech.com/newsandevents/reportersnotebook/0708/index_070908.asp>.
[34] L.P. Giannesi, J.E. Carpenter, Agricultural biotechnology: Benefits of transgenic soybeans, National Center for Food and Agricultural Policy, Washington, DC, 2000.
[35] H.C. Godfray, J.R. Beddington, I.R. Crute, L. Haddad, D. Lawrence, J.F. Muir, J. Pretty, S. Robinson, S.M. Thomas, C. Toulmin, Science 327 (2010) 812–818.
[36] M. Gomez-Barbero, E. Rodriguez-Cerezo, GM crops in EU Agriculture, European Commission, DG-JRC, Institute for Prospective Technology Studies, Seville, 2007.
[37] M. Gouse, C. Pray, J. Kirsten, D. Schimmelpfening, Int. J. Biotechnol. 7 (2005) 84–94.
[38] M. Gouse, J. Piesse, C. Thirstle, C. Poulton, AgBioForum 12 (2009) 78–89.

[39] Green, Contamination by Genetically Modified Papaya in Thailand, Greenpeace South Asia, Report, May 2006.
[40] J. Gressel, A. Hanafi, G. Head, W. Marasas, A.B. Obilana, J. Ochanda, T. Souissi, G. Tzotzos, Crop Prot. 23 (2004) 661–689.
[41] A. Gupta, ‘‘Impact of Bt Cotton on Farmers’ Health (in Barwani and Dhar District of Madhya Predesh),’’ Investigation Report, October–December 2005.
[42] B. Hammond, K. Campbell, C. Pilcher, T. Degooyer, A. Robinson, B. McMillen, S. Spangler, S. Riodan, L. Rice, J. Richard, J. Agric. Food. Chem. 52 (2004) 1390–1397.
[43] R. Hautea, M. Escaler, AgBioForum 7 (2004) 2–8.
[44] H.W. Heldt, Are there Hazards for the Consumer when Eating Food from Genetically Modified Plants? Union of the German Academies of Science and Humanities, Commission on Green Biotechnology, Universitat Gottingen, 2004. Available from: <http://www.akademienunion.de/pressemitteilungen/2006-06/english.html>.
[45] R.J. Herring, J. Dev. Stud. 43 (2007) 130–157.
[46] J. Huang, R. Hu, C. Pray, F. Quiao, S. Rozelle, Biotechnology as an alternative to chemical pesticides: a case study of Bt cotton in China, in: Fifth Inter. Consortium Ag. Biotech. Res., Ravello, Italy, June 15–18, 2001, pp. 109–110.
[47] J. Huang, S. Rozelle, C. Pray, Q. Wang, Science 295 (2002) 674–676.
[48] J. Huang, C. Pray, S. Rozelle, Nature 418 (2002) 678–684.
[49] J. Huang, R. Hu, S. Rozelle, C. Pray, Science 308 (2005).
[50] J. Huesing, L. English, AgBioForum 7 (2004) 87–95.
[51] ISAAA, International Service for the Aquisition of Agri-Biotech Applications: Crop Biotech Update, Newsletter, 2010.
[52] ISIS, Global GM Crops Area Exaggerated, Institute of Science in Society, ISIS Press Report, 2007.
[53] Y. Ismael, R. Bennett, S. Morse, Biotechnol. Dev. Monit. (2001) 15–19.
[54] C. James, Global Status of Commercialized Biotech/GM Crops: 1997 (ISAAA Brief No. 5), International Service for the Acquisition of Agri-biotech Applications, Ithaca, NY, 1997.
[55] C. James, Global Status of Commercialized Biotech/GM Crops: 1998 (ISAAA Brief No. 8), International Service for the Acquisition of Agri-biotech Applications, Ithaca, NY, 1998.
[56] C. James, Global Status of Commercialized Biotech/GM Crops: 1999 (ISAAA Brief No.12), International Service for the Acquisition of Agri-biotech Applications, Ithaca, NY, 1999.
[57] C. James, Global Status of Commercialized Biotech/GM Crops: 2000 (ISAAA Brief No. 21), International Service for the Acquisition of Agri-biotech Applications, Ithaca, NY, 2000.
[58] C. James, Global Status of Commercialized Biotech/GM Crops: 2001 (ISAAA Brief No. 24), International Service for the Acquisition of Agri-biotech Applications, Ithaca, NY, 2001.
[59] C. James, Global Status of Commercialized Biotech/GM Crops: 2002 (ISAAA Brief No. 27), International Service for the Acquisition of Agri-biotech Applications, Ithaca, NY, 2002.
[60] C. James, Global Status of Commercialized Biotech/GM Crops: 2003 (ISAAA Brief No. 30), International Service for the Acquisition of Agri-biotech Applications, Ithaca, NY, 2003.
[61] C. James, Global Status of Commercialized Biotech/GM Crops: 2004 (ISAAA Brief No.32), International Service for the Acquisition of Agri-biotech Applications, Ithaca, NY, 2004.
[62] C. James, Global Status of Commercialized Biotech/GM Crops: 2005 (ISAAA Brief No.34), International Service for the Acquisition of Agri-biotech Applications, Ithaca, NY, 2005.
[63] C. James, Global Status of Commercialized Biotech/GM Crops: 2006 (ISAAA Brief No. 35), International Service for the Acquisition of Agri-biotech Applications, Ithaca, NY, 2006.
[64] C. James, Global Status of Commercialized Biotech/GM Crops: 2007 (ISAAA Brief No. 37), International Service for the Acquisition of Agri-biotech Applications, Ithaca, NY, 2007.
[65] C. James, Global Status of Commercialized Biotech/GM Crops: 2008 (ISAAA Brief No. 39), International Service for the Acquisition of Agri-biotech Applications, Ithaca, NY, 2008.
[66] C. James, Global Status of Commercialized Biotech/GM Crops: 2009 (ISAAA Brief No. 41), International Service for the Acquisition of Agri-biotech Applications, Ithaca, NY, 2009.
[67] C. James, Global Status of Commercialized Biotech/GM Crops: 2010 (ISAAA Brief No.42), International Service for the Acquisition of Agri-biotech Applications, Ithaca, NY, 2010.
[68] A. Jamwal, U.M. Ohndorf, F. Boeuf, D. Herman, Bio-Visions 2015: Scenarios for Biotechnology (A Report), Siemens AG, Munich, 2006.
[69] H.T. Jensen, H.G. Jensen, M. Gylling, Adoption of GM Food Crop Varieties in the European Union, Institute of Food and Resource Economics, University of Copenhagen, 2009. Available from: <http://www.gtap.agecon.purdue.edu/resources/download/4765.pdf>.
[70] C. Juma, The New Harvest, Agricultural Innovation in Africa, Oxford University Press, 2011.
[71] M. Karembu, F. Nguthi, H. Ismali, Biotech crops in Africa: The Final Frontier, ISAAA AfriCenter, Nairobi, Kenya, 2009.
[72] L. Kent, AgBioForum 7 (2004) 63–69.
[73] E. Landais, Gulf News (2007).
[74] U. Lele, Am. J. Agric. Eco. 85 (2003) 1119–1125.
[75] R. Luther, K. Tucker, AgBioForum 5 (2002) 59–64.
[76] D. Makinde, L. Mumba, A. Ambali, Asian Biotechnol. Dev. Rev. 11 (2009) 1–10.
[77] M.P. Marra, P. Pardey, J. Alston, AgBioForum 5 (2002) 43–50.
[78] E. Mashood, The GM Debate-Who Decides? Analysis of decision-making about genetically modified crops in developing countries, Panos Report No 49. (2004).
[79] M. Millers, ‘‘Genetically modified crops in Africa’’, in: J. Cutler (Eds.), Encyclopedia of Earth, Cleveland, 2007 (Washington, DC: Environmental Information Coalition, National Council for Science and the Environment).
[80] S. Morse, R. Bennett, Y. Ismael, Int. J. Biotechnol. 7 (2005) 72–83.
[81] J. Mugabe, Biotechnology in developing countries and countries with economies: strategic capacity building considerations, African Centre for Technology Studies, Nairobi, Kenya, 2000.
[82] J.A. Nordlee, N. Engl. J. Med. 334 (1996) 688–692.
[83] D. Normile, Science 289 (2000) 843–845.
[84] M. O‘Callaghan, Banning GM Food and Crops in Europe, GM-Free Ireland Network, Dail Briefing on GMO Policy, 15 June 2005.
[85] R. Paarlberg, The Global Food Fight, Foreign Affairs May/June, pp. 24–38, 2000.
[86] R. Paarlberg, Int. J. Technol. Global. 2 (2006) 81–92.
[87] C.N. Pedleton, Biotechnol. Law Rep. 23 (2004) 1–29.
[88] G.J. Persley, M.M. Lantin (Eds.) Agricultural Biotechnology and Poor, in: Proceedings of an International Conference on Biotechnology, Washington, DC, 21–22 October 1999, Consultative Group on International Agriculture Research, Washington, DC, 2000.
[89] P. Pinstrup-Andersen, Selected Aspects of the Future Global Food Situation, 25th IFA Enlarged Council Meeting, Rome, 30 November–3 December 1999.
[90] I. Potrykus, Plant Physiol. 125 (2001) 1157–1161.
[91] I. Potrykus, GMO-projects for public goods are faced with prohibitive conditions. Paper Presented at the 13th ICABR Conference, Ravello, Italy 2009.
[92] C.E. Pray, J. Huang, R. Hu, S. Rozelle, Plant J. 31 (2002) 423–430.
[93] C. Pray, P. Bengali, B. Ramaswami, Q. J. Int. Agric. 44 (2005) 267–289.
[94] M. Qaim, Ann. Rev. Resour. Econ. 2009 (2009) 665–693.
[95] M. Qaim, A. De Janvry, Am. J. Agric. Eco. 85 (2003) 814–824.

[96] M. Qaim, A. De Janvry, Environ. Dev. Econ. 10 (2005) 179–200.
[97] M. Qaim, G. Traxler, Agric. Econ. 32 (2005) 76–86.
[98] M. Qaim, D. Zilberman, Science 299 (2003) 900–902.
[99] A. Qayum, K. Sakkhari, Bt Cotton in Andhra Pradesh A Three-year Assessment, The First Ever Sustained Independent Scientific Study of Bt Cotton in India, Deccan Development Society, Andhra Pradesh Coalition in Defense of Diversity, Permaculture Association of India, 2005.
[100] T. Raney, Curr. Opin. Biotechnol. 17 (2006) 1–5.
[101] K. Redenbaugh, M. Hiatt, B. Martineau, M. Kramer, R. Sheehy, R. Sanders, C. Houck, D. Emlay, Safety Assessment of Genetically Engineered Fruits and Vegetables; A Case Study of the FLAVR SAVRTM Tomato, CRC Press, Boca Raton, FL, 1992.
[102] RF, Rockefeller Foundation ''Food gains for the world's poor are being threatened by furor over genetically modified (GM) foods'', Press release, Rockefeller Foundation, Washington, DC, 1999.
[103] W. Roca, C. Espinoza, A. Panta, AgBioForum 7 (2004) 13–22.
[104] M.W. Rosegrant, P.B.R. Hazell, Transforming the rural Asian economy: the unfinished revolution (2020 Vision Brief 69). Washington, DC: International Food Policy Research Institute, 2001. Available from: <http://www.ifpri.org/2020/briefs/number69.htm>.
[105] RS, Where is the Evidence that GM Foods are Inherently Unsafe, Asks Royal Society. Press release, Royal Society (RS), 8 May, 2003. Available from: <http://royalsociety.org>/<http://royalsociety.org>/Submission-to-the-Governments-GM-Science-Review/<http://royalsociety.org>/GM-crops-modern-agriculture-and-the-environment—Report-of-a-Royal-Society-Discussion-Meeting-held-on-11-February-2003/.
[106] V.W. Ruttan, AgBioForum 2 (1999) 54–60.
[107] O. Sanvido, J. Romeis, F. Bigler, Adv. Biochem. Eng. Biotechnol. 107 (2007) 235–278.
[108] I. Scoones, D. Glover, Nature 460 (2009) 797–798.
[109] A. Sharma, Moratorium on GM Crops Sought, The Financial Express, December 2, 2006.
[110] H.C. Sharma, J.H. Crouch, K.K. Sharma, N. Seetharama, C.T. Hash, Plant Sci. 163 (2002) 381–395.
[111] S. Stone, A. Matysek, A. Dooling, Modelling Possible Impacts of GM crops on Australian Trade, Staff Research Paper, Productivity Commission, Melbourne, 2002.
[112] C. Thirstle, L. Beyers, Y. Ismael, J. Piesse, World Dev. 31 (2003).
[113] G. Traxler, S. Godoy-Avila, AgBioForum 7 (2004) 57–62.
[114] W.P. Williams, G.L. Windham, P.M. Buckley, J.M. Perkins, Field Crops Res. 91 (2005) 329–336.
[115] F. Wu, Perspect. Agric. Vet. Sci. Nutr. Nat. Resour. 2 (2007) 1–8.
[116] J. Yang, J.W. Kloepper, C.M. Ryu, Trends Plant Sci. 14 (2009) 1–4.
[117] R.H. Zhou, Z.C. Zhang, Q. Wu, R.X. Fang, K.Q. Mang, Y.C. Tian, Large-scale performance of transgenic tobacco plants resistant to both tobacco mosaic virus and cucumber mosaic virus, in: D.D. Jones (Ed.), Proceedings of the Third International Symposium on the Biosafety Results of Field Tests of Genetically Modified Plants and Micro-organisms, University of California, Oakland, CA, 1995, pp. 49–55.
[118] D. Zilberman, H. Ameden, M. Qaim, J. Dev. Stud. 43 (2007) 63–78.