Two decades of GMOs-how can the new technology help meet SDGs?

1) Introduction

Genetically modified organisms (GMOs) have been available commercially for over twenty years, however, they remain as controversial as ever. According to the new International Service for the Acquisition of Agri-biotech Applications (ISAAA) report, in 2017, the global biotech acreage increased by 3% or 4.7 million hectares, with over half of these increases coming from smallholder farmers in developing countries (James 2018). GM crops that were initially developed catered to farmers who wished to increase crop yield and resistance to biotic stresses, such as insects and other plant pathogens. With the advent of climate change, second generation biotech crops focused more on abiotic stresses such as tolerance to heat, drought and flooding. Crops that possessed 'stacked' traits (two or more new traits expressed from the same plant) were developed to better withstand environmental changes due to climate change. Currently, the world is entering a stage of third generation GM crops, that is, transgenic crops which cater to consumers as well as the food and manufacturing industries. Examples of such crops include crops which are biofortified, nutritionally-enhanced or can reduce food waste (James 2017).

The Millenium Development Goals (MDGs) were originally set up by the United Nations (UN) between 2000 to 2015 to fight poverty by establishing a series of eight measurable objectives that helped to promote political accountability, improved metrics and global awareness of world's poor (Sachs 2012). During this time period, great strides were made in the fight against poverty; much of this advance was a result of a boost in economic growth in China. However, although some countries have managed to achieve the majority of the MDGs, others have not. More recently, the advent of climate change, rising poverty and other pressing global challenges have necessitated a revision of these goals in order to incorporate overriding sustainability objectives that can be addressed alongside poverty-reduction objectives. Rising incomes, along with predicted population growth, will increase food demand particularly with respect to meat consumption, and in turn are expected to exert more pressure on ecosystems. The number of chronically hungry currently exceeds 1 billion, and the gap between wealthy and poor continues to grow. The Sustainable Development Goals (SDGs) were thus developed in response to these changes in parameters (Fullman, Barber et al. 2017). The SDGs and their corresponding indicators represent a broader range of sustainable development challenges than the MDGs; this enables more appropriate decision-making and implementation to take place. Given these challenges, radical new approaches including technological innovation is urgently required to implement SDGs[1]. In this regard, GMOs have great potential to help meet part of the SDGs especially in developing world.

The following chapter discusses the development of GM crops which have the ability to address several of the SDGs (Table 1). The chapter begins by describing the role of GMOs in achieving environmental goals laid out in the SDGs, including lowering greenhouse gas emissions, conserving biodiversity and reducing food waste. The chapter then describes potential direct and indirect health advantages to GMOs. Finally, various socio-economic dimensions and future challenges with respect to the employment of GMOs and possible solution to address the challenges, within the context of implementing SDGs, are described.

Table 1: Overview of GM Crops Traits which Address SDGs

Sustainable development Goals (SDGs)	Description	GM crop example	Reference
SDG 1	End poverty in all its forms everywhere	Bt cotton enabled reduced pesticide use, yield increase	(Qaim and Zilberman 2003)
SDG 2	End hunger, achieve food security and improved nutrition and promote sustainable agriculture	Golden rice, anthacyanin tomatoes, insect resistant cow peas	(Butelli, Titta et al. 2008) (De Steur, Blancquaert et al. 2015)
SDG 3	Ensure healthy lives and promote will being for all at all ages	Golden rice Folate biofortified rice	(De Steur, Blancquaert et al. 2015) (Wesseler and Zilberman 2014)
SDG 5	Achieve gender equality and empower all women and girls	Herbicide tolerant plants, Bt cotton reduces laborious tasks in the	(Gandhi and Namboodiri 2006)

[1] https://sustainabledevelopment.un.org/tfm

		field	
SDG 7	Ensure access to affordable, reliable, sustainable and modern energy for all	GM sugar-cane for biofuel, GM switchgrass	(Janda, Kristoufek et al. 2012) (Shen, Poovaiah et al. 2013)
SDG 8	Promote sustained, inclusive, and sustainable economic growth, full and productive employment and decent work for all	Maintenance of plant material, GM crops which assist with sustainable growth	(Smart, Blum et al. 2017) (Bovay and Alston 2018)
SDG 12	Ensure sustainable production and consumption patterns	Regulation of food prices Non-browning apples	(Ricroch and Henard-Damave 2016) (Bovay and Alston 2018)
SDG 13	Take urgent action to combat climate change and its impacts	Herbicide tolerant soybean reduces tillage, GE switchgrass for biomass	(Shen, Poovaiah et al. 2013) (Brookes and Barfoot 2015) (Barrows, Sexton et al. 2014)
SDG 15	Protect, restore and maintain sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	Bt cotton and retention of non-target insect populations GM maize	(Marvier, McCreedy et al. 2007) (Gouse 2012) (Barrows, Sexton et al. 2014)
SDG 16	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all, and build effective, accountable, and inclusive institutions at all levels	Regulation of transgenic seed, GMO governance inclusivity	(Smart, Blum et al. 2017) (European Commission 2010)

2) GMOs and Environmental dimension

The correlation between the application of GMOs and achievement of the sustainable development goals (SDGs) will be examined particularly in terms of positive impacts among GM producing countries with focus on SDGs 7, 12, 13 and 15.

2.1) Lowering greenhouse gases emissions

Unless serious action is taken to lower global warming greenhouse gas emissions (GHGs), climate change will continue to have damaging effects on populations around the world. Tackling the impact of climate change remains on the 2030 agenda of the United Nations and Paris Agreement, especially with respect to lowering GHGs emissions.

The agricultural sector remains the third largest producer of global GHG emissions, leading to environmentally unfriendly practices. Technological innovation such as GM technology could help solve part of these problems particularly with regard to the implementation of SDG 13. GM crops have been engineered to lower the amount of chemicals through the use of pesticides, thereby lowering GHG emissions. According to James (2016), the adoption of commercialised GM crops, for example, GM maize, cotton, soybean and canola, have contributed to a reduction of global GHG emissions over the past two decades.

This is consistent with the analysis of Brookes and Barfoot between 1996 and 2015, who showed that, on a global scale, the agricultural environmental footprint was reduced by 613 million kg of active ingredient among GM producing countries including the United States, China, India, South Africa, Brazil and Argentina (Brookes and Barfoot 2017). Also, these authors estimate that 174 million hectares of land were saved through the adoption of GM crops. During the past decade, a number of studies (mostly in developed countries), have shown an environmental benefit of GM crops, particularly with regard to pesticide reduction (Gianessi and Carpenter.J.E. 2000; Gianessi 2005; Cerdeira and Duke 2006; Fernandez-Cornejo, Wechsler et al. 2014; Brookes and Barfoot 2015). Recently, the meta-analysis of 147 studies showed that 37% in reduction of chemical pesticide was a result of adoption of GM technology, especially in developing countries (Klümper and Qaim 2014).

The use of genetically engineered herbicide-tolerant and insecticide-resistant crops is known to have facilitated the adoption of conservation tillage practices among farmers, ranging from minimum to zero tillage. For example, according to Brookes and Barfoot (2015), in 2013, the adoption of GM crop such as soybean that required conservation tillage practices, represent 80% and 89% in US and Argentina, respectively. These authors reported that the reduced level of GHG emissions is associated with fuel savings and soil carbon sequestration due to adoption of GM crops in these countries. According to the FAO report, the soil carbon sequestration has been attributed to the adoption of best agricultural practices such as conversation tillage (FAO 2008). Their report indicates that a conservation tillage system offers better recycling of soil nutrients during the first decade of adoption, resulting in a decrease of 1.8 ton CO_2 release per hectare per year. In view of this report, reduction in GHG emissions is more likely to be encouraged when GM technology is combined with the conservation tillage practices, thereby contributing directly to SDG 13.

There has also been a great deal of interest in the application of GM technology to improve biofuel production, thus producing renewable energy and reducing GHG emissions. A growing body of literature has reported that the potential role of genetic engineering in biofuel production. For example, in the US, the yield of cellulosic ethanol increased by more than two fold through the genetically engineered biomass such as switchgrass (*Panicum virgatum*) (Shen, Poovaiah et al. 2013). Moreover, a team of researchers (Brennan and Owende 2010; Singh, Nigam et al. 2011) have reported that genetic engineering can help develop new types of microalgae strains for biodiesel production by increasing lipid quality. According to Brennan and Owende (2010), biofuel production from microalgae has great potential for carbon capture under different conditions. The algae biofuel production research related program, particularly through genetic engineering, continues to emerge and is expected to contribute to a positive environmental impact.

2.2) Conserving biodiversity

A fast growing population presents a significant challenge to biodiversity conservation around the world. There is an urgent need to respond to population increases through increased agricultural production. In order to cope with increased demands for agricultural products from growing populations, there will be more competition for land and water, which in turn, will contribute to deforestation, depletion of soil, and the loss of biodiversity. Responding to this challenge can be partly addressed by the use of GM technology (Barrows, Sexton et al. 2014), thereby helping to achieve SDG 15.

The implication of introducing GM technology for biodiversity can be complex, and of course, has generated a lot of heated debate as to whether or not GM technology can impact biodiversity positively. A large number of studies have been conducted on the introduction of GM technology for biodiversity. The positive impact of GM technology has been reported for less cultivated land. The conservation tillage system forms part of agriculture management practices as described in Section 3.1. A study by (Carpenter 2010) analysed 49-peer reviewed publications on the adoption of GM crops from 12 countries by comparing the yields between adopters and non-adopters. The author showed that out of 168 results (based on yield outcome), 124 results were positive for GM adopters (most of these farmers came from developing countries) when compared to non-adopters. This result is consistent with the ISAAA report that 18 million poor smallholders have benefited from the adoption of GM crops in the past two decades (James 2016). Taken together, these authors argue that, fewer lands have been converted to agricultural production through the adoption of GM crops while the yields increased, thereby conserving biodiversity in land and forest areas.

The beneficial role of insects and other arthropods remains crucial in maintaining soil fertility (Culliney 2013). Multiple times the potential positive and negative impacts of GM technology on non-target invertebrates have been discussed in the literature. In this regard, several studies have revealed the impact of GM technology (*Bacillus thuringensis-Bt*) on soil biodiversity. Using meta-analysis studies, the results of 42 field experiments of *Bt* maize and *Bt* cotton vs. non-*Bt* crops were analysed based on the abundance of non-target invertebrates (Marvier, McCreedy et al. 2007). Their results showed that there was greater abundance of non-target invertebrates in *Bt* crops compared to non-*Bt* crops. In a similar study, another author analysed the effect of *Bt* on soil biodiversity over a period of 15 years and concluded that little or no effects of Bt on soil biodiversity have been recorded, although some differences reported in soil biodiversity are known to be due to differences in temperature, soil type and crop varieties (Carpenter 2011). Overall, the adoption of GM crops has created more environmentally friendly farming practices particularly through the enhancement of soil biodiversity.

2.3) GMOs in the context of implementation of SDG 7, SDG12, SDG 13 and SDG 15

In view of explanation above, there is causal relationship between GM technology and SDG7, SDG13 and SDG15; therefore, promotion of GM technology can help meet SDGs around the world, especially in developing countries.

One of the key targets for SDG7 is to increase the share of renewable energy mix by the year 2030. Brazil is arguably the only country in the world where ethanol remains an important component of the energy mix since the 1930s when a 5% ethanol blend with gasoline was introduced (Cerqueira Leite, Verde Leal et al. 2009), and now at 18-25% for gasoline (Janda, Kristoufek et al. 2012). In 2003, the Brazilian government introduced Flex Fuel Vehicle to cut down on gasoline use in order to reduce GHG emissions. Because of the mandatory blend, 50% of gasoline has been replaced by ethanol for transport (Janda, Kristoufek et al. 2012). The energy mix policy is largely driven by huge investment in agricultural research and development (R&D) programs. The main Brazilian agricultural institution EMBRAPA is leading the research effort in developing various GM products including sugar-cane drought resistant for biofuel production. Brazil, being one of the largest producers of GM crops, can be argued to be in an excellent position to achieve the SDG7 goal. Other advanced developing countries such as Argentina and South Africa also have extensive biotechnology R&D programs, but their R&D activities will have to be shifted toward biofuel production among other renewable energy programs in order to meet SDG7 targets. More importantly other developing countries will have to follow in Brazil's footsteps in their efforts to achieve SDG7 targets.

The ability to invest in biotechnology R&D, especially among GM producing countries, has been partly attributed to adoption of GM crops. The development of robust strategies for new GM crop traits can help achieve both SDG 13 and SDG 15 in these countries. Brookes and Barfoot (2017) argue that the reduction of GHG emissions in 2015 alone is equivalent to removing 12 million cars off the road, suggesting that promotion of GM technology in agricultural practices, particularly in developing countries, can help achieve SDG 13. According to James (2016) and Brookes and Barfoot (2015) *inter alia,* the application of GM technology has contributed considerably to a reduction of GHGs into the atmosphere, due to limited spraying of pesticides and herbicides. While industrialised countries have largely benefitted from adoption of GM crops, it is important to emphasise the potential role of other GM crops that are under R&D programs or confined field trials and how these GM crops can help contribute to meeting the SDGs in developing countries. GM technologies such as drought and salinity tolerance traits can play a crucial role toward implementing SDGs especially in meeting the target of SDG13 of strengthening resilience and adaptive capacity related to the impact of climate change. Drought tolerant GM crops can help protect high biodiversity areas and reduce soil contamination, thereby resulting in land savings and maintaining soil fertility. Moreover, GM drought tolerant crops could make a significant reduction in the use of water with huge environmental benefits, particularly in drought prone regions of Africa. This could potentially meet the target of SDG 15 by taking significant action to reduce natural habitat degradation, drought and desertification. The availability of new GM crop varieties (for example, GM maize, Wesseler et al., 2017) can position many African countries to achieve SDG 15 and other relevant SDGs. Taken together, the combined benefits of GM crops can reduce the impact of climate change, improve the health of farmers and put their economy on a sustainable path of growth.

More recently, GM technology has also been used to combat food waste along the chain. According to FAO, up to one third of all food is lost before it is consumed (FAO 2018). Through eliminating cosmetic issues associated with crops, GM technology can contribute to SDG 12 and its targets to halve global food waste at retail and consumer levels. For example, several varieties of late-blight disease resistant potato have recently been approved for commercialization. These transgenic potatoes will not only increase yield and reduce the use of fungicides as much as 45%, but will also reduce food wastage through its non-browning trait (James 2017). Similarly, several apple varieties were genetically modified to be resistant to browning and, oftentimes, bruising, two attributes causing retailer and consumer reluctance (Thompson and Kidwell 1998; Waltz 2015). This new technology is much anticipated, as approximately 31% or 133 billion pounds of food is wasted annually (GMO Answers, 2016). Simplot and Okanagan Specialty Fruits, owned by Intrexon Corporation, have successfully completed field trials and apples and potatoes are currently on the market. Another example is the non-browning mushroom, which is the first application of the CRISPR-CAS9 technique that is approved in the US (Waltz 2016).

3) GMOs and Health Dimension

Whereas the majority of commercialized GMOs are targeted at increased productivity in order to help ensure food security and end hunger, GM technology also has the potential to reduce the global burden of malnutrition and hidden hunger. Health oriented GMOs, like vitamin or mineral enriched GM foods (GM biofortified foods), are considered to be part of the third generation of GMOs, by which output/quality traits are introduced or improved (James 2017). With direct, tangible benefits for the end-user (nutritious, anti-allergic, improved ripening/extended shelf life, and improved taste/appearance) (Parisi, Tillie et al. 2016), this generation complements farmer-oriented generations, which typically focused on the improvement (first) and stacking of input traits (second generation). Nutritionally enhanced GMOs can be considered to be potentially promising means to contribute to the achievement of SDG 2. Furthermore, GMOs with agronomic traits can also indirectly improve farmers' health through lowering exposure to insecticides and herbicides (e.g., (Pray, Ma et al. 2001)), which aligns with SDG 3 on health.

3.1. Direct effects on public health

Biofortification is the process of improving the nutritional quality of (staple) food crops through conventional plant breeding (conventional biofortification), fertilizer optimization or soil improvement (agronomic biofortification) and/or use of biotechnology (GM biofortification) (Johns and Eyzaguirre 2007; Hirschi 2009; Adenle, Aworh et al. 2012; Carvalho and Vasconcelos 2013). Non-GM biofortified crops are widely developed and commercialized (Bouis and Saltzman 2017; Cakmak and Kutman 2018), but the applied conventional breeding techniques are inadequate when dealing with crops with a low or absent level of a certain micronutrient (Beyer 2010). This is where GM technology comes into play. A recent review has summarized successful R&D efforts in the field of GMOs with increased micronutrient content in staple crops (De Steur, Blancquaert et al. 2015). They have identified 35 studies that reported a substantial fold change in one of the following micronutrients: pro-vitamin A (rice, potato, corn, wheat, cassava, sorghum), vitamin B9/folate (rice, corn), vitamin C (corn, potato), iron (rice, corn, barley), zinc (rice, barley), copper (rice).

Two well-known, advanced examples of GM biofortification are Golden Rice, enriched with pro-vitamin A (β-carotene)(Ye, Al-Babili et al. 2000; Paine, Shipton et al. 2005) and vitamin B9 (folate) enhanced rice (Storozhenko, De Brouwer et al. 2007; Blancquaert, De Steur et al. 2014). Here, conventional breeding techniques were not applicable given the absence and low content of these micronutrients in rice. For Golden Rice, a combination of transgenes from daffodil and *Pantoea* were inserted to introduce pro-vitamin A levels in the rice endosperm (Ye, Al-Babili et al. 2000). Initially developed in 2000, Golden Rice was further improved to contain up to 23-fold increase in carotenoid content as compared to the original, known as GR2 (Paine, Shipton et al. 2005). Folate biofortified rice was developed through overexpression of transgenes from *Arabidopsis* in rice endosperm. Through transgenic breeding, a four-fold increase of the baseline folate concentrations in rice could be reached (Storozhenko, De Brouwer et al. 2007), while folate stability of long term storage could be improved (Blancquaert, Van Daele et al. 2015). Aside from these promising cases, there has been considerable advancements in the use of biotechnology for micronutrient enhancement, as illustrated in reviews pro-vitamin A (Giuliano 2017; Lee 2017), B1 (thiamin)(Pourcel, Moulin et al. 2013; Goyer 2017), B6 (Fudge, Mangel et al. 2017), B9 (folic acid)(Blancquaert, Storozhenko et al. 2010; Van Der Straeten and Strobbe 2017), Vitamin C (ascorbate)(Macknight, Laing et al. 2017) Vitamin E (Mène-Saffrané and Pellaud 2017), iron (Vasconcelos, Gruissem et al. 2017) and iodine (Gonzali, Kiferle et al. 2017).

Furthermore, as knowledge on vitamin and mineral metabolic pathways steadily grows, there has been a recent interest and shift towards research on multi-biofortification, i.e. the simultaneous enhancement of the level of multiple micronutrients (De Steur, Blancquaert et al. 2015). While several researchers targeted rice for the enhancement iron and zinc (Vasconcelos, Datta et al. 2003; Johnson, Kyriacou et al. 2011; Trijatmiko, Dueñas et al. 2016; Wu, Gruissem et al. 2018) and copper (Lee, Jeon et al. 2009), few researchers successfully accumulated micronutrient levels in corn (pro-vitamin A, folate, vitamin C)(Naqvi, Zhu et al. 2009) and barley (iron, zinc)(Ramesh, Choimes et al. 2004).

Whereas most applications of GM biofortification aim to elevate vitamin and/or mineral concentrations in staples (such as zinc, iron and pro-vitamin A), GM biofortification could also involve the reduction of anti-nutrients in foods (e.g. phytic acid reduction in cereals (Shahzad, Rouached et al. 2014), the enhancement of macronutrients (e.g. amino acids and fatty acids)(Galili and Höfgen 2002), with the aim to correct or prevent deficiency and provide a health benefit (Zhao and Shewry 2011; Codex Alimentarius Commission 2015). In the US, for example, Innate™ potato varieties, which have bacterial blight resistance and non-browning traits as well as potential health benefits through lower toxin concentrations of acrylamide, have been approved for cultivation (Rommens, Yan et al. 2008; Waltz 2015). Other GMOs with health traits that were approved for commercialization are high-oleic acid soybeans (low in trans-fats; only small scale commercialization) and high-lauric acid canola (currently not commercialized due to inferior agronomic traits) (Kramer, Hoppe et al. 2001; National Academies of Sciences and Medicine 2016). Research on GMOs with lower natural toxin concentrations, e.g. reduction in aflatoxin in crops like Bt maize (Bhatnagar-Mathur, Sunkara et al. 2015; Ostrý, Malíř et al. 2015), or macronutrients, e.g. omega-3 enhanced oilseed crops (Venegas-Calerón, Sayanova et al. 2010; Ruiz-Lopez, Haslam et al. 2014) or protein-rich potato (‘protato’)(Changat and Krishna 2006; Chakraborty, Chakraborty et al.

2010), is ongoing and could serve a significant purpose of preventing the accumulation of these types of toxins in the future.

To further underpin the impact of the aforementioned R&D efforts, researchers have assessed the nutrition/health effects of GM biofortification, either *ex ante* or *ex post*. Regarding the latter, only one clinical trial on Golden Rice is available. A randomized trial in the United States resulted in a high bio-conversion factor of b-carotene in Golden Rice (3.8:1), by which 100 g of uncooked Golden Rice would provide about 80–100% of the estimated average requirement (EAR) and 55–70% of the recommended dietary allowance (RDA) for adult men and women (Tang, Qin et al. 2009). Findings from 15 simulation analyses, as reported in economic evaluation studies and biotechnology studies, confirmed the promising effects of GM biofortified crop consumption on dietary intake and nutritional outcomes in humans (De Steur, Mehta et al. 2017). The relatively high micronutrient concentrations in targeted GM biofortified crops that could be reached through the use of biotechnology led to substantial effects on closing the micronutrient intake gap in human populations. In nearly all studies, a regular portion of the targeted biofortified crop would provide the daily micronutrient requirements. A good case in point is the recent simulation analysis of Golden Rice in Asia (De Moura, Moursi et al. 2016). Its implementation could reduce the prevalence of dietary vitamin A inadequacy by up to 30% (children) and 55-60% (women) in Indonesia and the Philippines, and up to 71% (children) and 78% (women) in Bangladesh, thereby contribute to SDG 3 targets.

In addition to biofortification, transgenic plants have been used to create crops which possess other health benefits. For example, transgenic lines of tomato with increased expression of flavonols and carotinoids such as lutein, B-carotene and zeathanthin have been shown to provide anti-inflammatory properties and act against cardiovascular disease and even cancer (Butelli, Titta et al. 2008). A panel of consumers liked the flavour of these tomatoes and indicated that they would purchase these GM tomatoes that promote improved health benefits (Lim, Miller et al. 2014). Similarly, transgenic tomato expressing flavonols were demonstrated to improve bone mass (Choudhary, Pandey et al. 2016). In all of these examples, tomato has been the crop of choice for improved health benefits as it is easy to grow, low in cost and is accessible to consumers worldwide.

3.2.) Indirect effects on farmers' health

While GMOs with nutritional benefits could improve human health directly (see 3.1.), GMOs with improved agronomic traits could also generate health effects, though indirectly, through its impacts on the environment and insecticide and herbicide use. A review of Klümper and Qaim (2014) has demonstrated a substantial lower use of chemical pesticides for GMOs, i.e. an average reduction of pesticide quantity of 37%. Substantial reductions are mainly reported for insect-resistant (*Bt*) crops (Racovita, Obonyo et al. 2015), as herbicide-tolerant crops may both increase and decrease different types of herbicide use (Zhang, Hu et al. 2016). Furthermore, the decline in insecticide treatments is often associated with a lower number of farmers reporting poisonings. This has been illustrated in studies with Bt cotton farmers in China (Huang, Hu et al. 2002), India (Kouser and Qaim 2011), Pakistan (Kouser and Qaim 2013) and South Africa (Bennett, Morse et al. 2006). Besides, the adoption of *Bt* cotton has been associated with adoption of eco-friendly rather than chemical pesticides (Veettil, Krishna et al. 2017).

The effects of herbicides that are used in association with herbicide-tolerant plants have also been examined in detail. By far the most well-known herbicide that is used in conjunction with a GM crop is glyphosate. Commercialised in 1977, glyphosate is a broad-spectrum weed killer that acts by inhibiting the synthesis of three amino acids in plants (Duke, Lydon et al. 2012). As glyphosate breaks down easily and is less toxic than many herbicides that were used earlier, it quickly became popular among farmers around the world and was widely adopted into their farming practices. Resistance to this herbicide was identified by Monsanto from a microorganism and used to generate transgenic plants (Duke 2015). The planting of glyphosate tolerant crops, in combination with the herbicide, greatly simplified weed management. The first glyphosate-resistant crops were commercialized in 1996. Today, over 90% of corn, soybean and cotton produced in the US are genetically modified to be tolerant to glyphosate (James 2010).

Benefits associated with herbicide tolerant transgenic plants include a decrease in CO_2 release resulting from low-tillage farming (e.g. (Smyth 2017)). Thus, HT plants reduce soil erosion and offer significant economic savings, while at the same time improve crop yield. After planting of seeds and as little as one dose of herbicide, farmers can block weed growth while saving on tractor fuel. In developing countries, this labour-saving feature can free the time of women who work in agriculture, so that they can focus on other things. Limitations include the fact that weed management is solely based on herbicides, and as a result, the amount of herbicide used has not lessened (Bonny 2016), while the toxicity level of active ingredients emitted into the environment declined (Wesseler, Scatasta et al. 2011). Recently, glyphosate-resistant weeds have been identified and have become an environmental concern (de Castilhos Ghisi and Cestari 2013). It is important to note that herbicide resistance in weeds can also found in the absence of transgenic technology (Wesseler, Scatasta et al. 2011).

Controversial results regarding the link between glyphosate and cancer, as well as its impact on soil, water and aquatic species have been published. This series of contradictory statements by regulatory bodies have caused much public confusion regarding the safety of glyphosate (Landrigan and Belpoggi 2018). On the other hand, less health risks among farmers that adopted herbicide tolerant crops have been reported (Qaim and Kouser 2013), suggesting that glyphosate is less harmful to human health.

3.3) GMOs in the context of implementation of SDG 2 and SDG 3

While GM biofortified crops, once approved, could help meet nutrition targets of SDG 2 (End hunger, achieve food security and improved nutrition, and promote sustainable agriculture) especially in the developing world, GMOs with agronomic traits could offer indirect health effects and thereby contribute to SDG 3.

Despite great progress in the reduction of micronutrient malnutrition (Hay, Abajobir et al. 2017) and the achievement of the nutrition targets of SDG 2 (Fullman, Barber et al. 2017), about 2 billion people are still considered to suffer from one or more micronutrient deficiencies. This points out the need for complementary strategies to existing, effective micronutrient interventions, like vitamin A or iron supplementation (Wesseler, Smart et al. 2017). Given the fact that current food systems in developing countries are not capable to provide adequate amounts of micronutrients to their populations (Welch and Graham 2005), nutrition-sensitive agriculture is often proposed as an alternative solution to alleviate the burden of malnutrition (Zhao and Shewry 2011; Masset, Haddad et al. 2012; Ruel and Alderman 2013). Not surprisingly, there has been made considerable progress of conventional biofortification since the turn of the century, with many micronutrient enriched crops being implemented in over 50 priority countries (HarvestPlus 2015). There is considerable and ever-growing number of evidence showing that such crops are a highly cost-effective strategy (Meenakshi, Johnson et al. 2010) to improve micronutrient status among target populations (Low, Arimond et al. 2007; Haas, Finkelstein et al. 2013).

Similar conclusions can be drawn for the future implementation of GM biofortified crops, illustrating its potential to contribute to the nutrition targets of SDG 2. In view of the various successful applications of biotechnology for biofortification, and their potential to substantially increase micronutrient intake levels, *ex ante* assessments have demonstrated that GM technology could offer a sustainable agriculture-based, health strategy through nutritionally enhanced GMOs. In terms of economic impacts, for example, *ex-ante* assessments have convincingly shown that GM biofortified crops like Golden Rice (Stein, Sachdev et al. 2006; De Moura, Moursi et al. 2016) would be highly cost-effective investments to reduce target micronutrient deficiencies, like vitamin A, iron and zinc (De Steur, Wesana et al. 2017). This is particularly the case for policy interventions targeting multi-biofortified crop varieties, as they would generate economies of scale and, hence, larger benefits at a relatively low cost (Nguema, Norton et al. 2011; De Steur, Gellynck et al. 2012; Fiedler, Kikulwe et al. 2013).

Unlike GM crops with agronomic traits, GM foods with quality traits (such as health traits) are only starting to be introduced in the global pipeline of GMOs (Parisi, Tillie et al. 2016), of which only few health oriented GMOs are already approved for cultivation, i.e. low-acrylamide GM potatoes (Rommens, Yan et al. 2008; Waltz 2015) and GM oilseed crops (National Academies of Sciences and Medicine 2016). Within the context of SDG 2, however, GMOs that address highly prevalent vitamin and mineral deficiencies are not (yet) approved. Main reason is the current regulatory climate and anti-GMO lobbying efforts (Moghissi, Pei et al. 2015; Potrykus 2017). Nevertheless, proof of concept has been realized for various nutritionally enhanced GMOs (De Steur, Blancquaert et al. 2015; Van Der Straeten, Fitzpatrick et al. 2017), which triggered the number of nutritional traits in the global GM crops pipeline the last two decades and is expected to be further reinforced in the near future (Parisi, Tillie et al. 2016). Another reason behind the growing interest in output traits relates to the consumer. A meta-analysis of studies on consumers' willingness-to-pay revealed general positive reactions towards GM biofortified crops. This is in line with conventional biofortified crops (Birol, Meenakshi et al. 2015), indicating that consumers' opinion on nutritious crops are hardly affected by the applied technology (De Steur, Wesana et al. 2017). Worldwide, they are willing to pay on average 24% more for GM biofortified food as compared to conventional food (De Steur, Wesana et al. 2017). Price premiums for a health policy intervention like this should be only interpreted as positive preferences. Consumers' optimism, however, can be significantly influenced by information provision, in both ways. While positive information on the nutritional content/benefits or technology increased consumers' intention to purchase, the opposite was true for negative information on GM technology. This lends support for the significant effect of lobbying which polarized the public opinion, regardless of the scientific basis of given arguments (Wesseler and Zilberman 2014).

As such, GM biofortified crops are still marked by contradiction. On the one hand, evidence underpins their impacts on nutritional crop content and potential effects on nutrient intake, public health and social welfare. On the other hand, these well accepted GMOs are prevented from meeting the needs for contributing to SDG 2 and saving threatened lives of malnourished populations in developing regions.

Given that the indirect health effects of GMOs on farmers' health are generated by GMOs with improved agronomic/input traits that are widely cultivated in the world, like pest resistant GMOs (James 2017), a large body of ex-post evidence is available. While the design of the impact studies is sometimes criticized (Kathage and Qaim 2012; Racovita, Obonyo et al. 2015), the role of insect-resistant (*Bt*) crops on reducing the use of chemical pesticides is well established (Klümper and Qaim 2014). Although its negative association with lower poisonings needs more underpinning, evidence on farmers' health impacts is growing (National Academies of Sciences and Medicine 2016). As such, GMOs with input traits could also help to meet SDG3 (Ensure healthy lives and promote well-being for all at all ages) and its particular target 3.9 that deals with disease reduction from hazardous chemicals.

4) GMOs and Socio-Economic Dimension

The adoption of GMOs has improved the well-being of many farm-households in developing countries. The reduction in pesticide use in cotton production in India and China has generated substantial health benefits. Pesticide use has been reduced by more than 80%. The health benefits of reduced pesticide use can be substantial (Antle and Pingali 1995). This not only benefits farm-households but also provides positive benefits for farm labourers (Beckmann and Wesseler 2004). Among farming households, children and women household members benefit in particular. They are the ones mainly involved in pesticide applications in cotton while in other production systems in particular farm-laborers may benefit. Pesticides saving technologies are not only appreciated for directly reducing time and costs but also for saving the burden of labour. The adoption of broadband herbicides in Africa can be explained by reducing the burden of manual weeding. This contributes to empowerment of woman and contributes to SDG5: *Achieve gender equality and empower all women and girls.* In the United States the wide and rapid adoption of herbicide resistant crops such as soybeans has been explained among other factors by reducing the burden of "thinking" how to control weeds. Herbicide resistant weeds have simplified weed control (Marra, Pardey et al. 2002). The implication for weed control in developed as well as developing countries and the nutritional and food safety contributions support SDG3: *Ensure healthy lives and promote well-being for all at all ages.*

One of the major advantages of the GMO technology is that poorer households in developing countries benefit from the technology. In regions where the use of pesticides is low but pest pressure high, which is more often observed among poorer households, substantial yield increase has been observed benefitting in particularly poor households. This has been shown by several studies including (Klümper and Qaim 2014).

While cotton is a non-food crop, using GMOs in food crops has even wider socio-economic implications for poor households. Corns resistant to lepidopteran pests such as corn borers have lower levels of mycotoxins. This is in particular important for countries where the post-harvest storing facilities are not well developed. Insect resistant corn varieties show substantially lower levels of mycotoxins even after longer post-harvest periods, generating health benefits for subsistence farm households. Overall, GM crops currently available, generate substantial benefits for poor farm households, and children and women in particular, in developing countries. Delaying the introduction harms those societal groups. Not all groups assess the introduction of GM crops positively. An urban-rural divide has been observed (Paarlberg 2008). Wealthy and well-educated urban consumers show on average a lower willingness-to pay for GM food than poor rural and less formal educated consumers (Kikulwe, Wesseler et al. 2011). This has not only been observed among consumers in developing countries but also in developed countries.

In developed countries many societal groups have expressed concerns about GMOs (Tosun and Scaub 2017). They are related to the potential negative effects on the environment and human health, ethical issues, but also the implications for market structure of the seed industry and related intellectual property rights. The environmental and human health effects are related to unknown risks. This has been rejected as a logical inconsistent line of reasoning as the same can be said about plants produced using "conventional" breeding technologies (Wesseler 2014). Furthermore, the properties of transgenic plants are often better known than those of "conventional" ones. Ethical issues mainly refer to the "unnaturalness" of transgenic plants. Deciding about what is to be considered "natural" or "unnatural" is a difficult issue. The majority of EU citizens prefer a governance system where experts decide based on scientific evidence, while about a third prefers a governance system based on public views considering moral and ethical issues (European Commission 2010). Taking different societal views into consideration and providing opportunities for interested getting involved in the policy processes contributes to peaceful and inclusive societies for *sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels* (SDG16).

The concerns about IPRs relates to the argument that large international seed companies own the rights over transgenic plants and can charge farmers a higher price and restrict their ability to save seeds, thus undermining farmers' rights. Plant breeders right's apply not only to transgenic crops but to other seeds as well. Industry concentration has increased over the past two decades. An analysis of the recent mergers in the seed sector shows an increase in concentration but at levels below measures of concentration that regulators in the European Union or the United States use for intervention. Nevertheless, the recent merger between Bayer and Monsanto required a sale of some of the seed production to maintain a sufficient level of competition (Bonanno, Materia et al. 2017). Several authors have related the concentration in the seed industry with the regulation companies face and in particular the more stringent regulation for the approval of transgenic crops (Smart, Blum et al. 2017). The Nagoya Protocol has been implemented to protect farmer rights and to ensure benefit sharing of plant genetic resources maintained by farmers mainly in the Global South. The seed industry has complained about the additional costs and negative implications for developing improved plants targeting in particular agriculture production in developing countries. Addressing this problem at an international level will be important for the achievement of several SDGs (SDG8, SDG12, SDG16).

Several countries such as the European Union and Japan have introduced mandatory labelling policies for food derived from GMOs (Carter and Gruere 2003; Adenle 2017). As a result, there are hardly any GMO labelled food products to be found in those countries (Venus, Drabik et al. 2018). According to these authors, in Europe and the United States, a voluntary market for "GMO-free" labelled food products has emerged, driven by private sector initiatives. Several retailers in the European Union have a "GMO-free" policy for their own brands and some have linked this with their sustainability strategy (Wesseler 2014). This is partly a response to consumer demands but also serves retailers' own interests to product differentiation in response to consumer demand and can increase revenues. This can result in an increase in food prices that negatively affect low income households in particular (Bovay and Alston 2018). Depending on the country, policies can have negative implications for consumption and production patterns (SDG12) as well as the achievement of sustainable economic growth (SDG8).

In summary, the socio-economic impacts of GMOs can contribute to a number of the SDGs. The adoption of GMOs in developing countries has already contributed to alleviate poverty in many regions including China, India, and South Africa. They have great potential to further reduce poverty in many other regions of the world. As the technology in many cases is embodied in the seeds, GMOs are scale neutral. Poor as well as better-off farm-households can benefit. In addition they increase food availability and food safety at farm-household level, and in particular among poor farm-households. Hence, the main contributions of GMOs are to achieving sustainable and inclusive economic growth including full and productive employment and decent work for all (SDG8).

5) Challenges facing modern agricultural biotechnology- an obstacle to the implementation of SDGs

The problems facing modern agricultural biotechnology, especially GMOs, are enormous. These obstacles include limited biotechnology R&D programs, politics and regulatory delays (Smyth 2017), and the perception on the potential risks of GMOs, among others. They present a major challenge to the application of GMOs to meeting SDGs, especially in developing countries.

Many developing countries especially those in Africa have limited biotechnology R&D programs, weak laboratory facilities and a lack of well-trained experts. This problem continues to undermine the application of GMOs in developing countries in addition to the controversy surrounding the use of GMOs (Paarlberg 2008; Adenle, Aworh et al. 2012). Over the past decade, a number of new GM crop varieties have been in the R&D pipeline, while some have undergone confined field trials in different parts of the continent. However, there has been little or no progress in finalizing many of these GM products, mainly because of the institutional capacity problem and government policy failure. A three year intensive study conducted by Adenle and his team concluded that lack of scientific capacity and poorly equipped laboratory remain a huge constraint in developing new GMO products in Africa (Adenle, Morris et al. 2013). For example, super GM cassava (beta-carotene biofortified GM cassava has undergone confined field trials in Nigeria) projects have been abandoned, partly due to lack of expertise required in conducting further lab research (Adenle, Aworh et al. 2012). Other GM products, including GM banana and GM maize (under R&D programs and confined field trials) will have to be sent to developed countries (e.g., USA, Australia) for laboratory analysis where there is an ongoing collaboration (Adenle 2017; Wesseler, Smart et al. 2017). Apart from South Africa, Tunisia, Egypt, Kenya and Nigeria with relatively advanced biotechnology R&D programs, many African countries still lack the capacity to regulate and develop GMOs. Further to this, several African scholars (including one of the authors of this chapter) argue that the development of GMOs will have to be led by the African scientists from design phase to the final stage in order to facilitate its adoption in the continent. As a result of this problem, several pro-poor GM products continue to suffer delays at the various stages of R&D programs. Given this challenge, it may be difficult to meet the relevant SDGs where GM technology could play a part.

As in the example mentioned above, the challenges facing the application of GMOs are not limited to African countries, in fact, other developing countries are facing similar problems. The introduction of GMO malaria (genetically engineered to resist parasite causing malaria) in Mexico is stifled by regulatory logjam coupled with the limited expertise for transferring the technology from the laboratory to the field (Ramsey, Bond et al. 2014). Similarly, over the past decade, the release of Golden Rice has been hindered by the regulatory challenges in developing countries such as Philippine and Bangladesh, with several confined field trials destroyed by anti-GMOs in both countries (Potrykus 2010). Taken together, these two technologies (GMO malaria and Golden Rice) can make important contribution toward meeting SDG2 and SDG3 in light of growing poverty, hunger and malnutrition in developing world but current political challenges suggest limited roles.

Current GMO policy or politics continue to hinder the development and adoption of GMO products. International and national politics continue to shape GMO decision-making processes around the world (Adenle 2011; Adenle 2017). Over the past twenty years, differing European and US perspectives on the application of GMOs have constituted a substantial obstacle for accepting GMOs, as the former makes decisions based on political ground and the latter on scientific evidence. In fact, it has been reported that environmental non-governmental organisation and the European countries have spent over $10 billion in 2015, to prevent the use of GMOs around the world (Byrne 2015), when compared to $8.6 billion spent on agricultural biotechnology R&D by the US led multinational companies (Hobbs, Kerr et al. 2014). This overwhelming difference continues to dominate the debate, particularly at the international arena. The national GMO policy is often influenced by the international GMO regulatory framework designed as the precautionary principle by the United Nations of the Convention on Biological Diversity under the Cartagena Protocol on Biosafety- a stringent system that has delayed the use of GMOs for over two decades. The European factor as reflected in the precautionary principle continues to affect the public R&D programs of local GMO products in developing countries (Paarlberg 2008). One good example is that of the legal battle involving government officials and developers over the regulation of GM eggplant, chickpea and mustard in India (Adenle, Morris et al. 2018).

Two decades after its development, Golden Rice, one of the flagships of GM biofortified crops, is still struggling for approval. Despite its potential to fight malnutrition, its implementation has been delayed for many years. Given the enormous health benefits it could generate, delaying a valuable micronutrient intervention comes to a cost that cannot be justified (Zilberman, Kaplan et al. 2016). In Asia alone, the annual economic loss of its delayed adoption was estimated at about $15.6 billion (Anderson, Jackson et al. 2005). A more recent analysis in India estimated the annual losses to be about 1.4 million life years lost over the past decade, which translates into a cost of about US$199 million per year (Wesseler and Zilberman 2014). Not surprisingly, 107 Nobel Laureates have recently advocated for GM biofortified foods (Roberts 2018; The Washington Post June 30, 2016).

In terms of research, challenges on nutritionally enhanced GMOs itself will focus on stability (Blancquaert, Van Daele et al. 2015; Gayen, Ali et al. 2015), bioavailability (Lee, Jeon et al. 2009) and efficacy (De Steur, Mehta et al. 2017).

6) Conclusions

While genetic modification organisms (GMOs) can supply limited gene pools of a particular crop species with novel traits, policy controversies remain a significant hurdle that must be overcome. That countries have adopted current international regulatory processes for the approval of GM crops has hindered their progression into the international marketplace. Yet, the acreage of GM crops continues to increase with every new year, illustrating that farmers desire and take advantage of new traits that are offered, indicating the indisputable role of GMOs in meeting SDGs including SDG1 and SDG2. In the face of climate change, improved crops that can withstand drought yet maintain high yields will become critical. Furthermore, crops with improved micronutrient content that can be readily absorbed through human consumption will become even more necessary in meeting targets of SDG3, particularly in developing countries. Other new breeding techniques, including genome editing[2], will also play an important role. Genome edited crops could thus be a venue by which improved nutritional traits can be introduced to crops of the future (Ma, Mau et al. 2018). The fact that these crops do not retain foreign DNA sequences in their final products makes them exceedingly difficult to distinguish from their conventional crop counterparts. This feature may enable genome edited crops to avoid the public perception problems that have dogged GM crop acceptance for decades. Given current GMO regulatory hurdle, anti-GMOs are already debating that genome editing should be regulated like GMOs (Abbott 2015).

Given rapid adoption of GM crops, since over 20 years of commercialisation, the potential role of GMOs in contributing toward meeting SDGs cannot be overemphasised as discussed above. Indeed, GM technology is one of modern innovations that should be encouraged in view of recorded benefits (social, economics and environment) in addressing sustainable development challenges over the past two decades. But the current international GMO regulatory framework which remains one of the most significant challenges to the application of GMO in developing world must be overhauled (Adenle, Morris et al. 2017). According to Adenle et al., (2017), the Cartagena Protocol on Biosafety (CPB) that guides the use of GMOs is no longer fit for purpose, therefore, the international communities especially, the UN Convention on Biological Diversity, the UN Food and Agriculture organisation and the World Trade Organisation and others must together to review the controversial CPB. Also, a

[2] https://ghr.nlm.nih.gov/primer/genomicresearch/genomeediting; Genome editing is a group of technologies that give scientists the ability to change an organism's DNA. Several approaches to genome editing have been developed, with recent one called CRISPR-Cas9. The CRISPR-Cas9 system has generated a lot of excitement in the scientific community because it is faster, cheaper, more accurate, and more efficient than other existing genome editing methods.

recent article by Adenle et al., (2018) argue that the continued implementation of CPB will create more barriers rather solutions in developing countries, thereby limiting the access to the innovation which can play a part in meeting SDGs. They argue further that current CPB should be abandoned and that risk-assessment models focusing on local agricultural and environmental practices in developing countries rather than Western model should be encouraged. By so doing, it will reduce burdens on individual countries, particularly, in terms of risk assessment, thereby encourage safe and quicker assessments of local GM crops.

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