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Review

Modern Plant Biotechnology: An Antidote against Global Food Insecurity

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Abstract: Food insecurity has become a pressing issue on a worldwide scale as the globe plows through a food crisis. The disastrous impact of this menace has been exacerbated by climate change, frequent conflicts, pandemic outbreaks, and the global economic recession, which have been prevalent in recent years. Although food insecurity prevails globally, it is especially critical in some regions in Africa, East and Southeast Asia, and South America. Several efforts have been made to curb food insecurity; however, none have been able to curtail it sufficiently. Genetic engineering of crops is a fast-growing technology that could be a viable tool for mitigating food insecurity. Crop varieties resistant to pests and diseases, abiotic stress, spoilage, or specific herbicides have been developed using this technology. Crops have been modified for increased yield, nutritional content, essential vitamins, and micro-mineral fortification. More intriguing is the advent of plant-derived edible vaccines, which prove equally effective and significantly affordable. However, in many countries, government policies pose a limiting factor for the acceptance of this technology. This article discusses the genetic modification of crops, highlighting its origins, methods, applications, achievements, impact, acceptance, distribution, and potential as a viable antidote to global food insecurity.

Keywords: plant biotechnology; genetic engineering; GM; GMOs; crop production; crop improvement; food insecurity; edible vaccines; food crises; sustainable production

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1. Introduction

1.1. Food Insecurity: A Global Menace

Food insecurity persists all around the world [1]. According to Bickel et al. [2], the United States Department of Agriculture (USDA) elucidated that food insecurity pertains to a situation whereby access to safe, healthy, and nutritious meals is restricted, uncertain, limited, or unpredictable, as well as the capacity to acquire acceptable foods through socially acceptable means. This is a disheartening reality in many regions of the world.

Currently, there are about 8 billion people on planet Earth. It is unfortunate that about 1 billion people languish through undernutrition, living daily in hunger, and that 2 billion more people suffer from essential micronutrient deficiencies [3]. Since 2019, the number of people affected by severe hunger has surged from 135 million to 345 million. Recent statistics reveal that about 49 million people across 49 countries are at risk of famine [4], and a large proportion of the affected population is in sub-Saharan Africa and Asia.

Undernourishment, a tragic impact of food insecurity, is equally ravaging the world [5]. It affects 20% of developing nations, contributing to infant mortality in 50% of cases.

Globally, children are the hardest hit by food insecurity. Hundreds of millions of newborns and mothers are vitamin A and iodine deficient. Micronutrient deficiencies, such as iron and vitamin A, affect a substantially larger proportion of people, resulting in anemia. It has been estimated that 2 billion individuals (one out of every three) are anemic [1]. Anaemia, a disease caused by a lack of iron, accounts for approximately 20% of maternal deaths in Asia and Africa. In developing nations, in particular, food insecurity and malnutrition pose major challenges to public health [6,7]. The world is indeed in a food crisis [1]. Globally, more than one-third of children under 5 years of age are affected by malnutrition or undernutrition, not getting enough nutrients needed for optimum growth from their daily diet [8]. Also, more than 400 million mothers have stillborn or underweight infants owing to iron insufficiency. Energy and protein malnutrition affects over 160 million preschool children, resulting in the deaths of more than 5 million children (<5 years) each year [9,10].

The International Food Policy Research Institute [11] further revealed that more than one in every four children is affected by stunting, and wasting is also prevalent, affecting 9% of children. The situation is aggravated by natural disasters, wars, and pandemic outbreaks. For instance, the recent COVID-19 pandemic caused a severe increase in the world population affected by food insecurity, and the number of households experiencing this menace surged drastically. Figure 1 shows the rise in food insecurity in the USA and Africa, respectively. According to a United Nations Report, it is disheartening to note that global efforts toward achieving the eradication of hunger, food insecurity, and nutritional deficiency in all forms by 2030 do not appear to be getting close to the intended goals [12].

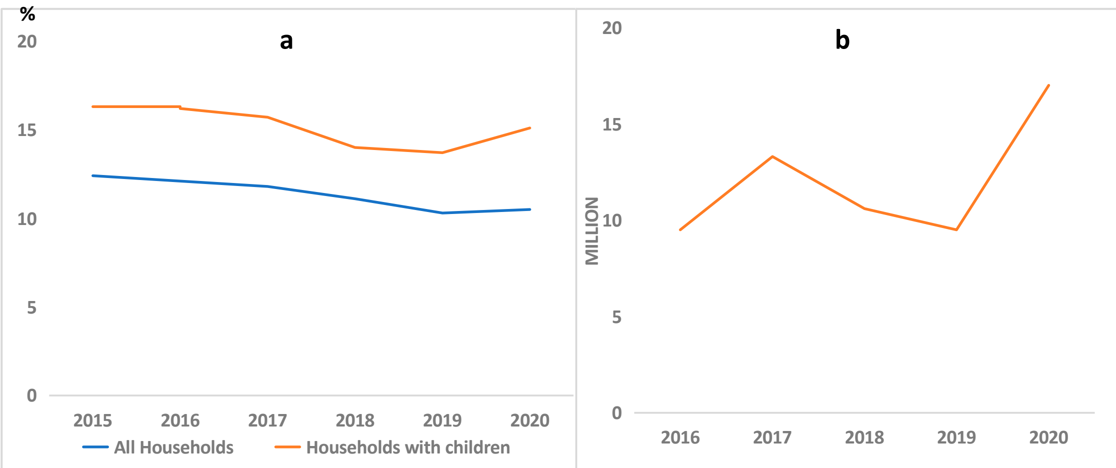

Figure 1. Food insecurity tipped up during the COVID-19 pandemic in (**a**) the USA [13]; (**b**) Africa [14].

In the face of diminishing land availability for agriculture and food production due to industrial and construction activities, the world is left with no alternative but to seek means to maximize the limited resources available and produce more food from the fast-depleting farmlands and the small amount of irrigation water. As a result, the requirement for additional food must be addressed by increasing yields per unit of resource input (land, water, energy, and time). It becomes imperative to examine how science can be deployed to increase productivity ceilings with no further harm to the ecosystem [15,16], a need that biotechnology duly meets.

Achieving food security is a matter of global urgency and all hands must be on deck. Several international agreements and institutions have been formed to this end. The Sustainable Development Goals (SDGs) are the main worldwide policy for reducing hunger and poverty. The second goal of the SDG, tagged 'The Zero Hunger Initiative', aims to achieve a set of universally agreed-upon goals that will put an end to hunger, ensure food security and improve nutrition, and promote sustainable agriculture by the year 2030. A question still needing an answer is how this can be achieved within a limited time and with limited resources. Biotechnology is a promising solution! As asked by

Habibi-Najafi [17], is it achievable without the use of innovative technology and methods capable of increasing agricultural productivity to minimize crop loss owing to attacks by pests, producing foods with superior nutrient content, and ultimately achieving global food security and sustainable agriculture with an expanding population? Is there an alternative to genetic engineering and biotechnology?

1.2. Defining a Food-Secure World

Food security is an overly broad concept. It is, therefore, difficult to capture the totality of this concept in a few words. Several attempts have been made by global bodies in recent decades before arriving at the current definition [18]. At the World Food Conference (1974), the concept of 'food security' was introduced, and it was defined as the consistent availability of sufficient global food supplies, including essential nutrients, to enable a steady increase in food consumption and counteract fluctuations in production and prices [19]. The definition was dynamic, as it reflected the prevalent protein–energy deficiency in 1970, which affected more than 25% of the global population. However, the definition has been consistently revised to broaden its coverage. In 1983, the Food and Agriculture Organisation (FAO) [20] introduced a new concept that emphasized the importance of guaranteeing the universal availability and affordability of basic food requirements for all individuals. Similarly, in 1986, the World Bank [21] incorporated a new notion of ensuring that everyone has access to adequate food to lead a healthy and productive life. These concepts highlight the critical role of equitable and sustainable food systems in promoting human well-being and development. A broader definition was achieved by the FAO in 1996 [22], which was revised again in "The State of Food Insecurity in the World 2001" with a social emphasis. Food security was then described as a situation in which all people always have sufficient, affordable, and nutritious food to satisfy their dietary demands for an active and healthy life [12]. However, the definition was deemed inadequate and was revised, adding another component, 'food stability', which emphasizes the ability of food systems to withstand alterations or declines, whether caused by natural or man-induced factors [23].

Food security is commonly associated with the level of assurance that a population has sufficient access to the required amounts of food from available sources to fulfill their dietary needs at the national or regional level. This is commonly linked to the adequacy of the national food balance. The degree of food security in a country is measured largely by the minimum per-capita dietary calories required by the lowest nutritional group, assuming that all locations and socioeconomic groups can equally access the available food supply for a prolonged period [24]. To this effect, the world aims to achieve high food security for all people regardless of social status, race, or location [25].

Food security is comprehensively defined across four dimensions, namely food availability, food accessibility, food utilization, and food stability, as illustrated in Figure 2.

Food availability refers to the availability of high-quality food in adequate amounts, whether produced domestically or imported. Food accessibility, on the other hand, ensures that food of acceptable quality is obtainable by the consumer at affordable costs. Food utilization focuses on "safe and nutritious food that fits individuals' dietary demands," or the body's capacity to efficiently absorb food nutrients, enabling a person to live and function optimally. The fourth entity, food stability, emphasizes that a population, household, or individual must always have access to adequate food to be considered food secure. Food access should not be threatened by economic or climatic disasters or cyclical events (such as seasonal food insecurity) [12,18,24]. The concept of stability can apply to both the accessibility and availability of food.

Figure 2. Essential components of food security [12,18].

Meeting the world's rising food demand is a global challenge, particularly in Africa, and agricultural sustainability is indispensable for achieving this [26]. Current agricultural production and conventional technologies are grossly incapable of meeting the increasing food demand of the expanding population, which is a critical concern [26,27]. There is a sense of urgency around the world to curtail the menace and ensure food security, but how can this be achieved? Any viable approach to ameliorating the situation by boosting food production in both quality and quantity should be considered [28]. To this effect, biotechnology is a promising panacea for world food insecurity [29]. Although genetic engineering and other biotechnological approaches available for improving the desirable traits of plants and animals offer massive benefits for combating food insecurity, debate is ongoing on their biosafety and unlikely aftermath.

2. Biotechnology: A Viable Approach to Curbing Food Insecurity

Biotechnology is an integration of numerous technologies that comprises several fields of science with wide applications. In modern agriculture, biotechnology plays key roles in the advancement of animal husbandry, cropping systems, soil science, soil conservation, plant physiology, seed technology, and crop management, all of which are pivotal to improving the quality and quantity of food production. It has also helped in the production of recombinant proteins, crops that are resistant to pests and pathogens and varieties with high nutrient content, and animals that produce more milk, among other applications [30].

Although biotechnology is not the only means of crop genetic improvement, it offers a faster and more accurate technology with broader applications to improve crops compared to its alternative, i.e., conventional plant breeding. While genetic modification (GM) targets the introduction of a foreign gene into the plant genome to produce the desired traits, conventional breeding interbreeds plants with the desired characteristics over many generations and then selects individuals with such traits among the progenies [31]. In addition, genetic engineering offers opportunities for improving crops that are sterile or asexually propagated [32]. Although the use of GM is becoming increasingly popular in crop improvement, it is not aimed at completely replacing conventional breeding; both approaches are indispensable, depending on the breeder's goal and selected crop [33].

Conventional breeding is very affordable, simple, and unrestricted by the government. The main constraint of conventional methods is the sexual procedure, especially the sexual compatibility of the organisms of interest; the desired gene might be in an unrelated species that cannot be effectively cross-pollinated with the recipient or from a non-plant species, such as genes from bacteria or insects. Another limitation is that the conventional approach cannot be used for improving sterile crops. If a valuable gene is identified in a wild relative, the conventional approach to improvement may not be suitable because performing a cross between the high-yield line and its wild relative creates a 'mix' of the parents' genomes, altering the carefully chosen and delicate assemblage of desirable genes present in the high-yield line [32].

Genetic Modification of Crops: A Silver Bullet to Combat Food Insecurity

As stated in [34], among the numerous possibilities for crop improvement, genetic modification of crops deserves special attention and could be a 'life jacket' in this ocean of food insecurity. Genetically engineered crops have the potential to reduce food insecurity to a minimum. Genetic modification of crops emerged with considerably lofty expectations and anticipations of enabling farmers to achieve a greater and better agricultural yield, counting on its limitless potential for crop improvement. Although it is still a subject of public debate, "super plants" offer a feasible alternative for addressing world hunger [31].

Plant genetic modification has occurred in distinct phases throughout history. The earliest crops were modified for resistance or tolerance to pests, diseases, abiotic stress, spoilage, or herbicides. The second generation of modified crops targeted an increase in the yield quality or nutritional content, e.g., fortifying crops with essential vitamins and micro-minerals. The third generation of genetically modified crops will have a wider scope and limitless applications. It will be used for non-food purposes like pharmaceuticals (edible vaccines), biofuel production, and bioremediation, as well as other critical areas. Many of these are already in use today [35,36].

3. Genetically Modified Crops; A Masterpiece

According to [37], the first instance of a genetically modified crop was reported in 1983. Specifically, a tobacco plant was the first crop to undergo genetic modification with the introduction of an antibiotic-resistance gene into its genome. Generally, tobacco plants dominated early developments in plant genetic modification in the 1980s and early 1990s, with several successes reported using *Agrobacterium*-mediated gene transfer. In 1994, the 'Flavr Savr' tomato became the inaugural genetically modified crop authorized for commercial sale in the United States. It was developed for extended shelf life [38], and over time, many GM crops have been produced [39].

The development of plant-genome editing tools has revolutionized the area of plant genetic engineering by making it possible for greater precision and effective modification of plants' genetic compositions [40]. Scientists employ genome editing as a method to explore potential genes and genetic variations that impact favorable characteristics, more effectively utilize genetic variability, and gain insight into the functioning of genes [41] (Figure 3). The technology allows the precise alteration of plant traits to introduce new characteristics into crops, such as disease resistance, drought tolerance, and improved nutritional content.

Plant gene editing uses an array of novel techniques, including CRISPR/Cas9, TALENs, and Zinc-Finger Nucleases [42,43]. The CRISPR/Cas system is the most widely used gene-editing tool in plants due to its simplicity, efficiency, and versatility. Its ease of use and cost-effectiveness have opened up gene editing to a much wider range of researchers, including those in developing countries [44]. Since the first successful application of CRISPR/Cas9 in plant gene editing in 2013 [42,45], CRISPR/Cas-based gene editing has been successfully used to generate crops with improved yields, increased resistance to pests and diseases, enhanced nutrient content (Table 1), and altered plant architecture across a wide range of crops [42], including soybean [46], rice [47–49], wheat [50,51], maize [52], tomato [53–55], cassava [56], tobacco, and potato [57,58], among others. Some achievements of gene editing in crop improvement are listed in Table 1.

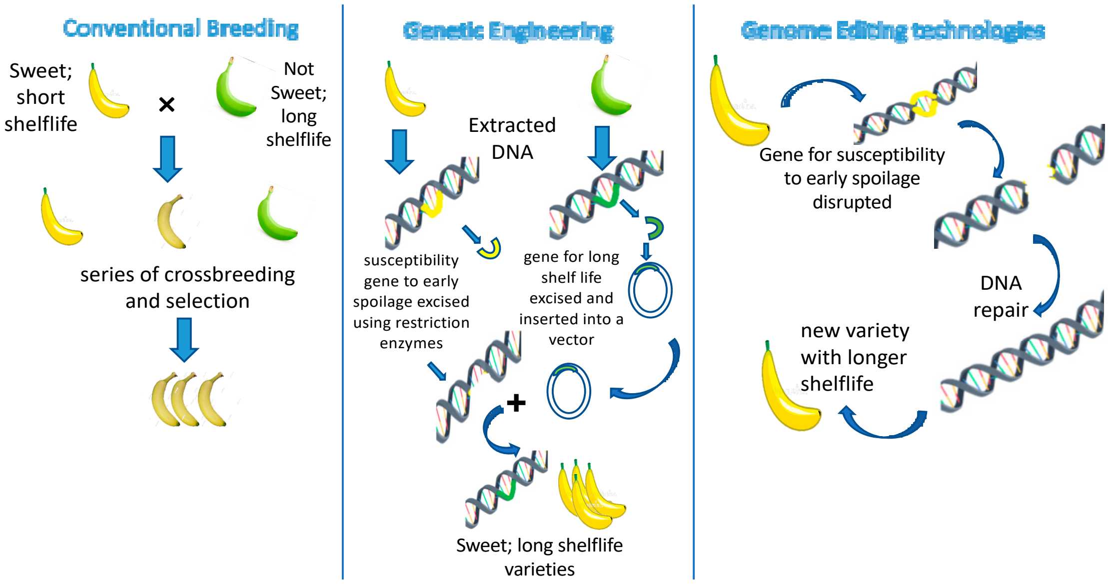

Figure 3. The concept of conventional breeding, genetic engineering, and genome editing technologies.

Table 1. CRISPR-CAS technologies used in crop improvement.

	Trait Modified	Crop	Target Gene(s)	Gene(s) Role	References
Yield parameters	Fruit size	Tomato	*CLV3*	Shoot and floral meristem development	[59]
			ENO	Encodes enolase, which catalyzes the conversion of 2-phosphoglycerate to phosphoenolpyruvate	[55]
			fas, lc	Determines locule number	[60]
			Fas, OVATE	Fruit shape and size	[59]
		Groundcherry	*ClV1*	Controls shoot and floral meristem size	[61]
	Grain size	Wheat	*TaGW2*	Determines grain weight	[50]
			GW5	Grain width and weight	[42]
		Rice	*OsGS3, OsGn1a, and OsGW2*	Grain size	[62]
			GS3, Gn1a	Controls grain number, size, and density of erect panicles	[63]
	Grain shape	Wheat	*TGW6, GW2, GW5*	Grain length	
			TaGW7	Cell division and organ growth	[51]
		Rice	*GS9*	Cell division and grain development	[64]
	Grain color	Rice	*ANT1*	Controls anthocyanin pigmentation in different vegetative tissues	[65]
			CRTISO	Catalyzes prolycopene to lycopene	[66]
			Psy1, CrtR-b2	Influences carotenoid accumulation	[53]
			SlMYB12	Flavonol biosynthesis	[67]
		Maize	*Psy1*	Phytoene synthesis	[52]
	Floral color	Ipomoea nil	*CCD*	Synthesis of apocarotenoid flavor and aroma volatiles	[68]
		Petunia	*F3H*	Flavonoid metabolism	[69]
Nutrient Quality	Increased carotenoid content	Rice	*ZmPsy, SSU-crtI*	Carotenoid biosynthetic genes	[48]
	Reduced amylose content	Sweet potato	*IbGBSSI*	Starch metabolism	[54]
		Cassava	*PTST1, GBSS*	Amylose biosynthesis	[56]
		Rice	*OsGBSSI*	Amylopectin and amylose synthesis	[49]

Table 1. *Cont.*

	Trait Modified	Crop	Target Gene(s)	Gene(s) Role	References
	Increased amylose content	Potato	*StGBSS*	Amylose biosynthesis	[58]
		Barley	*HvGBSSIa*	Starch metabolism	[70]
		Rice	*OsBEI and OsBEIIb*	Amylose biosynthesis	[71]
		Potato	*StSBE1*, *StSBE2*	Amylose biosynthesis	[57]
		Sweet potato	*IbGBSSI*, *IbSBEII*	Amylopectin and amylose synthesis	[54]
	Increased oleic acid content	Rice	*OsFAD2-1*	Controls oleic acid content	[72]
		Tomato	*BnFAD2*	Oleic acid regulation	[73]
		Camelina	*CsFAD2*	Synthesis of linoleic acid from oleic acid	[74]
	Reduced Phytic acid	Rapeseed	*BnITPK*	Critical in the phytic acid pathway	[75]
		Rice	*OsPLDα1*	Phytic acid biosynthesis	[76]
	Reduced gluten content	Wheat	*α-gliadin genes*	Gluten production	[77]
	Increased Gamma-Aminobutyric Acid (GABA) content	Rice	*SlGAD2*, *SlGAD3*	Regulates γ-aminobutyric acid levels	[78]
			OsGAD3	Gamma-aminobutyric acid synthesis	[79]
Biotic stress	Blast Resistance	Rice	*OsERF922*	Negatively regulates disease resistance in rice	[80]
	Bacterial blight		*OsSWEET13*	Sugar transport system	[81]
			OsSWEET11, *OsSWEET13, and OsSWEET14*	Resistance against *Xanthomonas*	[82]
	Powdery mildew	Tomato	Pmr4	Callose synthase	[83]
	Bacterial speck disease		SlJAZ2	Stomatal reopening by cor	[84]
	Brown streak disease	Cassava	nCBP-1, nCBP-2	Protein synthesis	[85]
	Bean yellow dwarf virus (BeYDV) resistance	*N. benthamiana*	*BeYDV*	Protein synthesis	[86]
	Virus resistance		*dsDNA of virus (A7, B7, and C3 regions)*	Protein synthesis	[87]
	Powdery mildew resistance	Bread wheat	*TaMLO-A1*, *TaMLO-B1, and TaMLOD1*	Protein synthesis	[88]
	Ipomovirus	Cucumber	eIF4E	mRNA translation initiation	[89]
Abiotic stress	Drought tolerance	*A. thaliana*	*MIR169a*	Regulates translation of target genes	[90]
			UGT79B2, *UGT79B3*	Catalyzes the transfer of a glycosyl moiety	
		Rice	*OsDERF1*, *OsPMS3*, *OsEPSPS*, *OsMSH1*, *OsMYB5*	Critical in plant development	[91]
		Tomato	*SlMAPK3*	Regulates plants' response to salt stress	[92]
		Maize	*ARGOS8*	Negative regulator of ethylene responses	[93]
	Heat stress	Tomato	*BZR1*	Regulates brassinosteroid response	[94]
	Herbicide tolerance	Soybean	*ALS1*	Branched-chain amino acid synthesis	[46]
		Sugarcane	*ALS*	Leucine, isoleucine, and valine biosynthetic pathways	[95]
	Potassium deficiency tolerance	Rice	*OsPRX2*	Regulates plants' response to k^+ deficiency	[96]
	Low cesium accumulation		*OsHAK-1*	Mediator of cs uptake, critical in potassium-mediated sugar metabolism	[97]
	Various abiotic stress tolerance		*OsAOX1a*, *OsAOX1b*, *OsAOX1c*, *OsBEL*	Regulates plants' response to stress	[98]

Additionally, gene editing can be used to reduce the use of pesticides and other harmful chemicals in agriculture by introducing traits that confer natural pest and disease resistance (Table 1) [43]. Another important application of plant gene editing is the reduction or elimination of allergens in crops. Food allergies affect millions of people worldwide and can cause severe and sometimes life-threatening reactions. Gene editing offers a promising solution to this problem by allowing the targeted removal of allergenic proteins from crops without affecting their nutritional value [99,100]. Researchers have used CRISPR/Cas-based gene editing to create hypoallergenic peanuts, wheat, and soybeans, among other crops [99,101–103].

Despite the potential benefits of plant gene editing, there are also concerns about its safety and ethical implications [104]. Critics argue that the technology could have unintended consequences, such as off-target effects or the creation of new allergens or toxins [105]. With continued research and development, plant gene-editing technologies could help transform the future of agriculture and ensure food security for generations to come.

3.1. Developing Crop Varieties with Higher Yield and Extended Shelf Life

Plants genetically modified for enhanced yield have greater productivity and faster growth in the face of limited growth resources and adverse climatic conditions compared to their unmodified relatives. According to a meta-analysis conducted between 1996 and 2013, the yield of genetically modified crops increased by 20%. Furthermore, in developing nations, yields and producer gains are higher than in developed countries [26,35]. Pellegrino et al. [106] discovered that genetically modified maize increased yields by up to 25% and significantly reduced dangerous food contaminants in their critical analysis of over 6000 peer-reviewed publications over 21 years (1996–2016). The findings further favor the global cultivation and consumption of GM maize owing to its improved quality and grain yield, as well as reduced human exposure to mycotoxins. Researchers have estimated the increase in food production attributed to the contributions of GM crops to be about $133 billion [107,108]. More is achievable if scientists are given the liberty to modify crops in this regard.

Extending the shelf life of agricultural products is another laudable achievement of plant biotechnology, as it can significantly reduce post-harvest losses due to spoilage, which claims a sizeable percentage of agricultural products every year. Since the commencement of this endeavor, researchers have successfully released new varieties of important crops with extended shelf life, many of which are still under development [31]. This has been achieved with tomatoes and bananas. For example, the antisense targeting of genes involved in ethylene generation and sensing in tomato plants has proven to be particularly successful in delaying fruit ripening [109]. Scientists from Israel's Agricultural Research Organization created transgenic banana plants with increased shelf life by lowering the expression of two transcriptional regulators, *MaMADS1* and *MaMADS2* (MADS-box genes) [110]. Furthermore, the researchers discovered that the flavor and quality of the genetically modified bananas remained unchanged. This technology can be applied to other crops to reduce food shortages caused by post-harvest spoilage, especially in countries without suitable technologies for fruit storage.

3.2. Insect Tolerance and Herbicide Resistance

Several crops have been genetically modified to resist specific insects (Tables 1 and 2). This is mainly achieved through the heterologous expression of proteins from *Bacillus thuringiensis* (*Bt*) that exhibit toxicity toward insects possessing alkaline digestive systems. When insects consume *Bt* protein, their digestive systems are interrupted, resulting in slower development and, eventually, death.

Table 2. Genetically modified crops approved by FDA for nutritional purposes in the last decade.

S/N	Plant	Identifier	Introduced Gene(s)	Gene Product(s)	Source(s)	Acquired Trait(s)	Method of Trait Introduction	Developer	Reference
1	Soybean	FAD2KO	Mutated *FAD2-1A* and *FAD2-1B*	Changed oil composition	*Glycine max*	Increased oleic acid content of oil	*Agrobacterium*-mediated plant transformation; TALENs	Calyxt, Inc., Minnesota, USA	[111]
2	Fuji apple	OKA-NBØØ3-1	*PGAS PPO* suppression gene	double-stranded RNA (dsRNA)	*Malus domestica*	Reduced polyphenol oxidase activity; non-browning	*A. tumefaciens*-mediated plant transformation	Okanagan Specialty Fruits, Inc., Summerland, British Columbia	
3	Cotton	TAM-66274-5	*dCS*	dsRNA that suppresses the expression of endogenous d-cadinene synthase gene	*Gossypium hirsutum L.*	Low gossypol	*A. tumefaciens*-mediated plant transformation	Texas A&M AgriLife Research, Texas, USA	
4	Sugar from sugarcane	CTC91Ø87-6	*Cry1Ac*	Cry1Ac delta-endotoxin	*Bacillus thuringiensis subsp.* Kurstaki strain HD73	Lepidopteran insect resistance	NA	Centro de Tecnologia Canavieira, São Paulo, Brazil	[112]
5	Maize	AGV-PY203-4	*phy02*	Express the phytase enzyme (Phy02)	*Escherichia coli*	Phytase production	*A. tumefaciens*-mediated plant transformation	Agrivida, Inc., Massachusetts, United States	[113]
6	Maize	DBN-Ø9936-2	*cry1Ab; epsps (Ag)*	Cry1Ab delta-endotoxin; 5-enolpyruvylshikimate-3-phosphate-synthase enzyme	*Bacillus thuringiensis* subsp. Kurstaki; *Arthrobacter globiformis*	Glyphosate herbicide tolerance, lepidopteran insect resistance	*A. tumefaciens*-mediated plant transformation	Beijing DaBeiNong Biotechnology Co. Ltd. (DBNBC), Beijing, China	[114]
7	Maize	DP-2Ø2216-6	*zmm28; mo-pat*	transcription factor (ZMM28); phosphinothricin acetyltransferase (PAT)	*Zea mays; Streptomyces viridochromogenes*	Glufosinate herbicide tolerance, enhanced photosynthesis/yield	*A. tumefaciens*-mediated plant transformation	Pioneer Hi-Bred International, Inc., Iowa, USA; Dow AgroSciences LLC, Indiana, USA.	[115]
8	Potato	SPS-ØØØZ6-5	*asn1; ppo5; PhL; Vlnv; Rpi-vnt1*	double-stranded RNA; late blight resistance protein	*Solanum tuberosum; Solanum venturii*	Lowered free asparagine, reduced black spot, lowered reducing sugars, foliar late blight resistance	*A. tumefaciens*-mediated plant transformation	J.R. Simplot Company, Idaho, USA	
9	Maize	DBN-Ø9858-5	*epsps (Ag); pat*	5-enolpyruvylshikimate-3-phosphate-synthase enzyme; phosphinothricin N-acetyltransferase (PAT) enzyme	*Arthrobacter globiformis; Streptomyces viridochromogenes*	Glyphosate herbicide tolerance, glufosinate herbicide tolerance		Beijing DaBeiNong Biotechnology Co. Ltd. (DBNBC), Beijing, China.	
10	Canola	NS-B5ØØ27-4	*Lackl-delta12D; Picpa-omega-3D; Micpu-delta-6D; Pyrco-delta-6E; Pavsa-delta-5D; Pyrco-delta-5E; Pavsa-delta-4D* and *pat*	Fatty acid desaturases (delta-12, omega-3/delta-15, delta-6, delta-5, and delta-4) and phosphinothricin N-acetyltransferase (PAT) enzyme	*Lachancea kluyveri; Pichia pastoris; Micromonas pusilla; Pyramimonas cordata; Pavlova salina* and *Streptomyces viridochromogenes*	Modified oil/fatty acid; glufosinate herbicide tolerance	*A. tumefaciens*-mediated plant transformation	Nuseed Americas Inc., California, USA	[116]

Table 2. *Cont.*

S/N	Plant	Identifier	Introduced Gene(s)	Gene Product(s)	Source(s)	Acquired Trait(s)	Method of Trait Introduction	Developer	Reference
11	Canola	BPS-BFLFK-2	*PsD12D; OtD6D; TcD5D; TcD4D, PlD4D; PiO3D, PirO3D; PpD6E; TpD6E; OtD5E; AtAHAS*	Fatty acid desaturases (delta-12; delta-6; delta-5; delta-4, and omega-3); Fatty acid elongases (delta-6 and delta-5); Large catalytic subunit of acetoxhydroxyacid synthase (At-AHAS-L)	*Phytophthora sojae; Ostreococcus tauri; Thraustochytrium sp.; Pavlova lutheri; Phytophthora infestans; Pythium irregulare; Physcomitrella patens; Thalassiosira pseudonana; Ostreococcus tauri; Arabidopsis thaliana*	Modified oil/fatty acid, imazamox herbicide tolerance	*A. tumefaciens*-mediated plant transformation	BASF Plant Science, NC, USA	
12	Soybean	BCS-GM151-6	*cry14Ab-1.b; hppdPf4Pa*	Cry14Ab1 protein; modified 4-hydroxyphenylpyruvate dioxygenase (HPPD-4) enzyme	*Bacillus thuringiensis; Pseudomonas fluorescens strain A32*	Nematode resistance, tolerance to hppd-inhibiting herbicides	*A. tumefaciens*-mediated plant transformation	BASF Corporation, TX, USA	
13	Wheat	IND-ØØ412-7	*Hahb-4*	Isolated nucleic acid molecule encoding the transcription factor Hahb-4	*Helianthus annuus*	Drought stress tolerance	Microparticle bombardment of plant cells or tissue	Bioceres Inc., Sante Fe, Argentina	[117]
14	Maize	MON-87429-9	*pat; dmo; cp4 epsps (aroA:CP4); ft_t*	phosphinothricin N-acetyltransferase (PAT) enzyme; dicamba mono-oxygenase enzyme; herbicide tolerant form of 5-enolpyruvulshikimate-3-phosphate synthase (EPSPS) enzyme; 2,4-D and FOPs dioxygenase protein (FT_T)	*Streptomyces viridochromogenes; Stenotrophomonas maltophilia strain DI-6; Agrobacterium tumefaciens strain CP4; Sphingobium herbicidovorans*	Glufosinate herbicide tolerance; dicamba herbicide tolerance; glyphosate herbicide tolerance; 2,4-d herbicide tolerance	*Agrobacterium tumefaciens*-mediated plant transformation	Bayer CropScience LP, Australia	[118]
15	Maize	DP-Ø23211-2	*IPD072Aa; pat; pmi*	IPD072Aa protein; Phosphinothricin N-acetyltransferase (PAT protein); Phosphomannose isomerase (PMI protein)	*Pseudomonas chlororaphis; Streptomyces viridochromogenes; Escherichia coli*	Insect resistance; Glufosinateherbicide tolerance	NA	Pioneer Hi-Bred International, Inc., Iowa, USA	[119]
16	Canola	MON-941ØØ-2	*dmo*	dicamba mono-oxygenase enzyme	*Stenotrophomonas maltophilia strain DI-6*	Dicamba herbicide tolerance	NA	Bayer CropScience LP, Australia	
17	Maize	MON-95379-3	*Cry1B; Cry1Da*	Cry1B.868; Cry1Da_7	*Bacillus thuringiensis*	Insect resistance	NA	Bayer CropScience LP, Australia	[120]

* NA—Not Available.

This observation has led to a growing interest in exploring the potential of transferring this *Bt* gene into plants [121–123]. Sweet corn, cotton, and potatoes are among the most commonly grown commercial crops that possess *Bt* insect resistance. This technology has helped to reduce the devastating impact of the Asian corn borer (Wilson), which causes approximately 40% yield loss in Indonesia's maize plantations [121,123]. The introduction of new varieties of cotton that are insect-resistant has brought great relief to cotton farmers globally. For instance, according to [29], five million farmers in India are growing *Bt* cotton on more than 7.6 million hectares of land. This improved variety has significantly promoted cotton production in India, as well as other parts of the world. The variety protects itself from insects without the use of an external pesticide. The switch to *Bt* cotton has resulted in a 31% increase in output, a 39% decrease in pesticide use, and an increased profit for farmers equivalent to USD 250 per hectare. In 2017, about 100 million hectares of farmland were cultivated with *Bt* crops, producing *Bt* toxins [124].

To broaden the impact range of GE crops, further pest-tolerance techniques against a wider range of devastating insects, using innovative technologies like RNAi and other non-*Bt* approaches, have been introduced [125]. Plant genetic modification for insect resistance has evolved from directed immunity against a single insect order to a wider immune response with various mechanisms to combat similar or multiple insect species (Tables 1 and 2).

Among the various genetic engineering technologies for combating insect pests, sequence-specific gene silencing using RNA interference (RNAi) has proven to be outstanding for successful pest management in agriculture. RNAi is a naturally occurring, conserved mechanism that is important for gene control and pathogen resistance. Crops are designed with a hairpin RNAi vector to generate dsRNA against the target gene of an insect pest in the plant-mediated or host-induced RNAi (HI-RNAi) technique. Upon eating plant components, dsRNA enters the insect gut, activating RNAi machinery and silencing the target gene in the insect pest. Many major successes have been recorded since its pioneering success in corn and *Nicotiana tobacum* in 2007 [126,127]. Jin et al. [128] engineered chloroplast dsRNA to silence target genes in the gut of *Helicoverpa armigera* (cotton bollworm) and impair larval development. Mamta and Rajam [129] used the HI-RNAi method to induce *H. armigera* resistance in tobacco and tomato plants. The host-induced RNAi (HI-RNAi) approach has gained increasing attention from researchers [130–133].

The application of genetic engineering in tackling these pests (insects) not only prevents production loss but also saves farmers money on insecticides. Klümper and Qaim [35] conducted an in-depth meta-analysis of approximately 147 published biotech crop research studies in which genetically modified (GM) crops were used to tackle insects, diseases, and weeds. The study examined the impact of GM crops from 1995 to 2014. Based on their findings, the opportunities and vast benefits of the genetic modification of crops in this regard are evident. The study also established that not only does it boost plant immunity and insect tolerance but it also reduces the usage of chemical pesticides (the majority of which are not environmentally friendly) by 37% and increases farmers' profits by 68 percent, a position corroborated by [26]. Also, as observed in some cases where insect-resistant varieties have been implemented, for example, *Bt* maize and *Bt* cotton in the US [134–136] and China [137], key target pests have been significantly suppressed across the region, thus bringing relief to all farmers, including non-adopters of the GM variety.

Engineering crops for herbicide resistance (HR) allows the plants to tolerate herbicides that would otherwise kill them. In 2015, genetic engineering produced herbicide-resistant (HR) traits in crops for nine herbicides. These traits are available in several commonly cultivated crops, e.g., maize, sugar beets, cotton, soybeans, and alfalfa (Tables 1 and 2). However, not all of these improved varieties are available for commercial production. For instance, glufosinate-resistant sugar beets have been created but have not yet been commercialized [138]. Generally, from 1996 to 2015, HR crops that were released were predominantly developed to resist a single, targeted herbicide, usually glyphosate. Glyphosate is a broad-spectrum, non-selective herbicide that suppresses the *EPSPS* gene, which is vital in the synthesis of aromatic amino acids [139]. Thus, glyphosate and glyphosate-resistant crops were the most prevalent herbicide–HR crop combinations that farmers employed. However, in 2015, certain crop varieties with stacked herbicide-resistance characteristics (for example, glyphosate and 2,4-D or glyphosate and dicamba) were already under development. Glyphosate resistance is now available in several other crops [140].

Transgenic technology has produced the majority of commercialized herbicide-resistant crops [141]. However, CRISPR/Cas-mediated genome editing is increasingly gaining prominence, as it provides a more efficient approach by permitting precise modifications of DNA sequences associated with herbicide resistance without the introduction of exogenous genes, thus being deemed safer [141]. Since its emergence, it has been applied to induce herbicide resistance in several crops, such as rice [142–144], maize [145], watermelon [146], rapeseed [147,148], wheat [149], tomato [58], and potato [58], among others (Tables 1 and 2).

3.3. Enhanced Nutritional Content

The development of transgenic crop varieties with higher nutritional content, for example, increased protein, essential vitamins, iron content, or higher amounts of folate, can offer adequate quantities of essential micronutrients that are typically deficient in diets in the developing world [150]. These improved varieties must be made readily available and accessible to local farmers to have a meaningful effect on the nutritional well-being of a community [151,152]. In recent years, there have been notable advancements in the utilization of biotechnology to create food crops with enhanced nutritional value, such as reduced amylose, phytic acid, and gluten contents, and increased amylose, oleic acid, and Gamma-Aminobutyric Acid (GABA) contents, among others (Tables 1 and 2). These advancements aim to reduce detrimental nutrient elements and provide essential nutrient elements, such as iron and vitamin A to consumers, especially poor populations across the globe, who are the worst hit by food insecurity [153].

Let us consider a well-known example: Golden Rice. Every year, an estimated three million children under the age of five (30% of children within the age group) are affected by vitamin A deficiency [154]. Golden Rice was created by Ingo Potyrus' research team and provides a viable solution. This novel variety was designed using two genes harvested from two unrelated species: one from the 'daffodil' plant and another from the '*Erwinia uredovoia*' bacterium [155]. Transgenic biofortified rice offers a low-cost solution to folate deficiency. Phytic acid (PA) is a recognized zinc-absorption inhibitor that is found in many grains. Today, new rice varieties, as well as a couple of cereals, have been developed with an extremely low content of this acid. These varieties were created by altering the phytic acid biosynthesis pathway. Although beneficial, these tactics are occasionally linked to some degree of reduction in yield and vigor [152,156].

As enhancing rice Fe content has proved challenging [157], significant achievements have been made using transgenic techniques [158,159]. RNAi silencing-based methods have also been used to create rice varieties with notable lysine content [160]. Another accomplishment in plant biotechnology is the development of triple-vitamin-fortified maize that has several times the usual amount of beta-carotene, ascorbate, and folate (Tables 1 and 2) [161]. The BioCassava Plus initiative was launched to focus on cassava, a nutritionally inadequate staple crop consumed in sub-Saharan Africa. These innovations suggest fortifying maize with vitamin A [162]. Crops like this can provide considerably more nutritionally balanced meals to malnourished populations in Africa [162]. In recent years, more and more genetic modification events to improve the nutritional value, quality, and marketability of food from crops have continued to emerge (Table 2).

3.4. Plant-Derived Edible Vaccines

Edible vaccines are a novel type of vaccine produced using transgenic plants and animals. They are created by introducing genes encoding antigens or immunostimulants into the genome of plants or animals, which activate the immune system and induce an immune response [163]. Edible vaccines are easy and relatively cost-friendly to produce since they require nothing more than the plant's basic growth requirements. They are administered orally, eliminating the occurrence of injection-related complications [164,165]. Like standard vaccines, edible vaccines include antigens rather than whole pathogen-forming genes. Antigens derived from several diseases can be produced in large quantities and their natural forms in plants. Plants can provide many antigens for recurrent inoculations since they can generate more than one transgene [165].

Edible vaccines have been fostered by the success of oral vaccines [166]. Edible vaccines require less refrigeration and can be stored at room temperature, making them more readily accessible and significantly more affordable, especially for developing countries. The difficulties in developing an edible vaccine include dosing, antigen selection, and distinguishing it from non-engineered varieties to prevent the wrong vaccination [165]. Plant-derived vaccines have been developed to protect against diseases such as diarrhea, enteritis, measles, hepatitis, cholera, malaria, and Newcastle disease, among others (Table 3).

Table 3. A sample of achievements in GM plant-derived vaccines.

Plant	Transgenic Product	Targeted Disease	Administration Method	References
Solanum tuberosum	*HBsAg*	Hepatitis B	Oral	[167]
	E. coli LT-B	Enteritis	Oral	[168]
	Norwalk virus cp	Diarrhea	Oral	[169]
Solanum lycopersicum	*CSP, MSP1*	Malaria	Oral	[170]
	SI protein of SARS-CoV-2	COVID-19	Oral	[171]
Oryza sativa	*Coli LTB and synthetic COE of PEDV*	Enteritis	Oral	[172]
	sCOE-CO1	Enteritis	Oral	[173]
Musa sp.	*HBsAg*	Hepatitis B	Oral	[174]
Lettuce sativa	*Synthetic LTB*	Enteritis	Oral	[175]
	sCTB-sCOE	Diarrhea	Oral	[176]
Spinacea oleraceae	*HIV-Tat*	HIV-1	Oral	[177]
Nicotiana tabacum	Newcastle disease virus	Newcastle disease	Subcutaneous	[178]
Zea mays	*ETEC*	Diarrhea	Oral	[179]
Daucus carota	*Taliglucerasealfa*	Gaucherdisease	Intramuscular	[180]

The idea of edible vaccines was first featured in 1990 in a patent application after the discovery of a surface protein from Streptococcus in tobacco plants that could help the body develop antibodies against the pathogen [181]. Shortly afterward, Arntzen and his team developed the first successful edible vaccine using genetically modified tomatoes, which expressed a protein from the virus that causes diarrhea in pigs [182]. Since then, several significant achievements have been reported in potatoes, rice, spinach, carrots, and bananas, among others (Table 3). In 1995, researchers at the John Innes Centre in the UK developed an edible vaccine for Hepatitis B using transgenic potatoes [183]. In 1999, a team of researchers developed an edible vaccine for the Norwalk virus, which causes gastroenteritis, using transgenic potatoes [184]. Another significant achievement was made in 2005 when scientists at the University of Tokyo developed an edible vaccine for Influenza A using genetically modified rice [185]. These accomplishments demonstrate the potential of edible vaccines as an alternative to traditional vaccines.

Embracing plant-derived vaccines will contribute immensely to public health by making vaccine production cheaper and more accessible, especially in underdeveloped nations. For the same cost, 1000 times more individuals would be reached with edible vaccines than would be through usual vaccination. Moreover, syringes and medical kits are not required [165].

4. Global Acceptance and Perspectives on Biotechnologically Developed Crops

The year 2023 marks the 28th year of biotech food commercialization. About 17 million farmers in 45 nations with GM crop approvals, largely in poor countries, cultivate GM crops throughout the world [186]. Almost every sector of the food industry is adopting this technology. Since 1994, at least 45 nations have received regulatory clearance for GM crops. Among these nations, Japan and the United States have had the most GM events approved [125,152,186]. Several genetically modified crops are currently being commercially cultivated around the world. These include potatoes and alfalfa in the USA, aubergine in Bangladesh, sugar beet in the USA and Canada, and papaya in the USA and China. Other crops that have been genetically modified and are being grown commercially in multiple countries include rapeseed oil in four countries, maize in seventeen countries, soybeans in eleven countries, and cotton in fifteen countries. Among these, the top five biotech plants that are cultivated on the largest areas of land are soybeans, covering 95.9 million hectares; maize, covering 58.9 million hectares; cotton, covering 24.9 million hectares; canola, covering 10.1 million hectares; and alfalfa, covering 1.3 million hectares. Between 1992 and 2016, significant success has been achieved in the genetic modification of crops, especially maize, which is a global staple food. A total of 148 improved varieties of maize have been developed, followed by cotton (58 events), potato (45 events), soybean (34 events), canola (38 events), and dozens of other crops (Figure 4). These crops have been significantly improved for abiotic stress tolerance, better yield, and resistance to diseases, herbicides, insects, and nematodes [125,186]. Over two decades since the introduction of GM crops, many countries across North America, Asia, Africa, and South America have begun commercial cultivation of several GM crop varieties to enhance their food production (Table 4). However, only one event (maize) has been commercially cultivated across Europe, reflecting the continent's cold receptivity to GM varieties.

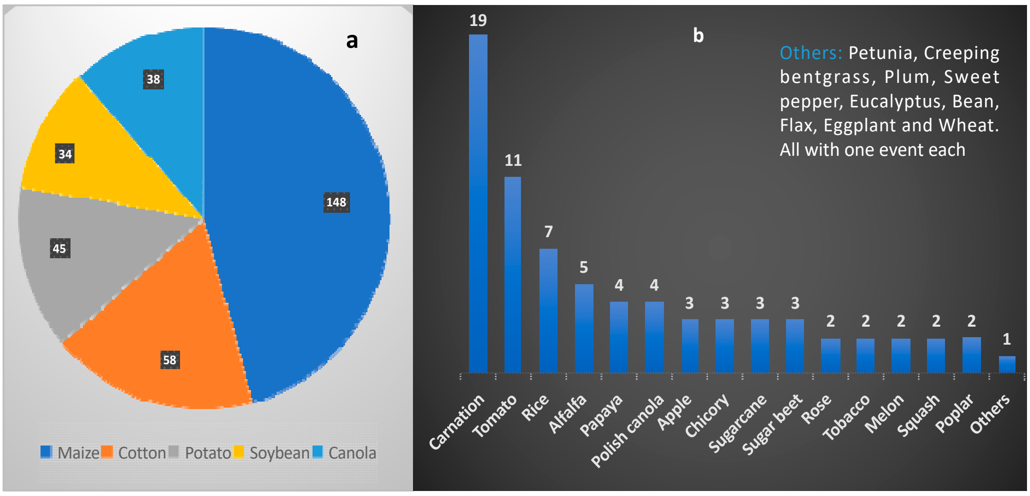

Figure 4. (**a**,**b**) Approved biotech crop events globally (1992–2016). (**a**) Crops with more than 30 events. (**b**) Crops with less than 30 events [125,186].

Table 4. Commercial cultivation of genetically modified crops by country (2015) [125,187].

Country	Cultivation Area (Million Hec.)	% of GM Crops in Total Crops Cultivated	GM Crops
USA	70.9	46.13	maize, soybean, cotton, canola, sugarbeet, alfalfa, papaya, squash, potato
Brazil	44.2	61.49	soybean, maize, cotton
Argentina	24.5	64.41	soybean, maize, cotton
India	11.6	7.39	cotton
Canada	11	25.74	canola, maize, soybean, sugarbeet
China	3.7	3.51	cotton, papaya, poplar
Paraguay	3.6	83.9	soybean, maize, cotton
Pakistan	2.9	13.63	cotton

Table 4. *Cont.*

Country	Cultivation Area (Million Hec.)	% of GM Crops in Total Crops Cultivated	GM Crops
South Africa	2.3	19.13	maize, soybean, cotton
Uruguay	1.4	79.2	soybean, maize
Bolivia	1.1	28.21	soybean
Philippines	0.7	1.47	maize
Australia	0.7	12.9	cotton, canola
Burkina Faso	0.4	7.2	cotton
Myanmar	0.3	2.78	cotton
Mexico	0.1	0.61	cotton, soybean
Spain	0.1	0.41	maize
Columbia	0.1	0.86	cotton, maize
Sudan	0.1	6.12	cotton
Honduras	<0.1	2.65	maize
Chile	<0.1	0.79	maize, soybean, canola
Portugal	<0.1	11.61	maize
Vietnam	<0.1	0.05	maize
Czech Republic	<0.1	0.03	maize
Slovakia	<0.1	0.01	maize
Costa Rica	<0.1	0.04	cotton, soybean
Bangladesh	<0.1	0	eggplant
Romania	<0.1	0	maize

4.1. Europe and Africa

As described in [188], the European Union has resisted GM technology since its inception, raising concerns about possible ecological and health impacts. The EU enacted stringent regulations and legislation to restrict the use of genetically modified organisms (GMOs) within its borders. Public acceptance of genetically modified crops in Europe is also relatively low. As of 2018, of the 4349 GM events registered and approved across countries around the globe, only 4.6 percent were allowed in the EU (199 events for food and feed and 3 maize events for cultivation). In 2018, only two countries (Spain and Portugal) cultivated GM maize varieties. It is also worth mentioning that plants that are transformed using wild-type *Agrobacterium* sp. (the so-called 'naturally transgenic plants') could potentially not be subject to EU GMO legislation because they do not contain recombinant DNA elements.

In Africa, genetically modified crops designed to tackle inadequate food production and macronutrient deficiencies are needed to help the continent overcome its nutrition challenges and make agriculture more profitable for farmers [31]. Nevertheless, African nations exercise caution in accepting GM varieties for commercial production owing to ethical issues about the crops. However, the number of nations cultivating developed varieties doubled from an initial three in 2018 to six a year later. Three African nations have approved GM cotton and maize for commercial production (South Africa, Burkina Faso, and Sudan), while several nations are conducting field experiments on selected GM varieties for their commercialization. According to [125,189], South Africa is among the top developing nations cultivating GM crops, with almost 6.7 million acres planted in 2019 with GM maize, soybeans, and cotton. Every year, there is a constant increase in the number of hectares of land cultivated with GM cultivars in South Africa. GM varieties are becoming increasingly popular in the country, accounting for more than 80% of the total crops planted.

Approximately 150,000 Sudanese farmers planted over 580,000 acres of GM cotton during the same year. Eleven additional nations—Burkina Faso, Ethiopia, Ghana, Kenya, Malawi, Mozambique, Nigeria, South Africa, Swaziland, Tanzania, and Uganda—have been undertaking field experiments on ten GM crops, with sixteen features related to abiotic stress tolerance (drought and salinity), nitrogen utilization efficiency, and increased nutritional content [152]. New GM crops, such as pest-resistant cowpea and cotton, are also being researched and developed to benefit poor Nigerian farmers [31].

Despite Africa's increasing openness to GMOs, they remain outlawed in Algeria and Madagascar, with strict laws against their cultivation and importation. Although GM crop cultivation, research, and development are permitted in Asia to address food and nutrient shortages, Turkey, Kyrgyzstan, Bhutan, and Saudi Arabia have implemented stringent regulations against GM crops. In the Americas, the USA is a strong voice for GMOs, with significant support for their development; however, GMOs are banned in Peru, Belize, Venezuela, and Ecuador.

4.2. GMO-Free CRISPR/Cas9 Crops—Global Thoughts and Acceptance

CRISPR/Cas9 technology has emerged as a potent genome-editing tool, with diverse applications for crop improvement and agricultural sustainability (Table 1). Global thoughts on GMO-free CRISPR/Cas9 crops range from appreciating the enormous prospects for crop enhancement and agricultural sustainability to addressing concerns about regulation, safety, and public perception.

The regulatory framework for CRISPR/Cas9 crops varies by country and region. Different jurisdictions have used different methods to regulate genetically modified organisms (GMOs) and genetically modified crops [190]. Some nations, such as the United States, have adopted a product-based strategy, emphasizing the end product's characteristics rather than the process adopted to develop it. In such regions, if the modified crop does not contain foreign DNA or has qualities that could not be acquired through traditional breeding, it may not be subject to the same regulatory restrictions as transgenic GMOs [191].

In contrast, other countries, such as those in the European Union, have adopted a more stringent process-based regulatory framework that treats gene-edited crops as GMOs, subjecting them to similar regulations and safety assessments as transgenic crops. This approach considers the process of genome editing as a form of genetic modification, irrespective of the presence of foreign DNA [190,192]. However, in recent times, there have been calls for a review of the current regulations in Europe to differentiate between genome-edited crops and transgenic GMOs, considering the precise and targeted nature of the former. This is now being debated in the EU scientific community [193–197].

4.3. Opposition to Global Acceptance of Biotech Crops

The adoption of GM crops for commercial production is highly disputed due to their uncertain consequences [26,27]. Nonetheless, GMO technology has expanded enormously across the world, and many poor countries see GM foods as an answer to increasing agricultural yield and attaining national food security. The environmental effect of genetically modified organisms should also be assessed in their adoption for achieving food security in poor nations. Opposition to GM crops is centered on concerns about biosafety and the possibility of altering the delicate balance of the ecosystem [189,198]. Thus, all GM crops must go through a rigorous and detailed risk assessment to evaluate their potential detrimental effects on humans and the environment. These restrictions are based on a thorough examination of the crop's molecular characterization, an evaluation of the crop's potential for toxicity and its potential allergen response, and a nutritional study of the crop. Researchers often disagree on the long-term consequences of GMO crops on human health and the environmental [26]. It was suggested in [5] that it appears that some businesses in the West are abusing the technology, using it to enhance crop appearances to the detriment of essential nutrients and safety for human consumption.

It has also been argued that using genetically modified crops could have a deteriorating impact on the economy of a nation, subjecting local farmers to predation by corporate monopolies because companies that produce the seeds will sell them at high prices that peasant farmers cannot afford, encouraging large-scale farmers (who can afford the expensive seeds) to dominate over the diversity contributed by small farmers who cannot afford the technology. Also, small-scale farmers could have limited access to seeds due to the patenting of the engineered varieties. However, several studies have proved this wrong. More than 90% of farmers who planted genetically modified crops were small-scale, impoverished farmers in developing nations [199]. Governments can still subsidize the price of GM seeds and put a price ceiling on the seeds to reach more peasant farmers.

Another unforeseen environmental consequence is the possibility of the transmission of herbicide-resistance genes to weeds or other wild plants. This is possible if the weeds are closely related and could cross-pollinate. These wild crops could acquire the herbicide-resistance gene over time, becoming 'super-weeds', thus creating more problems for farmers. Genetically modified crops may fail to germinate, kill microorganisms that are helpful to plants, deplete soil fertility, and potentially impart insecticidal or viral resistance to wild relatives of the crop species [29]. An instance of the unpredictable aftermath of GM varieties on the environment is *Bt* maize, which was engineered with a new gene to produce pollen that has toxins against the European corn borer; however, over time, pollen from *Bt* maize was dispersed by the wind, landing on milkweed on which the monarch butterfly feeds, and killing the caterpillars that feed on it. This accounted for the obvious decline in the Monarch butterfly population [200].

The acceptance of GM crops remains controversial due to varying regulatory approaches, public perceptions, and cultural factors. As technology advances and global conversations continue, it is essential to engage stakeholders, bridge the gap in public understanding, and establish regulatory frameworks that balance innovation, safety, and public trust.

4.4. Contributions to Food Security and Human Health

GM crops have proven their significance in increasing food production and quality. They have also enhanced farmers' incomes, especially smallholder farmers, who constitute the vast majority of undernourished people globally, thus improving their standard of living [201]. A survey conducted in 2018 revealed that farmers in underdeveloped nations earned USD 4.42 in return for each USD 1 spent on procuring engineered seeds [202]. GM crops are a great relief to farmers worldwide, not only in economic terms but also by contributing to their psychological and physiological well-being. With the introduction of GM crops, farmers can now farm with more confidence that their crops will not fail due to insect attacks, unpredictable climatic conditions, or weeds. Moreover, they are assured of optimum yields at reduced farming costs. This was substantiated by Gruère and Sengupta [203] in their research on the impact of *Bt* cotton in India, which showed a 25% decrease in the annual suicide rate among Indian farmers only a year after it was commercialized. GM crops are beneficial not only to farmers but also to the entire population. Biofortified staple varieties have significantly improved nutrient availability, promoting public health and preventing or treating several killer diseases, e.g., diabetes, cancer, hypertension, and immune disorders. Moreover, plant-derived vaccines strengthen their force in disease prevention. *Bt* maize has been proven to contain significantly lower concentrations of mycotoxins, which are toxic and carcinogenic to humans [106]. The consumption of foods with a balanced nutrient composition provides health benefits that last a lifetime. It may yet be too early to quantify these benefits until several decades from now, especially in developing countries where the majority of their nutrient intake is plant-derived [204].

5. Conclusions

Farmers throughout the world have enjoyed major benefits from growing GM crops, including improved yields and reduced production costs. The replanting rate for genetically modified cultivars in fields where they were introduced is about 100%, which indicates that this innovative technology is a top choice, and its performance is satisfactory. GM crops significantly aid in the alleviation of poverty, improving the livelihood of agricultural families across the globe (estimated at 65 million people). Giving more farmers access to genetically modified seeds is necessary for a country that aims to expand its domestic crop production. Higher agricultural yields and plant-mediated vaccinations can contribute to food and health security in developing nations. Edible vaccines have proven to have several advantages over usual vaccinations, including easy administration, decreased manufacturing costs, and the absence of injection-related complications. Embracing plant-derived vaccines would revolutionize global immunization and the vaccine delivery system, with endless prospects. Also, with the development of GM crops with higher agricultural yields, green revolutions may become a reality.

However, regional policies pose an obstacle to the global acceptance of GM crops. Governments with GM bans should consider removing restrictions on GM imports to meet their populations' nutritional (quality) and food-quantity demands. GM foods will help reduce our dependency on food imports from other countries while also greatly increasing domestic agricultural production. Biotech crops are promising, and much more could be achieved if the limiting policies and metered bans are lifted on the commercialization of biotech varieties. Indeed, biotech crops are the pill the world needs to overcome food insecurity!

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