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The Future of Genetically Modified Crops in India

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ABSTRACT: Genetically modified crops (GM crops) are plants used in agriculture, the DNA of which has been modified using genetic engineering methods. Plant genomes can be engineered by physical methods or by use of Agrobacterium for the delivery of sequences hosted in T-DNA binary vectors. In most cases, the aim is to introduce a new trait to the plant which does not occur naturally in the species. Examples in food crops include resistance to certain pests, diseases, environmental conditions, reduction of spoilage, resistance to chemical treatments (e.g. resistance to a herbicide), or improving the nutrient profile of the crop. Examples in non-food crops include production of pharmaceutical agents, biofuels, and other industrially useful goods, as well as for bioremediation.[1]

Farmers have widely adopted GM technology. Acreage increased from 1.7 million hectares in 1996 to 185.1 million hectares in 2016, some 12% of global cropland. As of 2016, major crop (soybean, maize, canola and cotton) traits consist of herbicide tolerance (95.9 million hectares) insect resistance (25.2 million hectares), or both (58.5 million hectares). In 2015, 53.6 million ha of Genetically modified maize were under cultivation (almost 1/3 of the maize crop). GM maize outperformed its predecessors: yield was 5.6 to 24.5% higher with less mycotoxins (−28.8%), fumonisin (−30.6%) and thricotecens (−36.5%). Non-target organisms were unaffected, except for Braconidae, represented by a parasitoid of European corn borer, the target of Lepidoptera active Bt maize. Biogeochemical parameters such as lignin content did not vary, while biomass decomposition was higher.[2]

KEYWORDS: genetically modified crops, genomes, biofuels, mycotoxins, future, India, herbicide, bioremediation

I.INTRODUCTION

A 2014 meta-analysis concluded that GM technology adoption had reduced chemical pesticide use by 37%, increased crop yields by 22%, and increased farmer profits by 68%.[3] This reduction in pesticide use has been ecologically beneficial, but benefits may be reduced by overuse.[4] Yield gains and pesticide reductions are larger for insect-resistant crops than for herbicide-tolerant crops.[5] Yield and profit gains are higher in developing countries than in developed countries.[3] Pesticide poisonings were reduced by 2.4 to 9 million cases per year in India alone and widespread introduction of Bt cotton led to 25% decline in farmer suicides in India.[6] A 2011 review of the relationship between Bt cotton adoption and farmer suicides in India found that "Available data show no evidence of a 'resurgence' of farmer suicides" and that "Bt cotton technology has been very effective overall in India."[7]

There is a scientific consensus[8][9][10][11] that currently available food derived from GM crops poses no greater risk to human health than conventional food,[12][13][14][15][16] but that each GM food needs to be tested on a case-by-case basis before introduction.[17][18][19] Nonetheless, members of the public are much less likely than scientists to perceive GM foods as safe.[20][21][22][23] The legal and regulatory status of GM foods varies by country, with some nations banning or restricting them, and others permitting them with widely differing degrees of regulation.[24][25][26][27]

However, opponents have objected to GM crops on grounds including environmental impacts, food safety, whether GM crops are needed to address food needs, whether they are sufficiently accessible to farmers in developing countries[28] and concerns over subjecting crops to intellectual property law. Safety concerns led 38 countries, including 19 in Europe, to officially prohibit their cultivation.[2]

Humans have directly influenced the genetic makeup of plants to increase their value as a crop through domestication. The first evidence of plant domestication comes from emmer and einkorn wheat found in pre-Pottery Neolithic A villages in Southwest Asia dated about 10,500 to 10,100 BC.[29] The Fertile Crescent of Western Asia, Egypt, and India were sites of the earliest planned sowing and harvesting of plants that had previously been gathered in the wild. Independent development of agriculture occurred in northern and southern China, Africa's Sahel, New Guinea and several regions of the Americas.[30] The eight Neolithic founder crops (emmer wheat, einkorn wheat, barley, peas, lentils, bitter vetch, chick peas and flax) had all appeared by about 7,000 BC.[31] Traditional crop breeders have long introduced foreign germplasm into crops by creating novel crosses. A hybrid cereal grain was created in 1875, by crossing wheat and rye.[32] Since then traits including dwarfing genes and rust resistance have been introduced in that manner.[33] Plant tissue culture and deliberate mutations have enabled humans to alter the makeup of plant genomes.[34][35]

Modern advances in genetics have allowed humans to more directly alter plants genetics. In 1970 Hamilton Smith's lab discovered restriction enzymes that allowed DNA to be cut at specific places, enabling scientists to isolate genes from an organism's genome.[36] DNA ligases that join broken DNA together had been discovered earlier in 1967,[37] and by combining the two technologies, it was possible to "cut and paste" DNA sequences and create recombinant DNA. Plasmids, discovered in 1952,[38] became important tools for transferring information between cells and replicating DNA sequences. In 1907 a bacterium that caused plant tumors, Agrobacterium tumefaciens, was discovered and in the early 1970s the tumor inducing agent was found to be a DNA plasmid called the Ti plasmid.[39] By removing the genes in the plasmid that caused the tumor and adding in novel genes researchers were able to infect plants with A. tumefaciens and let the bacteria insert their chosen DNA sequence into the genomes of the plants.[40] As not all plant cells were susceptible to infection by A. tumefaciens other methods were developed, including electroporation, micro-injection[41] and particle bombardment with a gene gun (invented in 1987).[42][43] In the 1980s techniques were developed to introduce isolated chloroplasts back into a plant cell that had its cell wall removed. With the introduction of the gene gun in 1987 it became possible to integrate foreign genes into a chloroplast.[44] Genetic transformation has become very efficient in some model organisms. In 2008 genetically modified seeds were produced in Arabidopsis thaliana by dipping the flowers in an Agrobacterium solution.[45] In 2013 CRISPR was first used to target modification of plant genomes.[46]

The first genetically engineered crop plant was tobacco, reported in 1983.[47] It was developed creating a chimeric gene that joined an antibiotic resistant gene to the T1 plasmid from Agrobacterium. The tobacco was infected with Agrobacterium transformed with this plasmid resulting in the chimeric gene being inserted into the plant. Through tissue culture techniques a single tobacco cell was selected that contained the gene and a new plant grown from it.[48] The first field trials of genetically engineered plants occurred in France and the US in 1986, tobacco plants were engineered to be resistant to herbicides.[49] In 1987 Plant Genetic Systems, founded by Marc Van Montagu and Jeff Schell, was the first company to genetically engineer insect-resistant plants by incorporating genes that produced insecticidal proteins from Bacillus thuringiensis (Bt) into tobacco.[50] The People's Republic of China was the first country to commercialise transgenic plants, introducing a virus-resistant tobacco in 1992.[51] In 1994 Calgene attained approval to commercially release the Flavr Savr tomato, a tomato engineered to have a longer shelf life.[52] Also in 1994, the European Union approved tobacco engineered to be resistant to the herbicide bromoxynil, making it the first genetically engineered crop commercialised in Europe.[53] In 1995 Bt Potato was approved safe by the Environmental Protection Agency, after having been approved by the FDA, making it the first pesticide producing crop to be approved in the US.[54] In 1996 a total of 35 approvals had been granted to commercially grow 8 transgenic crops and one flower crop (carnation), with 8 different traits in 6 countries plus the EU.[49] By 2010, 29 countries had planted commercialised genetically modified crops and a further 31 countries had granted regulatory approval for transgenic crops to be imported.[55]

The first genetically modified animal to be commercialised was the GloFish, a Zebra fish with a fluorescent gene added that allows it to glow in the dark under ultraviolet light.[56] The first genetically modified animal to be approved for food use was AquAdvantage salmon in 2015.[57] The salmon were transformed with a growth hormone-regulating gene from a Pacific Chinook salmon and a promoter from an ocean pout enabling it to grow year-round instead of only during spring and summer.[58]

II.DISCUSSION

Genetically engineered crops have genes added or removed using genetic engineering techniques,[59] originally including gene guns, electroporation, microinjection and agrobacterium. More recently, CRISPR and TALEN offered much more precise and convenient editing techniques.

Gene guns (also known as biolistics) "shoot" (direct high energy particles or radiations against[60]) target genes into plant cells. It is the most common method. DNA is bound to tiny particles of gold or tungsten which are subsequently shot into plant tissue or single plant cells under high pressure. The accelerated particles penetrate both the cell wall and membranes. The DNA separates from the metal and is integrated into plant DNA inside the nucleus. This method has been applied successfully for many cultivated crops, especially monocots like wheat or maize, for which transformation using Agrobacterium tumefaciens has been less successful.[61] The major disadvantage of this procedure is that serious damage can be done to the cellular tissue.

Agrobacterium tumefaciens-mediated transformation is another common technique. Agrobacteria are natural plant parasites.[62] Their natural ability to transfer genes provides another engineering method. To create a suitable environment for themselves, these Agrobacteria insert their genes into plant hosts, resulting in a proliferation of

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modified plant cells near the soil level (crown gall). The genetic information for tumor growth is encoded on a mobile, circular DNA fragment (plasmid). When Agrobacterium infects a plant, it transfers this T-DNA to a random site in the plant genome. When used in genetic engineering the bacterial T-DNA is removed from the bacterial plasmid and replaced with the desired foreign gene. The bacterium is a vector, enabling transportation of foreign genes into plants. This method works especially well for dicotyledonous plants like potatoes, tomatoes, and tobacco. Agrobacteria infection is less successful in crops like wheat and maize.

Electroporation is used when the plant tissue does not contain cell walls. In this technique, "DNA enters the plant cells through miniature pores which are temporarily caused by electric pulses."

Microinjection is used to directly inject foreign DNA into cells.[63]

Plant scientists, backed by results of modern comprehensive profiling of crop composition, point out that crops modified using GM techniques are less likely to have unintended changes than are conventionally bred crops.[64][65]

In research tobacco and Arabidopsis thaliana are the most frequently modified plants, due to well-developed transformation methods, easy propagation and well studied genomes.[66][67] They serve as model organisms for other plant species.

Introducing new genes into plants requires a promoter specific to the area where the gene is to be expressed. For instance, to express a gene only in rice grains and not in leaves, an endosperm-specific promoter is used. The codons of the gene must be optimized for the organism due to codon usage bias.

Transgenic plants have genes inserted into them that are derived from another species. The inserted genes can come from species within the same kingdom (plant to plant), or between kingdoms (for example, bacteria to plant). In many cases the inserted DNA has to be modified slightly in order to be correctly and efficiently expressed in the host organism. Transgenic plants are used to express proteins, like the cry toxins from B. thuringiensis, herbicide-resistant genes, antibodies,[68] and antigens for vaccinations.[69] A study led by the European Food Safety Authority (EFSA) also found viral genes in transgenic plants.[70]

Transgenic carrots have been used to produce the drug Taliglucerase alfa which is used to treat Gaucher's disease.[71] In the laboratory, transgenic plants have been modified to increase photosynthesis (currently about 2% at most plants versus the theoretic potential of 9–10%).[72] This is possible by changing the rubisco enzyme (i.e. changing C_3 plants into C_4 plants[73]), by placing the rubisco in a carboxysome, by adding CO_2 pumps in the cell wall,[74] or by changing the leaf form or size.[75][76][77][78] Plants have been engineered to exhibit bioluminescence that may become a sustainable alternative to electric lighting.[79]

Cisgenic plants are made using genes found within the same species or a closely related one, where conventional plant breeding can occur. Some breeders and scientists argue that cisgenic modification is useful for plants that are difficult to crossbreed by conventional means (such as potatoes), and that plants in the cisgenic category should not require the same regulatory scrutiny as transgenics.[80] Genetically modified plants can also be developed using gene knockdown or gene knockout to alter the genetic makeup of a plant without incorporating genes from other plants. In 2014, Chinese researcher Gao Caixia filed patents on the creation of a strain of wheat that is resistant to powdery mildew. The strain lacks genes that encode proteins that repress defenses against the mildew. The researchers deleted all three copies of the genes from wheat's hexaploid genome. Gao used the TALENs and CRISPR gene editing tools without adding or changing any other genes. No field trials were immediately planned.[81][82] The CRISPR technique has also been used by Penn State researcher Yinong Yang to modify white button mushrooms (Agaricus bisporus) to be non-browning,[83] and by DuPont Pioneer to make a new variety of corn.[84] With multiple trait integration, several new traits may be integrated into a new crop.[85]

III.RESULTS

GM food's economic value to farmers is one of its major benefits, including in developing nations.[86][87][88] A 2010 study found that Bt corn provided economic benefits of $6.9 billion over the previous 14 years in five Midwestern states. The majority ($4.3 billion) accrued to farmers producing non-Bt corn. This was attributed to European corn borer populations reduced by exposure to Bt corn, leaving fewer to attack conventional corn nearby.[89][90] Agriculture economists calculated that "world surplus [increased by] $240.3 million for 1996. Of this total, the largest share (59%) went to U.S. farmers. Seed company Monsanto received the next largest share (21%), followed by US consumers (9%), the rest of the world (6%), and the germplasm supplier, Delta & Pine Land Company of Mississippi (5%)."[91]

According to the International Service for the Acquisition of Agri-biotech Applications (ISAAA), in 2014 approximately 18 million farmers grew biotech crops in 28 countries; about 94% of the farmers were resource-poor in developing countries. 53% of the global biotech crop area of 181.5 million hectares was grown in 20 developing countries.[92] PG Economics comprehensive 2012 study concluded that GM crops increased farm incomes worldwide by $14 billion in 2010, with over half this total going to farmers in developing countries.[93]

Forgoing these benefits is costly.[94][95] Wesseler et al., 2017 estimate the cost of delay for several crops including GM banana in Uganda, GM cowpea in west Africa, and GM maize/corn in Kenya.[94] They estimate Nigeria alone loses $33–46m annually.[94] The potential and alleged harms of GM crops must then be compared to these costs of delay.[94][95]

Critics challenged the claimed benefits to farmers over the prevalence of biased observers and by the absence of randomized controlled trials. The main Bt crop grown by small farmers in developing countries is cotton. A 2006 review of Bt cotton findings by agricultural economists concluded, "the overall balance sheet, though promising, is mixed. Economic returns are highly variable over years, farm type, and geographical location".[96]

In 2013 the European Academies Science Advisory Council (EASAC) asked the EU to allow the development of agricultural GM technologies to enable more sustainable agriculture, by employing fewer land, water, and nutrient resources. EASAC also criticizes the EU's "time-consuming and expensive regulatory framework" and said that the EU had fallen behind in the adoption of GM technologies.[97]

Participants in agriculture business markets include seed companies, agrochemical companies, distributors, farmers, grain elevators and universities that develop new crops/traits and whose agricultural extensions advise farmers on best practices. According to a 2012 review based on data from the late 1990s and early 2000s, much of the GM crop grown each year is used for livestock feed and increased demand for meat leads to increased demand for GM feed crops.[98] Feed grain usage as a percentage of total crop production is 70% for corn and more than 90% of oil seed meals such as soybeans. About 65 million metric tons of GM corn grains and about 70 million metric tons of soybean meals derived from GM soybean become feed.[98]

In 2014 the global value of biotech seed was US$15.7 billion; US$11.3 billion (72%) was in industrial countries and US$4.4 billion (28%) was in the developing countries.[92] In 2009, Monsanto had $7.3 billion in sales of seeds and from licensing its technology; DuPont, through its Pioneer subsidiary, was the next biggest company in that market.[99] As of 2009, the overall Roundup line of products including the GM seeds represented about 50% of Monsanto's business.[100]

Some patents on GM traits have expired, allowing the legal development of generic strains that include these traits. For example, generic glyphosate-tolerant GM soybean is now available. Another impact is that traits developed by one vendor can be added to another vendor's proprietary strains, potentially increasing product choice and competition.[101] The patent on the first type of Roundup Ready crop that Monsanto produced (soybeans) expired in 2014[102] and the first harvest of off-patent soybeans occurs in the spring of 2015.[103] Monsanto has broadly licensed the patent to other seed companies that include the glyphosate resistance trait in their seed products.[104] About 150 companies have licensed the technology,[105] including Syngenta[106] and DuPont Pioneer.[107]

In 2014, the largest review yet concluded that GM crops' effects on farming were positive. The meta-analysis considered all published English-language examinations of the agronomic and economic impacts between 1995 and March 2014 for three major GM crops: soybean, maize, and cotton. The study found that herbicide-tolerant crops have lower production costs, while for insect-resistant crops the reduced pesticide use was offset by higher seed prices, leaving overall production costs about the same.[3][108]

Yields increased 9% for herbicide tolerance and 25% for insect resistant varieties. Farmers who adopted GM crops made 69% higher profits than those who did not. The review found that GM crops help farmers in developing countries, increasing yields by 14 percentage points.[108]

The researchers considered some studies that were not peer-reviewed and a few that did not report sample sizes. They attempted to correct for publication bias, by considering sources beyond academic journals. The large data set allowed the study to control for potentially confounding variables such as fertilizer use. Separately, they concluded that the funding source did not influence study results.[108]

Under special conditions meant to reveal only genetic yield factors, many GM crops are known to actually have lower yields. This is variously due to one or both of: Yield drag, wherein the trait itself lowers yield, either by competing for synthesis feedstock or by being inserted slightly inaccurately, into the middle of a yield-relevant gene; and/or yield lag, wherein it takes some time to breed the newest yield genetics into the GM lines. This does not reflect realistic field conditions however, especially leaving out pest pressure which is often the point of the GM trait.[109] See for example Roundup Ready § Productivity claims.

Combined features of increased yield, decreased land use, reduced use of fertilizer and reduced farming machinery use create a feedback loop that reduces carbon emissions related to farming. These reductions have been estimated at 7.5% of total agricultural emissions in the EU or 33 millions tons of CO_2.[110]

Gene editing may also increase yields non-specific to the use of any biocides/pesticides. In March 2022, field test results showed CRISPR-based gene knockout of KRN2 in maize and OsKRN2 in rice increased grain yields by ~10% and ~8% without any detected negative effects.[111][112]

GM crops grown today, or under development, have been modified with various traits. These traits include improved shelf life, disease resistance, stress resistance, herbicide resistance, pest resistance, production of useful goods such as biofuel or drugs, and ability to absorb toxins and for use in bioremediation of pollution.

Recently, research and development has been targeted to enhancement of crops that are locally important in developing countries, such as insect-resistant cowpea for Africa[113] and insect-resistant brinjal (eggplant).[114]

The first genetically modified crop approved for sale in the U.S. was the FlavrSavr tomato, which had a longer shelf life.[52] First sold in 1994, FlavrSavr tomato production ceased in 1997.[115] It is no longer on the market.

In November 2014, the USDA approved a GM potato that prevents bruising.[116][117]

In February 2015 Arctic Apples were approved by the USDA,[118] becoming the first genetically modified apple approved for US sale.[119] Gene silencing was used to reduce the expression of polyphenol oxidase (PPO), thus preventing enzymatic browning of the fruit after it has been sliced open. The trait was added to Granny Smith and Golden Delicious varieties.[118][120] The trait includes a bacterial antibiotic resistance gene that provides resistance to the antibiotic kanamycin. The genetic engineering involved cultivation in the presence of kanamycin, which allowed only resistant cultivars to survive. Humans consuming apples do not acquire kanamycin resistance, per arcticapple.com.[121] The FDA approved the apples in March 2015.[122]

Plants use non-photochemical quenching to protect them from excessive amounts of sunlight. Plants can switch on the quenching mechanism almost instantaneously, but it takes much longer for it to switch off again. During the time that it is switched off, the amount of energy that is wasted increases.[123] A genetic modification in three genes allows to correct this (in a trial with tobacco plants). As a result, yields were 14-20% higher, in terms of the weight of the dry leaves harvested. The plants had larger leaves, were taller and had more vigorous roots.[123][124]

Another improvement that can be made on the photosynthesis process (with C3 pathway plants) is on photorespiration. By inserting the C4 pathway into C3 plants, productivity may increase by as much as 50% for cereal crops, such as rice.[125][126][127][128][129]

Implications

The Harnessing Plants Initiative focuses on creating GM plants that have increased root mass, root depth and suberin content. Some GM soybeans offer improved oil profiles for processing.[130] Camelina sativa has been modified to produce plants that accumulate high levels of oils similar to fish oils.[131][132] Golden rice, developed by the International Rice Research Institute (IRRI), provides greater amounts of vitamin A targeted at reducing vitamin A deficiency.[133][134] As of January 2016, golden rice has not yet been grown commercially in any country.[135] A genetically modified cassava under development offers lower cyanogen glucosides and enhanced protein and other nutrients (called BioCassava).[136] In November 2014, the USDA approved a potato that prevents bruising and produces less acrylamide when fried.[116][117] They do not employ genes from non-potato species. The trait was added to the Russet Burbank, Ranger Russet and Atlantic varieties.[116] Plants have been engineered to tolerate non-biological stressors, such as drought,[116][117][137][138] frost,[139] and high soil salinity.[67] In 2011, Monsanto's DroughtGard maize became the first drought-resistant GM crop to receive US marketing approval.[140] As of 1999, the most prevalent GM trait was glyphosate-tolerance.[145] Glyphosate (the active ingredient in Roundup and other herbicide products) kills plants by interfering with the shikimate pathway in plants, which is essential for the synthesis of the aromatic amino acids phenylalanine, tyrosine, and tryptophan. The shikimate pathway is not present in animals, which instead obtain aromatic amino acids from their diet. More specifically, glyphosate inhibits the enzyme 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS).

This trait was developed because the herbicides used on grain and grass crops at the time were highly toxic and not effective against narrow-leaved weeds. Thus, developing crops that could withstand spraying with glyphosate would both reduce environmental and health risks, and give an agricultural edge to the farmer.[145]

Some micro-organisms have a version of EPSPS that is resistant to glyphosate inhibition. One of these was isolated from an Agrobacterium strain CP4 (CP4 EPSPS) that was resistant to glyphosate.[146][147] The CP4 EPSPS gene was engineered for plant expression by fusing the 5' end of the gene to a chloroplast transit peptide derived from

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the petunia EPSPS. This transit peptide was used because it had shown previously an ability to deliver bacterial EPSPS to the chloroplasts of other plants. This CP4 EPSPS gene was cloned and transfected into soybeans.

The plasmid used to move the gene into soybeans was PV-GMGTO4. It contained three bacterial genes, two CP4 EPSPS genes, and a gene encoding beta-glucuronidase (GUS) from Escherichia coli as a marker. The DNA was injected into the soybeans using the particle acceleration method. Soybean cultivar A54O3 was used for the transformation.

Drought resistance occurs by modifying the plant's genes responsible for the mechanism known as the crassulacean acid metabolism (CAM), which allows the plants to survive despite low water levels. This holds promise for water-heavy crops such as rice, wheat, soybeans and poplar to accelerate their adaptation to water-limited environments.[141][142] Several salinity tolerance mechanisms have been identified in salt-tolerant crops. For example, rice, canola and tomato crops have been genetically modified to increase their tolerance to salt stress.[143][144] Tobacco plants have been engineered to be resistant to the herbicide bromoxynil.[148] Crops have been commercialized that are resistant to the herbicide glufosinate, as well.[149] Crops engineered for resistance to multiple herbicides to allow farmers to use a mixed group of two, three, or four different chemicals are under development to combat growing herbicide resistance.[150][151] In October 2014 the US EPA registered Dow's Enlist Duo maize, which is genetically modified to be resistant to both glyphosate and 2,4-D, in six states.[152][153][154] Inserting a bacterial aryloxyalkanoate dioxygenase gene, aad1 makes the corn resistant to 2,4-D.[152][155] The USDA had approved maize and soybeans with the mutation in September 2014.[156] Monsanto has requested approval for a stacked strain that is tolerant of both glyphosate and dicamba. The request includes plans for avoiding herbicide drift to other crops.[157] Significant damage to other non-resistant crops occurred from dicamba formulations intended to reduce volatilization drifting when sprayed on resistant soybeans in 2017.[158] The newer dicamba formulation labels specify to not spray when average wind speeds are above 10–15 miles per hour (16–24 km/h) to avoid particle drift, average wind speeds below 3 miles per hour (4.8 km/h) to avoid temperature inversions, and rain or high temperatures are in the next day forecast. However, these conditions typically only occur during June and July for a few hours at a time.[159][160] Tobacco, corn, rice and some other crops have been engineered to express genes encoding for insecticidal proteins from Bacillus thuringiensis (Bt).[161][162] The introduction of Bt crops during the period between 1996 and 2005 has been estimated to have reduced the total volume of insecticide active ingredient use in the United States by over 100 thousand tons. This represents a 19.4% reduction in insecticide use.[163] In the late 1990s, a genetically modified potato that was resistant to the Colorado potato beetle was withdrawn because major buyers rejected it, fearing consumer opposition.[116] Papaya, potatoes, and squash have been engineered to resist viral pathogens such as cucumber mosaic virus which, despite its name, infects a wide variety of plants.[164] Virus resistant papaya were developed in response to a papaya ringspot virus (PRV) outbreak in Hawaii in the late 1990s. They incorporate PRV DNA.[165][166] By 2010, 80% of Hawaiian papaya plants were genetically modified.[167][168]

Potatoes were engineered for resistance to potato leaf roll virus and Potato virus Y in 1998. Poor sales led to their market withdrawal after three years.[169] Yellow squash that were resistant to at first two, then three viruses were developed, beginning in the 1990s. The viruses are watermelon, cucumber and zucchini/courgette yellow mosaic. Squash was the second GM crop to be approved by US regulators. The trait was later added to zucchini.[170]

Many strains of corn have been developed in recent years to combat the spread of Maize dwarf mosaic virus, a costly virus that causes stunted growth which is carried in Johnson grass and spread by aphid insect vectors. These strands are commercially available although the resistance is not standard among GM corn variants.[171]

In 2012, the FDA approved the first plant-produced pharmaceutical, a treatment for Gaucher's Disease.[172] Tobacco plants have been modified to produce therapeutic antibodies.[173] Algae is under development for use in biofuels.[174] The focus of Microalgae for mass production for biofuels modifying the algae to produce more lipid has become a focus yet will take years to see results due to the cost of this process to extract lipids.[175] Researchers in Singapore were working on GM jatropha for biofuel production.[176] Syngenta has USDA approval to market a maize trademarked Enogen that has been genetically modified to convert its starch to sugar for ethanol.[177] Some trees have been genetically modified to either have less lignin, or to express lignin with chemically labile bonds. Lignin is the critical limiting factor when using wood to make bio-ethanol because lignin limits the accessibility of cellulose microfibrils to depolymerization by enzymes.[178] Besides with trees, the chemically labile lignin bonds are also very useful for cereal crops such as maize,[179][180] Companies and labs are working on plants that can be used to make bioplastics.[181] Potatoes that produce industrially useful starches have been developed as well.[182] Oilseed can be modified to produce fatty acids for detergents, substitute fuels and petrochemicals. Besides the modified oilcrop above, Camelina sativa has also been modified to produce Helicoverpa armigera pheromones and is in progress with a Spodoptera frugiperda version. The H. armigera pheromones have been tested and are effective.[183] Scientists at the University of York developed a weed (Arabidopsis thaliana) that contains genes from bacteria that could clean TNT and RDX-explosive soil contaminants in 2011.[184] 16 million hectares in the US (1.5% of the total surface) are estimated to be contaminated with TNT and RDX. However A. thaliana was not tough enough for use on military test grounds.[185] Modifications in 2016 included switchgrass and bentgrass.[186]

Genetically modified plants have been used for bioremediation of contaminated soils. Mercury, selenium and organic pollutants such as polychlorinated biphenyls (PCBs).[185][187]

Marine environments are especially vulnerable since pollution such as oil spills are not containable. In addition to anthropogenic pollution, millions of tons of petroleum annually enter the marine environment from natural seepages. Despite its toxicity, a considerable fraction of petroleum oil entering marine systems is eliminated by the hydrocarbon-degrading activities of microbial communities. Particularly successful is a recently discovered group of specialists, the so-called hydrocarbonoclastic bacteria (HCCB) that may offer useful genes.[188

Crops such as maize reproduce sexually each year. This randomizes which genes get propagated to the next generation, meaning that desirable traits can be lost. To maintain a high-quality crop, some farmers purchase seeds every year. Typically, the seed company maintains two inbred varieties and crosses them into a hybrid strain that is then sold. Related plants like sorghum and gamma grass are able to perform apomixis, a form of asexual reproduction that keeps the plant's DNA intact. This trait is apparently controlled by a single dominant gene, but traditional breeding has been unsuccessful in creating asexually-reproducing maize. Genetic engineering offers another route to this goal. Successful modification would allow farmers to replant harvested seeds that retain desirable traits, rather than relying on purchased seed.[189] Genetic modifications to some crops also exist, which make it easier to process the crop, i.e. by growing in a more compact form.[190] Also, some crops (such as tomatoes) have been genetic modified to contain no seed at all.[191] Constant exposure to a toxin creates evolutionary pressure for pests resistant to that toxin.[207] Over-reliance on glyphosate and a reduction in the diversity of weed management practices allowed the spread of glyphosate resistance in 14 weed species in the US,[206] and in soybeans.[5]

To reduce resistance to Bacillus thuringiensis (Bt) crops, the 1996 commercialization of transgenic cotton and maize came with a management strategy to prevent insects from becoming resistant. Insect resistance management plans are mandatory for Bt crops. The aim is to encourage a large population of pests so that any (recessive) resistance genes are diluted within the population. Resistance lowers evolutionary fitness in the absence of the stressor, Bt. In refuges, non-resistant strains outcompete resistant ones.[208]

With sufficiently high levels of transgene expression, nearly all of the heterozygotes (S/s), i.e., the largest segment of the pest population carrying a resistance allele, will be killed before maturation, thus preventing transmission of the resistance gene to their progeny.[209] Refuges (i. e., fields of nontransgenic plants) adjacent to transgenic fields increases the likelihood that homozygous resistant (s/s) individuals and any surviving heterozygotes will mate with susceptible (S/S) individuals from the refuge, instead of with other individuals carrying the resistance allele. As a result, the resistance gene frequency in the population remains lower.

Complicating factors can affect the success of the high-dose/refuge strategy. For example, if the temperature is not ideal, thermal stress can lower Bt toxin production and leave the plant more susceptible. More importantly, reduced late-season expression has been documented, possibly resulting from DNA methylation of the promoter.[210] The success of the high-dose/refuge strategy has successfully maintained the value of Bt crops. This success has depended on factors independent of management strategy, including low initial resistance allele frequencies, fitness costs associated with resistance, and the abundance of non-Bt host plants outside the refuges.[211]

Companies that produce Bt seed are introducing strains with multiple Bt proteins. Monsanto did this with Bt cotton in India, where the product was rapidly adopted.[212] Monsanto has also; in an attempt to simplify the process of implementing refuges in fields to comply with Insect Resistance Management(IRM) policies and prevent irresponsible planting practices; begun marketing seed bags with a set proportion of refuge (non-transgenic) seeds mixed in with the Bt seeds being sold. Coined "Refuge-In-a-Bag" (RIB), this practice is intended to increase farmer compliance with refuge requirements and reduce additional labor needed at planting from having separate Bt and refuge seed bags on hand.[213] This strategy is likely to reduce the likelihood of Bt-resistance occurring for corn rootworm, but may increase the risk of resistance for lepidopteran corn pests, such as European corn borer. Increased concerns for resistance with seed mixtures include partially resistant larvae on a Bt plant being able to move to a susceptible plant to survive or cross pollination of refuge pollen on to Bt plants that can lower the amount of Bt expressed in kernels for ear feeding insects.[214][215]

Best management practices (BMPs) to control weeds may help delay resistance. BMPs include applying multiple herbicides with different modes of action, rotating crops, planting weed-free seed, scouting fields routinely, cleaning equipment to reduce the transmission of weeds to other fields, and maintaining field borders.[206] The most widely planted GM crops are designed to tolerate herbicides. By 2006 some weed populations had evolved to tolerate some of the same herbicides. Palmer amaranth is a weed that competes with cotton. A native of the southwestern US, it traveled east and was first found resistant to glyphosate in 2006, less than 10 years after GM cotton was introduced.[216][217]

Farmers generally use less insecticide when they plant Bt-resistant crops. Insecticide use on corn farms declined from 0.21 pound per planted acre in 1995 to 0.02 pound in 2010. This is consistent with the decline in European corn borer populations as a direct result of Bt corn and cotton. The establishment of minimum refuge requirements helped delay the evolution of Bt resistance. However, resistance appears to be developing to some Bt traits in some areas.[206] By leaving at least 30% of crop residue on the soil surface from harvest through planting, conservation tillage reduces soil erosion from wind and water, increases water retention, and reduces soil degradation as well as water and chemical runoff. In addition, conservation tillage reduces the carbon footprint of agriculture.[218] A 2014 review covering 12 states from 1996 to 2006, found that a 1% increase in herbicde-tolerant (HT) soybean adoption leads to a 0.21% increase in conservation tillage and a 0.3% decrease in quality-adjusted herbicide use.[218] The regulation of genetic engineering concerns the approaches taken by governments to assess and manage the risks associated with the development and release of genetically modified crops. There are differences in the regulation of GM crops between countries, with some of the most marked differences occurring between the US and Europe. Regulation varies in a given country depending on the intended use of each product. For example, a crop not intended for food use is generally not reviewed by authorities responsible for food safety.[219][220] In 2013, GM crops were planted in 27 countries; 19 were developing countries and 8 were developed countries. 2013 was the second year in which developing countries grew a majority (54%) of the total GM harvest. 18 million farmers grew GM crops; around 90% were small-holding farmers in developing countries.[1] Farmers have widely adopted GM technology (see figure). Between 1996 and 2013, the total surface area of land cultivated with GM crops increased by a factor of 100, from 17,000 square kilometers (4,200,000 acres) to 1,750,000 km^2 (432 million acres).[1] 10% of the world's arable land was planted with GM crops in 2010.[55] As of 2011, 11 different transgenic crops were grown commercially on 395 million acres (160 million hectares) in 29 countries such as the US, Brazil, Argentina, India, Canada, China, Paraguay, Pakistan, South Africa, Uruguay, Bolivia, Australia, Philippines, Myanmar, Burkina Faso, Mexico and Spain.[55] One of the key reasons for this widespread adoption is the perceived economic benefit the technology brings to farmers. For example, the system of planting glyphosate-resistant seed and then applying glyphosate once plants emerged provided farmers with the opportunity to dramatically increase the yield from a given plot of land, since this allowed them to plant rows closer together. Without it, farmers had to plant rows far enough apart to control post-emergent weeds with mechanical tillage.[225] Likewise, using Bt seeds means that farmers do not have to purchase insecticides, and then invest time, fuel, and equipment in applying them. However critics have disputed whether yields are higher and whether chemical use is less, with GM crops. Direct genetic engineering has been controversial since its introduction. Most, but not all of the controversies are over GM foods rather than crops per se. GM foods are the subject of protests, vandalism, referendums, legislation, court action[239] and scientific disputes. The controversies involve consumers, biotechnology companies, governmental regulators, non-governmental organizations and scientists.

Opponents have objected to GM crops on multiple grounds including environmental impacts, food safety, whether GM crops are needed to address food needs, whether they are sufficiently accessible to farmers in developing countries,[28] concerns over subjecting crops to intellectual property law, and on religious grounds.[240] Secondary issues include labeling, the behavior of government regulators, the effects of pesticide use and pesticide tolerance.

IV.CONCLUSIONS

A significant environmental concern about using genetically modified crops is possible cross-breeding with related crops, giving them advantages over naturally occurring varieties. One example is a glyphosate-resistant rice crop that crossbreeds with a weedy relative, giving the weed a competitive advantage. The transgenic hybrid had higher rates of photosynthesis, more shoots and flowers, and more seeds than the non-transgenic hybrids.[241] This demonstrates the possibility of ecosystem damage by GM crop usage.

There is a scientific consensus[8][9][10][11] that currently available food derived from GM crops poses no greater risk to human health than conventional food,[12][13][14][15][16] but that each GM food needs to be tested on a case-by-case basis before introduction.[17][18][19] Nonetheless, members of the public are much less likely than scientists to perceive GM foods as safe.[20][21][22][23] The legal and regulatory status of GM foods varies by country, with some nations banning or restricting them, and others permitting them with widely differing degrees of regulation.[24][25][26][27] No reports of ill effects from GM food have been documented in the human population.[242][243][244] GM crop labeling is required in many countries, although the United States Food and Drug Administration does not, nor does it distinguish between approved GM and non-GM foods.[245] The United States enacted a law that requires labeling regulations to be issued by July 2018. It allows indirect disclosure such as with a phone number, bar code, or web site.[246]

Advocacy groups such as Center for Food Safety, Union of Concerned Scientists, Greenpeace and the World Wildlife Fund claim that risks related to GM food have not been adequately examined and managed, that GM crops are not sufficiently tested and should be labelled, and that regulatory authorities and scientific bodies are too closely tied to industry. Some studies have claimed that genetically modified crops can cause harm;[247][248] a 2016 review that reanalyzed the data from six of these studies found that their statistical methodologies were flawed and did not demonstrate harm, and said that conclusions about GM crop safety should be drawn from "the totality of the evidence ... instead of far-fetched evidence from single studies".[249]

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   The literature about Biodiversity and the GE food/feed consumption has sometimes resulted in animated debate regarding the suitability of the experimental designs, the choice of the statistical methods or the public accessibility of data. Such debate, even if positive and part of the natural process of review by the scientific community, has frequently been distorted by the media and often used politically and inappropriately in anti-GE crops campaigns.
9. ^ "State of Food and Agriculture 2003–2004. Agricultural Biotechnology: Meeting the Needs of the Poor. Health and environmental impacts of transgenic crops". Food and Agriculture Organization of the United Nations. Retrieved 30 August 2019. Currently available transgenic crops and foods derived from them have been judged safe to eat and the methods used to test their safety have been deemed appropriate. These conclusions represent the consensus of the scientific evidence surveyed by the ICSU (2003) and they are consistent with the views of the World Health Organization (WHO, 2002). These foods have been assessed for increased risks to human health by several national regulatory authorities (inter alia, Argentina, Brazil, Canada, China, the United Kingdom and the United States) using their national food safety procedures (ICSU). To date no verifiable untoward toxic or nutritionally deleterious effects resulting from the consumption of foods derived from genetically modified crops have been discovered anywhere in the world (GM Science Review Panel). Many millions of people have consumed foods derived from GM plants - mainly maize, soybean and oilseed rape - without any observed adverse effects (ICSU).
10. ^ Ronald P (May 2011). "Plant genetics, sustainable agriculture and global food security". Genetics. 188 (1): 11–20. doi:10.1534/genetics.111.128553. PMC 3120150. PMID 21546547. There is broad scientific consensus that genetically engineered crops currently on the market are safe to eat. After 14 years of cultivation and a cumulative total of 2 billion acres planted, no adverse health or environmental effects have resulted from commercialization of genetically engineered crops (Board on Agriculture and Natural Resources, Committee on Environmental Impacts Associated with Commercialization of Transgenic Plants, National Research Council and Division on Earth and Life Studies 2002). Both the U.S. National Research Council and the Joint Research Centre (the European Union's scientific and technical research laboratory and an integral part of the European Commission) have concluded that

there is a comprehensive body of knowledge that adequately addresses the food safety issue of genetically engineered crops (Committee on Identifying and Assessing Unintended Effects of Genetically Engineered Foods on Human Health and National Research Council 2004; European Commission Joint Research Centre 2008). These and other recent reports conclude that the processes of genetic engineering and conventional breeding are no different in terms of unintended consequences to human health and the environment (European Commission Directorate-General for Research and Innovation 2010).

11. ^ Domingo JL, Giné Bordonaba J (May 2011). "A literature review on the safety assessment of genetically modified plants" (PDF). Environment International. 37 (4): 734–42. doi:10.1016/j.envint.2011.01.003. PMID 21296423. In spite of this, the number of studies specifically focused on safety assessment of GM plants is still limited. However, it is important to remark that for the first time, a certain equilibrium in the number of research groups suggesting, on the basis of their studies, that a number of varieties of GM products (mainly maize and soybeans) are as safe and nutritious as the respective conventional non-GM plant, and those raising still serious concerns, was observed. Moreover, it is worth mentioning that most of the studies demonstrating that GM foods are as nutritional and safe as those obtained by conventional breeding, have been performed by biotechnology companies or associates, which are also responsible of commercializing these GM plants. Anyhow, this represents a notable advance in comparison with the lack of studies published in recent years in scientific journals by those companies.

Krimsky S (2015). "An Illusory Consensus behind GMO Health Assessment". Science, Technology, & Human Values. 40 (6): 883–914. doi:10.1177/0162243915598381. S2CID 40855100. I began this article with the testimonials from respected scientists that there is literally no scientific controversy over the health effects of GMOs. My investigation into the scientific literature tells another story.

And contrast:

Panchin AY, Tuzhikov AI (March 2017). "Published GMO studies find no evidence of harm when corrected for multiple comparisons". Critical Reviews in Biotechnology. 37 (2): 213–217. doi:10.3109/07388551.2015.1130684. PMID 26767435. S2CID 11786594. Here, we show that a number of articles some of which have strongly and negatively influenced the public opinion on GM crops and even provoked political actions, such as GMO embargo, share common flaws in the statistical evaluation of the data. Having accounted for these flaws, we conclude that the data presented in these articles does not provide any substantial evidence of GMO harm.

The presented articles suggesting possible harm of GMOs received high public attention. However, despite their claims, they actually weaken the evidence for the harm and lack of substantial equivalency of studied GMOs. We emphasize that with over 1783 published articles on GMOs over the last 10 years it is expected that some of them should have reported undesired differences between GMOs and conventional crops even if no such differences exist in reality.

and

Yang YT, Chen B (April 2016). "Governing GMOs in the USA: science, law and public health". Journal of the Science of Food and Agriculture. 96 (6): 1851–5. doi:10.1002/jsfa.7523. PMID 26536836. It is therefore not surprising that efforts to require labeling and to ban GMOs have been a growing political issue in the USA (citing Domingo and Bordonaba, 2011). Overall, a broad scientific consensus holds that currently marketed GM food poses no greater risk than conventional food ... Major national and international science and medical associations have stated that no adverse human health effects related to GMO food have been reported or substantiated in peer-reviewed literature to date.

Despite various concerns, today, the American Association for the Advancement of Science, the World Health Organization, and many independent international science organizations agree that GMOs are just as safe as other foods. Compared with conventional breeding techniques, genetic engineering is far more precise and, in most cases, less likely to create an unexpected outcome.

12. ^ "Statement by the AAAS Board of Directors On Labeling of Genetically Modified Foods" (PDF). American Association for the Advancement of Science. 20 October 2012. Retrieved 30 August 2019. The EU, for example, has invested more than €300 million in research on the biosafety of GMOs. Its recent report states: "The main conclusion to be drawn from the efforts of more than 130 research projects, covering a period of more than 25 years of research and involving more than 500 independent research groups, is that biotechnology, and in particular

GMOs, are not per se more risky than e.g. conventional plant breeding technologies." The World Health Organization, the American Medical Association, the U.S. National Academy of Sciences, the British Royal Society, and every other respected organization that has examined the evidence has come to the same conclusion: consuming foods containing ingredients derived from GM crops is no riskier than consuming the same foods containing ingredients from crop plants modified by conventional plant improvement techniques.

Pinholste G (25 October 2012). "AAAS Board of Directors: Legally Mandating GM Food Labels Could "Mislead and Falsely Alarm Consumers"" (PDF). American Association for the Advancement of Science. Retrieved 30 August 2019.

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14. ^ "AMA Report on Genetically Modified Crops and Foods (online summary)". American Medical Association. January 2001. Retrieved 30 August 2019. A report issued by the scientific council of the American Medical Association (AMA) says that no long-term health effects have been detected from the use of transgenic crops and genetically modified foods, and that these foods are substantially equivalent to their conventional counterparts." "Crops and foods produced using recombinant DNA techniques have been available for fewer than 10 years and no long-term effects have been detected to date. These foods are substantially equivalent to their conventional counterparts.

   "Report 2 of the Council On Science and Public Health (A-12): Labeling of Bioengineered Foods" (PDF). American Medical Association. 2012. Archived from the original (PDF) on 7 September 2012. Retrieved 30 August 2019. Bioengineered foods have been consumed for close to 20 years, and during that time, no overt consequences on human health have been reported and/or substantiated in the peer-reviewed literature.
15. ^ "Restrictions on Genetically Modified Organisms: United States. Public and Scholarly Opinion". Library of Congress. 30 June 2015. Retrieved 30 August 2019. Several scientific organizations in the US have issued studies or statements regarding the safety of GMOs indicating that there is no evidence that GMOs present unique safety risks compared to conventionally bred products. These include the National Research Council, the American Association for the Advancement of Science, and the American Medical Association. Groups in the US opposed to GMOs include some environmental organizations, organic farming organizations, and consumer organizations. A substantial number of legal academics have criticized the US's approach to regulating GMOs.
16. ^ National Academies Of Sciences; Division on Earth Life Studies Engineering; Board on Agriculture Natural Resources; Committee on Genetically Engineered Crops: Past Experience Future Prospects (2016). Genetically Engineered Crops: Experiences and Prospects. The National Academies of Sciences, Engineering, and Medicine (US). p. 149. doi:10.17226/23395. ISBN 978-0-309-43738-7. PMID 28230933. Retrieved 30 August 2019. Overall finding on purported adverse effects on human health of foods derived from GE crops: On the basis of detailed examination of comparisons of currently commercialized GE with non-GE foods in compositional analysis, acute and chronic animal toxicity tests, long-term data on health of livestock fed GE foods, and human epidemiological data, the committee found no differences that implicate a higher risk to human health from GE foods than from their non-GE counterparts.
17. ^ "Frequently asked questions on genetically modified foods". World Health Organization. Retrieved 30 August 2019. Different GM organisms include different genes inserted in different ways. This means that individual GM foods and their safety should be assessed on a case-by-case basis and that it is not possible to make general statements on the safety of all GM foods.

   GM foods currently available on the international market have passed safety assessments and are not likely to present risks for human health. In addition, no effects on human health have been shown as a result of the consumption of such foods by the general population in the countries where they have been approved. Continuous application of safety assessments based on the Codex Alimentarius principles and, where appropriate, adequate post market monitoring, should form the basis for ensuring the safety of GM foods.
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   "Genetically modified foods and health: a second interim statement" (PDF). British Medical Association. March

2004. Retrieved 30 August 2019. In our view, the potential for GM foods to cause harmful health effects is very small and many of the concerns expressed apply with equal vigour to conventionally derived foods. However, safety concerns cannot, as yet, be dismissed completely on the basis of information currently available.

When seeking to optimise the balance between benefits and risks, it is prudent to err on the side of caution and, above all, learn from accumulating knowledge and experience. Any new technology such as genetic modification must be examined for possible benefits and risks to human health and the environment. As with all novel foods, safety assessments in relation to GM foods must be made on a case-by-case basis.

Members of the GM jury project were briefed on various aspects of genetic modification by a diverse group of acknowledged experts in the relevant subjects. The GM jury reached the conclusion that the sale of GM foods currently available should be halted and the moratorium on commercial growth of GM crops should be continued. These conclusions were based on the precautionary principle and lack of evidence of any benefit. The Jury expressed concern over the impact of GM crops on farming, the environment, food safety and other potential health effects.

The Royal Society review (2002) concluded that the risks to human health associated with the use of specific viral DNA sequences in GM plants are negligible, and while calling for caution in the introduction of potential allergens into food crops, stressed the absence of evidence that commercially available GM foods cause clinical allergic manifestations. The BMA shares the view that there is no robust evidence to prove that GM foods are unsafe but we endorse the call for further research and surveillance to provide convincing evidence of safety and benefit.

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