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Trends in Biotechnology

Special issue: 40th anniversary

Opinion

Agricultural biotechnology for sustainable food security

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Of late, global food security has been under threat by the coronavirus disease 2019 (COVID-19) pandemic and the recent military conflict in Eastern Europe. This article presents the objectives of the Sustainable Development Goals and the European Green Deal related to achieving food security and sustainable development in European Union (EU) agriculture, taking the aforementioned threats into account. In addition, it discusses the future of plant agricultural biotechnology and artificial intelligence (AI) systems, considering their potential for reaching the goal of food security. Paradoxically, the present challenging situation may allow politicians and stakeholders of the EU to realize opportunities and use the potential of the biotechnology sector.

Highlights

The COVID-19 pandemic and the geopolitical instability in Europe call for coordinated efforts from scientists, farmers, producers, and consumers to ensure food security.

Recent progress in molecular biology and biotechnology creates hope for the future. Using genetic engineering techniques, scientists continue to improve crops, aiming to diminish the losses caused by biotic and abiotic stresses and to increase yield.

There is an urgent need for communication between scientists and society based on reliable scientific knowledge, as is appropriate legislation.

The EU's ways to ensure food security: why do many initiatives seem unreachable?

Before the global crisis, the European Commission (EC) introduced many initiatives to make the economy and agriculture sustainable. The most ambitious and challenging among them is the European Green Deal, which aims to make the EU – the world's second-largest economy – climate-neutral by 2050 [1]. One of the important agendas of the European Green Deal is a fair, healthy, and environmentally friendly food system. For this purpose, the EC designed a strategic document – the 'Farm to Fork Strategy' [2] – the overall goal of which is to transform the way food is produced and consumed. In the EU Farm to Fork Strategy, the EC indicated targets for various actions: for example, to reduce the use and risk of chemical pesticides by 50% and the use of more hazardous pesticides by 50%, to reduce the use of fertilizers by at least 20%, and to increase organic production to achieve 25% of the EU's agricultural land use, all by 2030 [2]. However, the recent events unfolding in the world have significantly influenced the feasibility and consequences of this strategy. Hence, to ensure food security in Europe and neighboring countries, a new policy consensus is needed. In addition, all actions to ensure food security need to be supported by a Common Agricultural Policy (CAP) that focuses on the Green Deal. The new CAP strategies will be implemented in all EU countries from 1 January 2023[i]. The proposals have outlined a more straightforward and more efficient approach that is implementing the policy goals of the European Green Deal [3]. However, the CAP may have a devastating impact on the southern hemisphere, where government subsidies are not as high, and the sectors are less competitive, for instance, by destroying local farming economies and causing detrimental effects on the environment as well as working conditions in the global south[ii,iii].

Initiatives such as the Biodiversity Strategy [4], Zero Pollution Action Plan [5], and the EU action plan for the Circular Economy [6] are a significant part of the European Green Deal [1]. Within the framework of the European Green Deal, the EC has published the 2030 Biodiversity Strategy in response to the COVID-19 pandemic, which is a roadmap for the upcoming 10 years regarding the objectives of the EU [4]. As shown in the literature, environmental degradation increases the risk of outbreaks of zoonotic diseases, and resilient ecosystems decrease it[iv]. The Biodiversity

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Strategy is a core part of the EU's recovery plan following the COVID-19 pandemic, and is essential for protecting EU and global food security [4]. One of its targets is to protect at least 30% of the land and 30% of the sea. Interestingly, in 2021, about 26% of the EU's land area and only 11% of its seas were protected[v]. According to the EU Forest Strategy, at least three billion trees have to be planted in the EU by 2030 while respecting ecological principles [7]. By June 2022, 4 475 977 trees have been planted in the EU countries, which constitutes only 0.14% of the proposed three-billion goal[vi]. To achieve this ambitious target by 2030, more than 427 million plants need to be planted annually in the EU. These numbers show that the ambitious goals set out in many EU strategic documents require clear and specific actions in their implementation, otherwise they might be difficult to achieve.

Moreover, the EU adopted the United Nations' (UN's) Sustainable Development Goals (SDGs) that were introduced in 2015. The aim of the 17 SDGs, with 169 associated targets, is to end extreme poverty, reduce inequality, and protect the planet, all by 2030 [8][vii]. Achieving the SDGs was always a challenge, and now it seems even more improbable. At present, the most important actions that need to be taken are: to build more sustainable and resilient food systems, to build resilience against the pandemic, to tackle inequality across countries, and to invest in people. One of the targets (no 12.3) of the UN's SDGs is to decrease food loss and waste [8][viii]. However, globally, around 14% of food produced is lost between harvest and retail, and around 17% is wasted (11% in households, 5% in food service, and 2% in retail)[ix]. This amounts to around 87.6 million tonnes of food every year in the EU, roughly 173 kg per person, but the numbers differ significantly depending on the region and country [9,10].

Importantly, the need to move beyond the traditional four-pillar framework for food security – namely availability, access, utilization, and stability – to a six-dimensional one incorporating agency and sustainability has been highlighted in the 15th *Food Security and Nutrition: Building a Global Narrative Towards 2030* report [11], prepared by the High Level Panel of Experts on Food Security and Nutrition (HLPE) of the UN Committee on World Food Security [12] (Box 1). To increase the resilience of food systems, a policy that supports all dimensions of food security should be designed. This is especially important in scenarios such as the current food crisis triggered by the conflict in Ukraine. The COVID-19 pandemic highlighted the need for transformation of food systems worldwide [15]. Searching for new solutions in agriculture to improve productivity and reduce food waste is required. Information technology (IT) solutions are especially important during crises such as a pandemic or a war as they could be used to automate factories by smart sensors, thus reducing contact and communication with objects and enabling them to be monitored remotely [16,17] (Box 2).

This opinion article presents challenges and opportunities for the development and usage of new **genome-editing (gene-editing) techniques** (see Glossary) in the context of the objectives of the European Green Deal and the SDGs after the unexpected global pandemic and the current geopolitical instability in Europe. It also presents the benefits and risks of genomic techniques used to improve agriculture practices and ensure **food security**.

Impact of the COVID-19 pandemic and geopolitical instability in Europe on global food security

In the past few years the hunger crisis has reached unprecedented proportions worldwide. Alarmingly high levels of hunger surpassing all previous records were observed in 2021. Nearly 193 million people across 53 countries/territories were acutely food-insecure and in need of immediate assistance [26]. Almost 40 million more people suffered from hunger compared with the previous high reached in 2020 (reported in the GRFC 2021) [26]. In just 2 years, the number

Glossary

Agricultural biotechnology: a range of tools, including traditional and new breeding techniques, which alter living organisms, or parts of organisms, to make or modify products, improve plants or animals, or develop microorganisms for specific agricultural uses.
Artificial intelligence (AI): the science and engineering of making intelligent machines, especially intelligent computer programs. It is related to the similar task of using computers to understand human intelligence, but AI does not have to confine itself to methods that are biologically observable [68].
Food security: exists when 'all people, at all times, have physical and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life' [69].
Genetically modified (GM) crops: crops in which the genetic material (DNA) has been altered in a way that does not occur naturally by mating or natural recombination.
Genome-editing (gene-editing) techniques: a subset of NGTs that allow precise modification of DNA in the target genome in a variety of ways. Genome editing encompasses a variety of techniques, which may be applied in mutagenesis, cisgenesis, intragenesis, or transgenesis.
Internet of Things (IoT): the 'network of physical objects – 'things' – that are embedded with sensors, software, and other technologies for the purpose of connecting and exchanging data with other devices and systems over the internet'[xxxiv].
New genomic techniques (NGTs): an umbrella term used to describe a variety of techniques that can alter the genetic material of an organism and that have emerged or have been developed since 2001, when the existing GMO legislation was adopted.
New plant-breeding techniques (NPBTs): techniques to develop new varieties in a manner that is faster and more precise than conventional breeding techniques by modifying the DNA of seeds and cells. Using these techniques, a number of limitations of conventional breeding can be overcome. Examples include zinc-finger nucleases, transcription activator-like effector nucleases (TALENs), and the meganuclease and clustered regularly interspaced short palindromic repeats (CRISPR) systems.

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Box 1. Pillars of food security

The six elements forming the framework of food and nutrition security are availability, access, use/utilization, stability, agency, and sustainability.

Food availability refers to sufficient quantities of food of appropriate quality, free from adverse substances and acceptable within a given culture, supplied through stores, food outlets, imports, and primary production. At local and community levels, this dimension also includes the location of the stores/food outlets and the price, quality, and variety of food, and encompasses core and traditional foods and food aid.

Food access is ensured when all households have enough financial and physical resources to obtain food in sufficient quantity, quality, and diversity for a nutritious diet for everyone, including vulnerable individuals and groups. Entitlements are defined as the set of all commodity bundles over which a person can establish command given the legal, political, economic, and social arrangements of the community in which they live (including traditional rights such as access to common resources).

Food use/utilization relies on knowledge and understanding of an adequate diet to reach a state of nutritional well-being where all physiological needs are met. It takes into account clean water, sanitation, health care, cultural considerations, social environments, and preparation, storage, and cooking skills.

Stability refers to having the ability to ensure food security in the event of sudden shocks (e.g., an economic, health, conflict, or climatic crisis) or cyclical events (e.g., seasonal food insecurity). Its concept can therefore refer to both the availability and the access dimensions of food security.

Agency refers to the capacity of individuals and groups to exercise a degree of control over their own circumstances (to make choices about what they eat, the foods they produce, and how that food is produced, processed, and distributed) and to provide meaningful input into governance processes that shape food systems.

Sustainability refers to food system practices that contribute to the long-term regeneration of natural, social, and economic systems, ensuring that the food needs of the present generations are met without compromising the food needs of future generations [11–14].

of severely food-insecure people has increased by more than 200 million, from 135 million in 53 countries (before the COVID-19 pandemic) to 345 million in 82 countries. In addition, it has been estimated that up to 811 million people go to bed hungry every night[xix].

Box 2. IT solutions in the agricultural sector

The increase in population adds more pressure on cultivable land as there will be only an additional 4% of the land that can be turned cultivable by 2050 [18]. Traditional agricultural methods are not sufficient to address the huge demand of the growing population. This prompts farmers and agricultural companies to find new methods to improve productivity and reduce waste[x]. Artificial intelligence (AI) can be applied in the technological evolution of the agricultural industry as it can be used in crop yield and price forecasts, intelligent spraying, predictive insights, agriculture robots, crop and soil monitoring, and disease diagnosis [19–21]. The use of AI in agriculture can be categorized into two types: AI software and AI robots [21]. AI robots are used in various activities such as crop scouting, pest and weed management, harvesting, spraying, pruning, milking, phenotyping, and sorting [22]. Most of these robots are still in the early stages of development, and very few have reached the commercial scale. AI can be used in drones and self-driving tractors. Drones are useful in spraying water, pesticides, and herbicides on fields and mapping farms and arable fields, whereas self-driving tractors are still in the early stages of development and have not been used commercially [21]. Farmers use AI in applications and software to determine the health or illness of plants and to provide recommendations [23]. One of the examples of using IT in agriculture is the 365FarmNet software (an international platform developed in 2013) currently operating in 25 countries, of which Poland is one of the leaders in terms of the number of users/area of farms managed[xi,xii]. In the food industry, many waste management startups use AI, such as Winnow (UK), Wasteless (Israel), Gamaya (Switzerland), Greyparrot (UK), and The 77 Lab (USA)[xiii–xviii].

Internet of Things (IoT) solutions are increasingly adopted in agriculture. Interestingly, COVID-19 has positively affected the application of the IoT in the agricultural sector. Disruptions in the supply chain and a lack of qualified workers have led to an increase in the compound annual growth rate to 9.9% [24]. Studies reveal that IoT solutions are the best methods to increase the efficiency and productivity of many sectors, such as industry and agriculture [25].

The major factors driving the profound hunger crisis are as follows: (i) military conflicts (with 60% of the hungry people of the world living in areas affected by war and violence), (ii) climate shocks that have globally displaced 30 million people from their homes in 2020 (destroyed crops, livelihood, and lives), and (iii) economic consequences of the COVID-19 pandemic (driving hunger to unprecedented levels)[xix]. Amid the COVID-19 pandemic, supply chain issues, and soaring inflation, food prices have been on the rise globally since mid-2020 and are now at an all-time high[xx]. At present, heavy fighting is destroying livelihoods and displacing millions of people across Ukraine, restricting humanitarian access, disrupting food supply chains, and likely imposing severe constraints on the production of agricultural products in one of the most important global producers and exporters of food commodities. Events unfolding in Ukraine elucidate how conflict feeds hunger, forcing people out of their homes and wiping out their sources of income.

Disturbances and problems in marketing, logistics, and trade systems may restrict access to food, thus leading to hunger and malnutrition problems [27]. During the COVID-19 pandemic, panic buying temporarily reduced the availability of food for both consumers and suppliers [28]. More recently, food availability has also been weakened by the conflict between Ukraine and Russia because both these countries are important producers of agricultural commodities [29]. In particular, they significantly contribute to the global production of sunflower seed (53% of the world's production), barley (18%), and wheat (15%)[xxi]. Ukraine and Russia are also global exporters of wheat, barley, maize, rapeseed and rapeseed oil, and sunflower seed and sunflower oil. They were the highest global exporters of sunflower oil (65%) and wheat (28%) in 2020. The EC has reported that food availability is currently not at stake in the EU, since the continent is largely self-sufficient for many agricultural products[xxii]. However, the conflict in Ukraine has exposed the dependency of agricultural production in the EU on energy, animal feed and feed additives, and agricultural fertilizers (31% of EU nitrogen fertilizer imports come from Russia) [30].

Importantly, several countries rely on imports from Russia and Ukraine for their basic food supply. North African and Middle East countries import more than 50% of their cereals from Russia and Ukraine, whereas Eastern African countries import 72% of their cereals from Russia and 18% from Ukraine [30]. The conflict in Ukraine has also disrupted the country's agricultural production. Furthermore, agricultural production in Ukraine is estimated to decline by 25–50% in 2023 [31].

Access to food is extremely restricted by the sharp increase in food prices across the world. The COVID-19 pandemic and the conflict in Ukraine have caused serious distresses to global commodity markets and will have longer-term consequences. The supply of several commodities has been broken, leading to significant increases in prices, especially for energy resources, fertilizers, and some grains [32]. The Food and Agriculture Organization (FAO) Food Price Index (FFPI) is a measure of the monthly change in international prices of food commodities. The FFPI averaged 157.4 points in May 2022, whereas it was 98.1 before the COVID-19 pandemic[xxiii]. Food prices were already high in mid-2021, and the conflict is pushing them even higher. Wheat, maize, edible oils, and fertilizers are the most affected commodities. Besides food prices, access to transportation is disrupted. As Russia has blocked Ukraine's Black Sea ports (mainly Odessa and Mykolayiv), about 20 million tonnes of grains remain stuck in Ukraine [33][xxiv]. It means that currently grain exports are largely dependent on the goodwill of the parties involved in the war. However, the agreement between Russia, Ukraine, the UN, and Turkey, signed on 22 July 2022, allows safe passage for ships going in and out of three Ukrainian Black Sea ports that have been blocked by Russia since its 24 February 2022 invasion[xxv]. Nevertheless, as the WFP Executive Director David Beasley said: 'it will take more than grain ships out of Ukraine to stop world hunger, but with Ukrainian grain back on global markets we have a chance to stop this global food crisis from spiraling even further'[xxvi].

Food supply needs to be stable to ensure food security; it is also necessary to stabilize the price of commodities as the world food markets and prices have been extremely unstable of late. According to the International Food Policy Research Institute (IFPRI), prices of all major staple foods have been excessively volatile due to the crisis[xxvii]. According to Glauber and Smith [34], the same trend in agricultural prices will continue through 2022 and 2023. Interestingly, the authors calculated that the global area outside Ukraine for wheat, feed grain, and soybean cultivation in 2022/2023 will increase by 4.4 million hectares, almost compensating for the predicted loss of 4.7 million hectares in Ukraine [34]. Furthermore, Zhang *et al.* [35] have predicted that in the future, global wheat prices will show more steep spikes with global warming of 2°C (a 6.2% increase in the 95th percentile of global consumer price anomalies) despite a 1.7% increase in production, given that CO_2 fertilization is beneficial for crops [35].

Food utilization, or nutrition, is also influenced by the crises. As commodity prices increase, the variety of food consumed decreases. In 2020, due to the increased cost, almost 3.1 billion people could not afford a healthy diet [36]. According to the United Nations Children's Fund (UNICEF) report from May 2022, the cost of lifesaving treatment for the most severely malnourished children is estimated to increase by up to 16% due to the conflict in Ukraine, which imposes an additional strain on the food systems already affected by the COVID-19 pandemic and climate change [37]. As highlighted in the report, in 2020, approximately 5 million children were treated with cost-efficient, ready-made therapeutic food (RUTF) proven to save lives. However, the price of RUTF is increasing due to the COVID-19 pandemic and the conflict in Ukraine, and more funding is needed to maintain its supply [37].

Clapp *et al*. proposed that food policy bodies should update their understanding of food security in policy frameworks to incorporate new insights brought forward in the literature on the importance of agency and sustainability for food security [12]. The COVID-19 pandemic and the conflict in Ukraine demonstrated a concentrated character of food production and markets that weakened the society's agency in food systems. Some countries such as Russia and Ukraine have a big share in grain production and export, whereas developing countries (e.g., in North Africa) are dependent on food imports.

Agricultural biotechnology in ensuring global food security

New plant breeding techniques (NPBTs) constitute a toolkit of **agricultural biotechnology**, which are used in the food and agriculture sectors for genetic improvement of plant varieties and animal populations, characterization and conservation of genetic resources, diagnosis of plant and animal diseases, and other purposes [38–44]. They offer various science-driven approaches to mitigate global food insecurity and the impacts of climate change, both of which are accelerating at an alarming pace. It was estimated nearly a decade ago that global food production must be doubled by 2050 if the needs of the continuously growing human population are to be met [45,46]. In addition, the COVID-19 pandemic and geopolitical instability have seriously threatened food security worldwide. Farmers can adopt an integrated set of tools, such as biotech crops that are climate-resilient and can better withstand various stresses, including drought, heat, and flooding (reviewed in [47–50]). To date, 44 countries have granted regulatory approvals to 385 genetic modification events (either stacked or singular traits) for use in food (direct use or additive), covering 24 plant species[xxviii]. The most widely modified plants (by the number of genetic modification events) are maize (*Zea mays*) 150, cotton (*Gossypium hirsutum* L.) 58, potato (*Solanum tuberosum* L.) 46, soybean (*Glycine max* L.) 37, and Argentine canola (*Brassica napus*) 39. The most widely targeted traits are herbicide tolerance (248) and insect resistance (204), followed by modified product quality (60), pollination control system (27), disease resistance (27), abiotic stress tolerance (11), altered growth/yield (4), and nematode resistance (1)[xxviii].

Genetically edited crops have the potential to lower both pesticide use and soil damage (cultivating disease-resistant, herbicide-resistant, and stress-tolerant plants and increasing the nutritional quality of plants) and reduce greenhouse gas (GHG) emissions. Brookes and Barfoot reported that through the adoption of **genetically modified (GM) crops** (herbicide-tolerant and insect-resistant) in agriculture, a significant reduction in the total amount of herbicides and pesticides used (by 775.4 million kilograms, or 8.3%) has been achieved between 1996 and 2018 [51]. As a consequence, the environmental impact of these chemicals decreased the Environmental Impact Quotient by 18.5%. Moreover, a considerable reduction in fuel use (by 920 million liters) and tillage practices (equivalent to removing 15.27 million cars from the roads) resulted in a significant reduction in the release of GHG from the GM crop area [51]. In addition, researchers

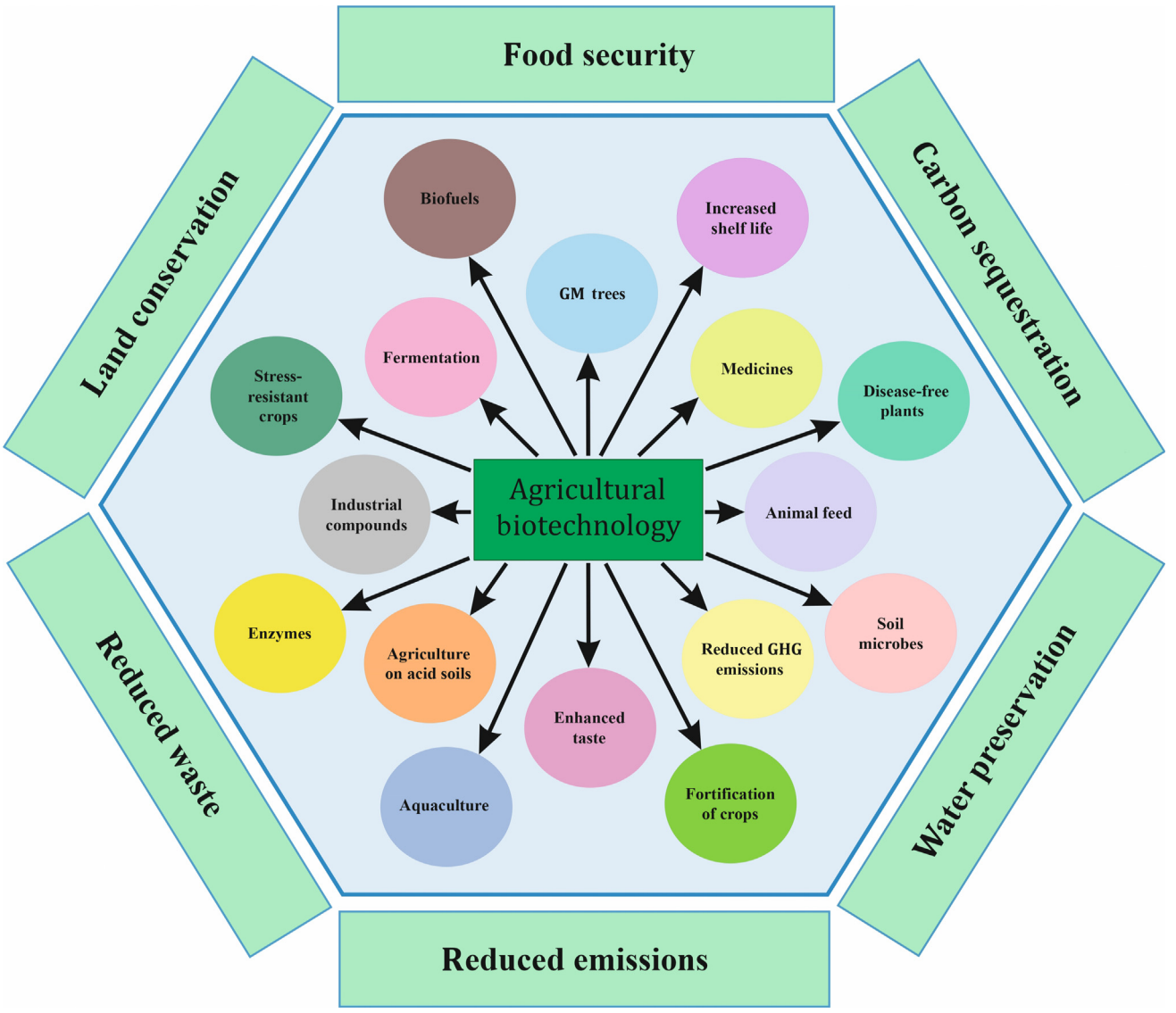


Figure 1. Potential applications of agricultural biotechnology in food security, land conservation, waste reduction, reduced emissions, water preservation, and carbon sequestration. Modified from[xxix]. Abbreviations: GHG, greenhouse gas; GM, genetically modified.

are focusing on designing many traits for conserving water and land, while increasing yields [38–40,52,53].

One of the important objectives of plant research is to increase crop productivity without expanding farm footprint [54]. Without the use of biotech crops, to maintain the global production at 2016 levels, planting an additional 22.4 million hectares (Mha) of soybean, maize, cotton, and canola would have been necessary [55], most probably at the expense of rainforests [56], leading to intensification of CO_2 emission and further contributing to climate change [57]. GM crops have a great potential and, indeed, are likely to make critical contributions to food security and adaptation to climate change, but these potential benefits will be hampered, delayed, and diminished in the absence of a regulatory framework including statutory requirements based on product risks and allowing for predictable ways to market stage. The potential applications of agricultural biotechnology are presented in Figure 1. The results of the analysis presenting strengths, weaknesses, opportunities, and threats (SWOT) of new plant breeding techniques are presented in Table 1. As seen from the analysis, the strengths outweigh the weaknesses and opportunities surpass threats. Modern biotechnology represents unique applications of science that can be used for the benefit of society. Nevertheless, the use of transgenic organisms should always proceed with caution to ensure that they pose no environmental or health risks, or at least no more than the use of current crops and practices.

To adopt genome-editing technologies, support is needed from governments in setting up an updated regulatory framework, which has to be designed after discussion with different stakeholders and society [46]. Recently, much attention has been paid to **new genomic techniques (NGTs)** in the European discussion. According to the EU Farm to Fork Strategy, 'new innovative techniques, including biotechnology and the development of bio-based products, may play a role in increasing sustainability, provided they are safe for consumers and the environment while bringing benefits for society as a whole' [2]. On 29 April 2021, the EC presented a study on the status of NGTs under EU law [66]. According to the study, NGT products can potentially contribute to sustainable agri-food systems in line with the objectives of the European Green Deal and the Farm to Fork Strategy. Moreover, the EC introduced public consultation for the initiative related to the legislation of plants produced by certain new genomic techniques [66][xxxii]. Individual answers have been published on the EC website[xxxiii]; however, no complete report has been published yet.

The EC has not yet provided an interpretative opinion of which organisms developed via new genomic techniques fall under the EU definition of GMO. The full potential of genome editing cannot be realized if we proceed with a regulatory framework which leads to an effective ban on the technology. Importantly, in other parts of the world, the products of new genomic techniques are cultivated, produced, and consumed (reviewed in [67]). Africa, for example, is currently the region with the greatest potential in adopting GM crops, with Nigeria emerging as a leader; of late, positive attitudes towards GMOs are also being shaped in Kenya. Latin American countries, together with the US and Canada, lead the cultivation and production of GM crops. Alongside the North American countries, several Latin American countries, as well as the Philippines, China, Japan, Australia, and China, among others, have already established criteria to determine the regulatory statutes of NPBTs [67].

Concluding remarks

The COVID-19 pandemic and geopolitical instability threaten food security worldwide. Plans to improve food security and sustainability are now at severe risk (see Outstanding questions). However, the COVID-19 pandemic and the geopolitical instability in Europe can trigger a change in the field of agricultural biotechnology.

Outstanding questions

How to make food security independent of crises such as pandemic and war?

Is agricultural biotechnology the only way of increasing food production?

Is genome editing a necessary strategy to address current and potential agricultural challenges?

Can the public perception of plant gene technologies be improved?

Will using **artificial intelligence (AI)** in agriculture help ensure food security?

Table 1. SWOT analysis of new plant breeding techniques in the EU[a]

New plant breeding techniques			
Strengths	Weaknesses	Opportunities	Threats
1. **Increased crop productivity** (by introducing qualities such as disease resistance and increased stress tolerance to the crops) 2. **Reduction of pesticide use** (designing crops that have high resistance to diseases and pests) 3. **Improvements of desired plant characteristics** (resistance to abiotic stresses by inserting certain genes into a plant's genome) 4. **Improvements in food processing** (increased purity, a reliable supply, cost reduction, and high yield efficiency) 5. **Improved nutritional value** (improving the nutritional value, flavor, and texture of foods) 6. **Better flavor** (flavor can be altered by enhancing the activity of plant enzymes that transform aroma precursors into flavoring compounds) 7. **Reducing food waste** (improved keeping properties to make transport of the fresh produce easier, giving consumers access to nutritionally valuable whole foods and preventing decay, damage, and loss of nutrients) 8. **Healthier produce** (lower contents of mycotoxins, fumonisin, and trichothecenes, lower contamination by fungi) 9. **Health benefits** (less pesticide residues on foods) 10. **Economic gains to the farmers** (increase in yield, production gains, and cost savings of GM crop cultivation) 11. **Benefits for developing countries** (improvement in health conditions in less developed countries)	1. **Allergens and toxins** (the risk of introducing allergens and toxins into otherwise safe foods) 2. **Antibiotic resistance** (the insertion of antibiotic resistance genes into a plant's genome could be detrimental to health because they could reduce the effectiveness of antibiotics. The resistance gene could also be transferred to pathogens, thus increasing their resistance to antibiotics) 3. **Impacts on 'nontarget' species** (once transgenic crops have been released into the environment, they could have unforeseen and undesirable effects; however, research on Bt plants shows the opposite) 4. **Insecticide resistance** (the question of whether insect pests could develop resistance to crop protection features of transgenic crops) 5. **Loss of biodiversity** (it is assumed that genetically engineered modifications may affect the genetic diversity of a population through crossbreeding or uncontrolled growth) 6. **Low adoption and skepticism** (low adoption of CRISPR stems from the regulation policies, which are often based on political and socioeconomic grounds, and are not necessarily scientific) 7. **Potential gene escape and creation of superweeds** (transfer of unwanted genes into wild relatives, into weeds and pests, thus making them more difficult to eradicate; it may create new microorganisms such as bacteria and viruses through the transfer of genes that make them more virulent, new products such as proteins that might be toxic to wildlife) 8. **Undesired genomic aberrations** (off-target effects such as unintended gene mutation; although mass deletions are yet to be reported in plants, we cannot rule out them in the future)	1. **New tools for biological exploration and crop improvement** (key to potential scientific inventions that solve challenges in modern agriculture) 2. **Fighting food insecurity** (biotechnology methods allow transferring these important agronomic-efficient traits to other crops to increase the viability of the transgenic plant, thereby increasing the yield and promoting commercialization in developing countries) 3. **Fighting malnutrition** (the application of biotechnology in crop production improves the nutritional content of agricultural products. Golden rice is nutritionally improved and contains three genes that facilitate the production of vitamin A in humans. The Banana 21 project has resulted in the improvement of the nutritional quality of bananas to contain iron and vitamin A) 4. **Fighting poverty among smallholder farmers** (farmers benefit from insecticide savings, higher effective yields and sizable income gains; NPBTs are employment-generating and poverty-reducing) 5. **Fighting climate change** (agricultural biotechnology provides ways to both mitigate and enhance adaptation to environmental changes: e.g., reduction in greenhouse gas emissions) 6. **Improving food quality** (more functional products, with improved and enhanced nutritional values: e.g., Golden Rice)	1. **Long duration and high cost of the approval processes** (the regulatory phase is of the longest duration in the overall process, accounting for almost 40% of the total cost of commercialization and more than half of the time) 2. **Technology-transcending risks** (including the social and ethical concerns that modern biotechnology may increase the prosperity gap between the rich and the poor, both internationally and within individual societies, and that may contribute to a loss of biodiversity. There are also ethical concerns as to the moral dimensions of patenting living organisms and the cross-species movement of genes) 3. **Possible misuse of gene editing technologies** (such technologies can be used to engineer biological pathogens, which opens the door for possible weaponization) 4. **Challenges in legal regulation** (different and diverging statutory regulations across jurisdictions of GM plants in general and NPBTs in particular) 5. **Biosafety concerns** (fears on whether off-target effects of CRISPR that lead to undesirable phenotypes can be controlled are increasing. The biosafety concerns revolve around all organisms in the environment)

[a]Sources: [39,50,58–65][xxx,xxxi].

In 2022, we are at critical crossroads. Either we rise to the challenge of meeting urgent needs by supporting programs that build long-term resilience (by 2050), or we will face even bigger problems in the future. The consequences of not investing in resilience activities will be felt across borders. If we are not empowered to withstand the shocks and stresses we are exposed to, this could result in increased migration and, possibly, destabilization and conflict. As we have observed recently, when the WFP ran out of funds to feed Syrian refugees in 2015, they had no choice but to leave their camps and seek help elsewhere, resulting in one of the greatest refugee crises in recent European history.

Declaration of interests

No interests are declared by the authors.

Resources

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