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Executive summary

Gene editing (GE) is a set of novel techniques used to manipulate the genome of an organism at desired locations. The Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR-Cas9) technique is the most popular GE method to achieve desired traits in plants. In addition to CRISPR-Cas9, other commonly used GE techniques are meganucleases (MNs), zinc finger nucleases (ZFNs), and transcription activator-like effector-based nucleases (TALENs). All the above-mentioned GE systems exploit natural gene repair mechanisms after double-stranded deoxyribonucleic acid (DNA) breaks caused by nucleases. In agriculture, these techniques are becoming increasingly popularized as new plant-breeding techniques (NBTs).

The GE system is being utilized extensively by the private and public sectors to develop new traits in crops of interest. As of now, more than 500 products are being developed worldwide using the technology and are at different stages of product development, ranging from basic research to advanced research and development (R&D) and near commercialization. Currently, the private sector contributes to 43% of the total product development, with 5% of the products at the precommercialization stage and 49% in the advanced research phase. The most active companies in the agricultural GE space are Corteva Agriscience, Yield10 Bioscience, Benson Hill, Arcadia Biosciences, Calyxt, and Inari Agriculture.

The market for GE products and traits is highly competitive as the competition for improving plant genetics comes from conventional and advanced plant-breeding techniques and from genetically modified (GM) plants. In the private sector, there are two types of players in GE: large multinational seed companies and small GE-focused companies. Small GE companies face challenges from limited market presence, lower financial and technical resources, limited R&D locations, and seed storage facilities, and they need collaborations with third parties to commercialize their products. Hence, we are observing a change in their business strategies, especially in row crops, owing to competition with large players.

Unlike genetically modified organisms (GMOs), where trait development is focused on cereals and oilseeds crops, in GE the research focus is more diversified by crops and traits, with around 23% of the products being developed for the vegetable segment; 7% for fruits; and 3% each for ornamentals, legumes, and forage and grasses. In vegetables, gamma-aminobutyric acid (GABA) tomatoes have already been commercialized in Japan by Sanatech Seed in 2021. In 2023, Pairwise's GE green leafy vegetable range, Conscious™ Foods, modified to enhance the palatability, flavor, and colors for healthy snacking options, is expected to enter the US market through retail channels and restaurants. However, 55% of the products belong to the grains and oilseed categories, both still dominating the product development by crops.

Through GE, companies are not only diversifying crops but also developing a variety of traits for biotic stress tolerance and modified composition, plant yield, and abiotic stress tolerance, which was restricted to input-oriented traits in the case of GMOs. Traits are also being developed for bioenergy crops using GE, and companies are also developing partnerships in the bioenergy space. A few examples of such alliances in alternate energy crops are pennycress with Bayer (majority stakeholder), Bunge, and Chevron; Carinata with Nuseed (Nufarm) and BP; and camelina with Sustainable Oils (owned by Global Clean Energy Holdings [GCEH]), World Energy, ExxonMobil (25% stake in GCEH), and several agribusiness companies.

The ongoing Russia and Ukraine conflict has highlighted the importance of food security. Owing to the need for higher yields, governments worldwide are becoming more open to adopting GE agricultural products. However, potential regulatory requirements, trade barriers, environmental and ethical concerns, and consumer and retailer acceptance are all factors that might still slow the adoption of some GE crops and traits in certain countries, as with the established GMOs. Harmonization of GE regulatory policies in major agricultural producing and importing countries will remain the biggest challenge for the adoption and successful commercialization of technologies.

The United States, Brazil, Argentina, Paraguay, Ecuador, Colombia, Israel, and Chile do not impose any regulations on this technology. These countries accept GE as equivalent to conventional breeding when used for genome modifications through a base pair addition or deletion (known as targeted mutagenesis and cisgenesis). Countries including Canada, Nigeria, Russia, Japan, Australia, India, Pakistan, the Philippines, and Indonesia have clear rules and procedures in place for the case-by-case evaluation of GE products and are considering targeted mutagenesis and cisgenesis as non-GM. However, the European Union (EU), mainland China, and the United Kingdom are developing a new regulatory framework for plants produced using GE techniques.

Introduction and methodology

The market for GE products and traits is highly competitive. The competition for improving plant genetics comes from conventional and advanced plant-breeding techniques and GM plants. Public and private sectors are contributing equally to product development using plant GE techniques. However, a large percentage of products from the public sector are at the early stages of development.

In the private plant GE space, there are two types of players:

- Large multinational seed companies, including Corteva Agriscience, Bayer Crop Science, Syngenta, and BASF.
- Small GE companies, including Cibus, Calyxt, Inari Agriculture, Benson Hill, and Yield10 Bioscience.

These companies can generate revenue on their GE products through the following means:

- Trait licensing
- Seed sales
- Grain sales, if an identity-preserved channel can be established and a way of value-sharing agreed.
- Sales of processed products derived from GE produce, if an identity-preserved channel can be established and a way of value-sharing agreed.

Between 2019 and 2022, 14 corn, canola, camelina, and soybean GE products were commercialized; 11 in the United States and 3 in Canada.

List of commercialized GE products by 2022

Country	Crop	No. of products	Company
United States	Corn	9	Commercialized (8 by Inari Agriculture; 1 by Brownseed Genetics)
United States	Soybean	1	Commercialized (Calyxt)
United States	Canola	1	Commercialized Cibus
Canada	Canola	2	Commercialized Cibus, BASF
Canada	Corn	1	Commercialized (waxy corn, Corteva Agriscience)

Source: S&P Global Commodity Insights.

Around 55 corn, canola, camelina, soybean, rice, and wheat products are in the precommercialization phase.

The market for GE seeds has been estimated based on the 69 products noted above. In addition, nine products related to alfalfa, sorghum, mustard, barley, and flax are also in the precommercialization phase; however, these are not part of our GE seed market estimates because of their small share in the global commercial seed market.

GE product development status by country for grains and oilseed crops in 2022

Country	Commercialized	Near commercialization	Total
United States	11	49	61
Canada	3	2	5
China	0	1	1
Argentina	0	3	3
Brazil	0	2	2
England	0	3	3
South Korea	0	1	1
Belgium	0	3	3
Total	14	64	78

Source: S&P Global Commodity Insights.

Looking at the number of products entering the market every year, it is not feasible to estimate the market at the grain and processed product levels for each product because of a lack of baseline data and the large number of possible processed products. Primary processed products include animal feed, oil (including Calyxt's high oleic soybean oil), various food and

food ingredients such as plant proteins, additives (including starch from Corteva's waxy corn), pasta and cookies (including Arcadia wheat), and biofuels from bioenergy crops like camelina.

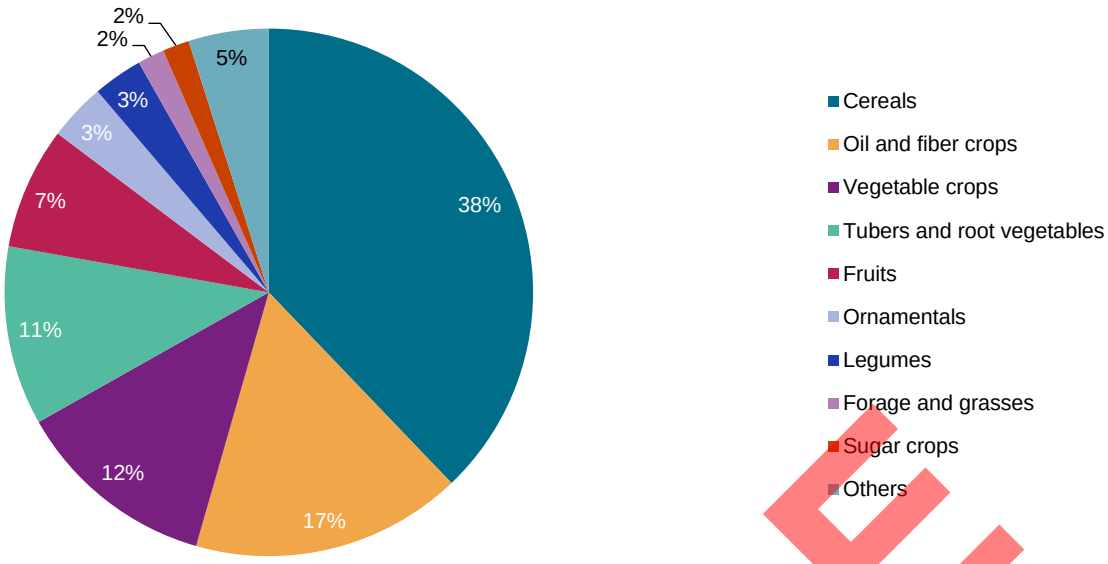
For this report, we have estimated the GE seeds and trait sales. Looking at the product development status and approvals, the United States and Canada will initially be the key markets for GE seeds. In both markets, some of the products are either commercialized or are in the precommercialization phase. At this time, their current sales are negligible owing to issues related to regulatory harmonization at the global level.

The current market size for GE seeds and traits is zero for other important countries like Brazil and Argentina, where a large number of products are being developed; hence, we have provided market scenarios for those countries instead of market estimates. We have estimated the size of the US and Canadian GE seed markets based on the products that are commercialized and near commercialization.

We have followed the methodology and assumptions outlined below:

- GE products will reach their peak sales 7–10 years after product commercialization.
- We have estimated the peak sales year for all the products considered in this study.
- Based on our proprietary seed prices data and trait premium data, we have estimated seed prices/acre and trait premiums by crop for all the products.
- We have used several S&P Global Commodity Insights resources:
  - Proprietary data for crop area forecasts between 2025 and 2032 to estimate the GE market sizes.
  - A special report on biofuels to obtain area data on crops like camelina.
  - The Seed Market Analysis service and GM seeds outlooks for seed market values by crop between 2022 and 2032.
  - The Seed Breeding Techniques Database to track the number of GE products in development.
- We have estimated the trait penetration data using historical data on GM traits and secondary research on the currently commercialized products. To decide the trait penetration and trait premium, we considered criteria including the importance of the trait, existing GMO traits, market competition with existing GM and conventional seed varieties, and the competitive position of the company commercializing the product.
- To calculate the size of a GE trait crop seed segment in the United States, we have used the following formula: *2032 crop acres x (seed price + trait premium/acre) x expected % trait penetration in 2032*

Global gene edited product development status by crop, 2021



Data compiled Jan. 2023.
Source: S&P Global Commodity Insights.

Although still dominated by the grains and oilseed crops with a 55% share, it is evident that GE technology is being used outside these crops: vegetables, tubers, and fruits together account for a 30% share of the total GE product development activity during 2021.

In contrast to GM crops, where 100% of the existing and upcoming traits are input-related traits, in GE the trait focus is primarily on biotic stress tolerance and modified composition, followed by plant yield and abiotic stress tolerance.

Around the world, it is estimated that there are about 570 million farms with less than 2 hectares (ha). These smallholder farms operate on 12% of the world's agricultural land and produce 80% of the food that is consumed in Asia and sub-Saharan Africa. Developing crops based on the needs of small-holder farmers can create tremendous opportunities for start-ups owing to lower competition from the seed giants. This is because the type of crops being developed may not be the row crops being concentrated on by the global crop majors. GE could therefore become the technology of choice for the small holder for the following reasons:

- Simple accessible format of technology, i.e., seed.
- Traits developed using GE technology may include high yield or improved nutritional content varieties, which were lacking in GMOs.
- GE crops do not require any equipment or special training (husbandry) by smallholder farmers.
- In most countries, the GE process is considered as “natural” and wholesome than GM, as it does not involve transgene insertion, and hence will have more public acceptance compared with transgenic crops.

The acceptance of GE technology by small-holder farms may lead to increased area penetration, which will lead to higher GE seed demand and market growth.

Food security and climate change

An article in *Wired* (September 13, 2022) discusses the factors that may drive increased uptake and adoption of GE technologies. A research paper published in *PLOS ONE* by Kyungpook National University, South Korea suggests crop yields are projected to decrease under future climate conditions, and the study suggests that climate change has already impacted crop yields and global food production. A recent FAO paper discusses the opportunity provided by GE technology to precisely edit the genomes of crop plants to alter nutritional content to combat malnutrition, remove toxins from staple foods like cassava, increase yields to fight hunger, and improve pest resistance, thereby reducing the need for agrochemical inputs. Gene-edited products could also introduce adaptations to address drought and flood resistance; increase biodiversity; and help to capture carbon, restoring farm soils, and improving the fertility of marginal lands.

"concise information" about their products, allowing the public to have information on the types of GE plant products that may be used as food in the country.

In October 2022, the Canadian authorities issued a discussion paper focusing on the country's New Substances Notification Regulations (Organisms) under the Canadian Environmental Protection Act. The paper initiated a consultation on rules involving GE organisms and covers several industries including agriculture. The development is a further step toward assessing developments in biotechnology before products derived through such innovations are introduced onto the nation's markets. The consultation highlights the use of GE technologies within the country's agriculture sector with an eye on fighting climate change through the development of drought-tolerant, high-yield, and long-storage crops. It notes that the exercise would focus on providing a context to uses of biotechnology, including improving openness and transparency; responding to advances in science and technology; and addressing inefficiencies identified under the country's new substances program.

Mexico

Mexico has not issued any biotechnology food or feed product approvals since May 2018. Permits for planting herbicide-resistant cottonseed, which is the only genetically engineered crop allowed to be grown commercially in Mexico at this time, have also been delayed or denied by the Secretariat of Environment and Natural Resources (SEMARNAT) based on concerns about impacts on seed biodiversity and inadequate consultation with indigenous communities. Also in 2021, Mexico's highest court upheld an injunction on the cultivation of GM corn on the basis that it poses a credible threat to Mexico's rich store of native corn biodiversity through uncontrolled cross-pollination. That injunction has been in place since 2013. The USMCA entered into force on 1 July 2020; it has updated and, in some respects, significantly changed the original North American Free Trade Agreement (NAFTA) that had been in effect since 1 January 1994. One of the new provisions, incorporated at the request of the biotechnology industry and industrial agricultural conglomerates, is a section on "Agricultural Biotechnology." However, the final text of the agreement does not restrict domestic policy choices and appears to have limited impact in persuading Mexico to overturn its current stance on GM and other GE technologies.

Latin America

In most South and Central American countries, GE crops are regulated as conventional plants unless they contain foreign DNA. In certain countries, however, notification to the authorities is required to approve this exemption.

Brazil

The Brazilian technical biosafety regulator (CTNBio) regulates GE products on a case-by-case basis and exempts these products from regulation when there is no insertion of transgenes. That mirrors the protocol in neighboring Argentina and Paraguay.

In January 2018, CTNBio published Normative Resolution (NR) 16, which established the requirements to evaluate precision breeding innovation and encompasses GE products. In some cases, the full risk assessment and management of GMOs must be applied, while in other cases products deriving from precision breeding may be exempt.

The system considers information on how the manipulated genes or genetic elements function and whether the product has already been approved for marketing in other countries.

While CTNBio can exempt new products from GMO regulatory assessment, Brazil's previous provisions consisted of GMO regulation heavily influenced by the genetic modification procedures used at that time, so NR 16 contains an annex with a list of GM procedures that may create a product not considered a GMO and includes the caveat that the resolution is not limited to those examples and may ultimately apply to other forthcoming technologies.

As a recent example, in September 2022, CTNBio approved a GE soybean. The Brazilian agricultural research corporation, Embrapa, developed the soybean, deactivating "antinutritional" elements with the use of the CRISPR technique. CTNBio concluded that the technology does not come under rules governing GMOs as it does not include DNA from a different species, a distinction defined under CTNBio Resolution No 16/2018. Approval now awaits from a government council based on CTNBio's recommendation.

Argentina

Argentina's biotechnology resolution 173/2015 set the framework for case-by-case evaluations and was later streamlined by Resolution 763/11, issued by the Ministry of Agriculture, which set the regulatory process for GM crops in a three-step protocol, which applies equally to local and imported events. First, an environmental assessment is performed by the

of this is thousands of vegetable seed varieties with high-yield, natural-disease resistance and improved nutritional quality, and hundreds of new such varieties enter the market every year.

Mainland China is the world's largest vegetable seed market, with a 26% share in the global commercial vegetable seed market in 2021. Over the past 10 years, the vegetable seed segment has been the second-fastest growing segment in the Chinese seed market after maize, witnessing a CAGR of 5% between 2011 and 2021.

Several companies are developing GE vegetable crops, though very few have yet to enter the commercial stage. Benson Hill is scaling up cultivation of its enhanced-taste, high-protein yellow peas in the United States.

In the research stages, ToolGen is developing enhanced function potatoes, drought-tolerant peppers, and Chinese cabbages resistant to soft rot. Pairwise gained USDA-APHIS clearance on its enhanced flavor mustard oilseed in 2020.

Yield10 has out-licensed its seed yield/biomass potato traits to JR Simplot, which also has a long-standing agreement on developing increased yield potato varieties with Benson Hill. Calyxt is also developing potatoes with improved cold storage and decreased browning (a trait in research in other companies, including Tropic Biosciences).

Bioheuris is working on input traits in peanuts through a recent agreement with AgIdea.

Agribody Technologies has completed two years of field trials for enhanced-yield alfalfa and is also conducting R&D into other crops, including sugar beet, beans, lettuce, okra, peanuts, potatoes, and peas. Amfora is also working on alfalfa plus leafy vegetables and legumes, while Calyxt's alfalfa with enhanced digestibility was licensed to S&W Seed Company in 2020 and expected to be on the market from 2022.

Corteva Agriscience licensed the intellectual property (IP) on its non-browning potato to JR Simplot in 2018 and its traits for abiotic stress and disease resistance in vegetables to Bejo in 2021. Pairwise plans to launch its GE leafy greens in 2023 in the United States.

Rice

Rice is the fourth-largest seed segment with sales at $2,108 million in 2021 and representing 4% of the global seed market.

Large-scale commercial planting of GM rice has been very limited. The Philippines approved the use of GM vitamin A-enriched rice line, Golden Rice (IR-00GR2E), for use in food and feed, or in processing in December 2019 with the Philippine Department of Agriculture issuing a biosafety permit for the commercial cultivation of Golden Rice in July 2021. The crop was at the transplanting stage in the Philippines in August 2022 and expected to be harvested in October with an average yield of 5 metric tons per hectare – production will be expanded as soon as more supply of seeds becomes available. Approval in Bangladesh remains pending.

Research into GE rice is very active in the public sector, particularly in academic institutions in the Asia Pacific region.

In the private sector, several companies are conducting R&D on rice traits, though none have confirmed commercial status. Agribody Technologies has completed proof-of-concept studies, Amfora is targeting high protein rice, Benson Hill licensed its improved cultivars to RiceTec in 2019, and Bioheuris has a development program with Itá Caabó, which is part of the Adecoagro group, one of the main food and renewable energy companies in South America and the largest rice breeder and producer in Argentina; the project aims to optimize integrated management of rice through GE of elite varieties and hybrids.

Cibus started field trials in 2021 for non-GM, herbicide-tolerant, and disease-resistant rice lines for the US and Chinese markets. Tropic Bioscience is researching traits for resistance to rice blast and increased yield. Corteva Agriscience has been working since 2018 with IRRI on enhanced yield and stress tolerance traits, while Syngenta has early-stage projects in rice. Yield10 Bioscience has been evaluating its series C4000 yield-enhancing traits since 2018.

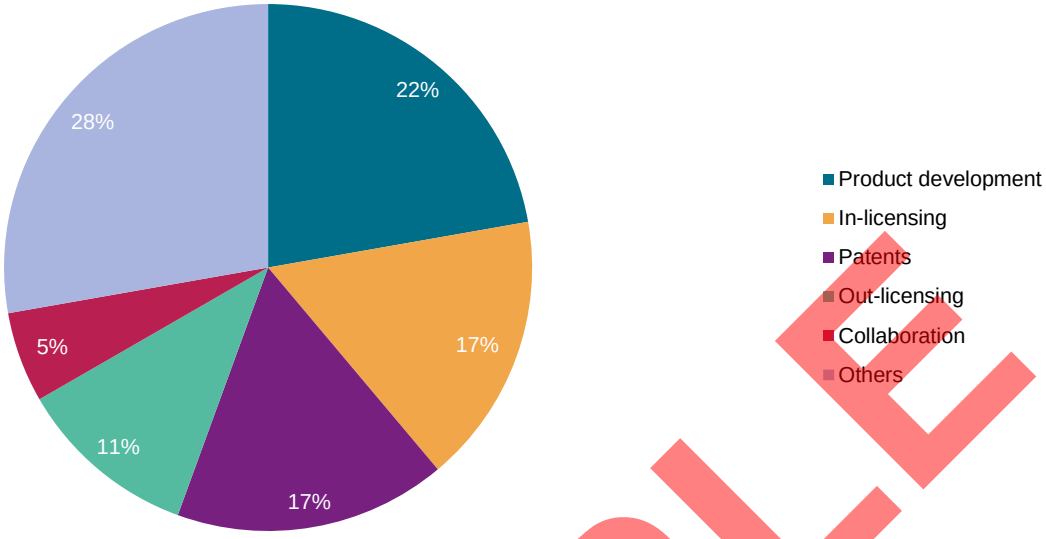
Oilseed rape (canola)

The global rapeseed market was valued at $1,944 million in 2021 and dominated by Canada and Europe. Canadian rapeseed is known as canola, a spring planted variety that is now predominantly genetically modified to possess herbicide tolerance. European rapeseed varieties do not possess GM traits and are commonly planted in the autumn. The market for GM rapeseed now accounts for 57% of the global oilseed market.

Based on the overall companies' activity related to GE from 2020 to 2022, the company is leading in product development (late-stage R&D products are considered for this category), followed by in-licensing, patents, out-licensing, and collaboration. The company has reported 18 activities in the past five years.

Over the longer period, 2014-2022, Yield10's activities break down as summarized in the chart below.

Yield10 Bioscience gene editing activities, 2014-2022



Data compiled Jan. 2023.
Source: S&P Global Commodity Insights.

Yield10 Bioscience's principal activities for 2020-22 are covered below:

- In 2020, Yield10 signed a nonexclusive research license with GDM for the evaluation of three traits in soybean germplasm through to 2023.
- Yield10 harvested its first 50 acres of camelina biofuel feedstock seed (stacked input traits and performance traits) grown under contract in Montana in 2020. During 2021 and into early 2022, seed scale-up activities were conducted with both spring and winter lines. Prototype PHA bioplastic camelina traits were field tested in 2020 and 2021 ahead of producing the best line at a larger scale during the 2022 growing season for seed process development and plastic prototyping. Yield10 states this is at an early technology readiness level.
- Yield10 signed an exclusive collaboration and option agreement for an omega-3 seed product with Rothamsted Institute (United Kingdom) in November 2020. Yield10 plans to launch a proprietary camelina omega-3 seed product into the food and nutrition market based on the trait developed over the last 10 years by Rothamsted and is working on the business strategy to enable production of seed in Canada as early as the 2025 spring planting season.

Benson Hill

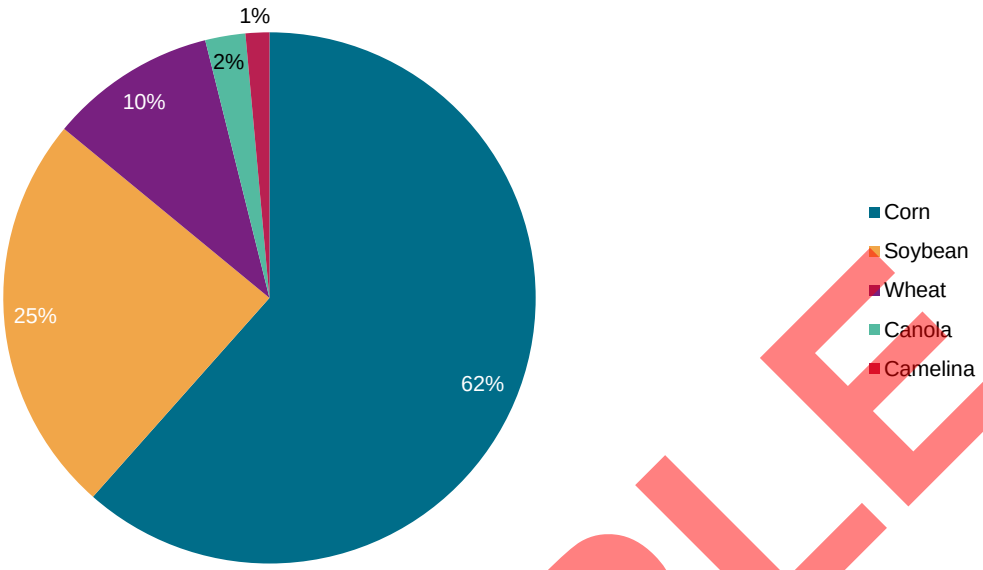
Benson Hill, formerly known as Benson Hill Biosystems, is a US-based food technology company. Incorporated in 2012, the company operates in two segments: Ingredients and Fresh, both launched in 2021. It offers the CropOS® cognitive computational technology platform and associated suite of genomics tools, which uses artificial intelligence, data, and various advanced breeding techniques that combine data, plant, and food sciences to deliver crops optimized for food, ingredient, and feed products. The company's platform focuses on discovering traits in soybean and yellow peas, a crop with relatively little GE research and high potential as a plant protein source. To its seed and food industry partners, the company provides the technology, partnership model, and infrastructure necessary to deliver research outputs. Benson Hill focuses on growing, packing, and selling fresh produce products to retail and food service customers.

Benson Hill developed a patented portfolio around the CRISPR Cms1 family, which offers alternative GE solutions with clear IP rights and a simple licensing model. From 2018, the company licensed Cms1 nuclease in a wide range of microbial and crop applications, including soybeans, wheat, and rice.

US GE seed market

The US GE seed market is expected to grow from $XXX.X million in 2025 to $X,XXX.X million in 2032, demonstrating a CAGR of XX.X%. GE corn seeds will be the largest market segment by crop in 2025 and will retain their position by 2032, with an expected CAGR growth of XX.X% between 2025 and 2032.

US gene edited seed market share by crop to 2032 ($ million)



Data compiled Jan. 2023.
Source: S&P Global Commodity Insights.

US GE seed market ($ million) estimates by crop, 2025–32

Crop	2025	2026	2027	2028	2029	2030	2031	2032
Corn								
Soybean								
Canola								
Wheat								
Camelina								
Total								

As of December 2022.
Source: S&P Global Commodity Insights.

US GE corn seed market

The US GE corn seed market is estimated to be around $XX.X million in 2025 and is expected to reach $XXX.X million by 2032, representing a CAGR of XX.X% between 2025 and 2032.

The US GE corn seed market has the most significant number of GE corn seed products commercialized by 2022 and the largest number of products in the pipeline. Among the nine commercialized GE corn seed products in the United States, eight were commercialized by Inari Agriculture for improved seed and grain production traits. For Inari corn hybrids, the first sales started in 2019 after gaining national authorization in the United States, and those products are expected to reach their peak sales by 2027.

Another product commercialized in GE corn is E+ Hybrid corn seed for ethanol production, developed by Benson Hill Group and Brownseed Genetics and commercialized by Brownseed Genetics for increased oil and amino acid content. E+ Hybrid corn seeds were cultivated in the United States for the first time in 2020.

The market share of all commercialized GE corn seed products in the United States is minimal at the current stage. We expect the products/traits to reach their maximum potential after five to seven years of commercialization.

In October 2016, Benson Hill Biosystem announced a strategic partnership and grant from the National Corn Growers Association (NCGA). The primary goal of the funding and partnership initiative will be to accelerate breeding and development of new corn hybrids utilizing CropOS.

In April 2015, Benson Hill Biosystems, and Limagrain announced the establishment of a partnership to develop and commercialize traits to increase corn and wheat yields.

In July 2014, Benson Hill Biosystems, and Centro de Tecnologia Canavieira (CTC), a market leader in Brazilian sugarcane, announced the establishment of a partnership to develop and commercialize traits to increase sugarcane crop yield.

Product launches

In October 2017, Benson Hill Biosystems announced the commercial launch of Edit, which combines the analytical power of the CropOS computational platform with a robust portfolio of novel GE nucleases to create the first comprehensive GE system. Edit is designed to optimize plant characteristics such as flavor profiles, nutrient-density, and environmental sustainability with greater speed and precision than previously possible.

In September 2017, Benson Hill Biosystems announced the commercial launch of CRISPR 3.0, a novel family of Cms1 nucleases as part of its suite of genomics tools to accelerate crop performance improvements.

In May 2016, Benson Hill Biosystems announced the commercial launch of CropOS, a cognitive engine using cloud biology to empower a new era of plant genomics innovation. CropOS uses powerful data analytics and biological knowledge to identify the most promising plant genetics in weeks instead of multiple growing seasons.

Bioheuris

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Introduction

BioHeuris is a privately held, start-up Argentine company founded in 2016 that combines synthetic biology and GE technology to develop herbicide-resistant crops. It has two main technology platforms: Heurik, a high throughput process, which integrates rational design and directed evolution to identify gene variants, which confer herbicide tolerance and compares their efficiency in microorganisms as a means to anticipate their effect in crops; Swap is a non-GMO platform that introduces these mutations in crops using GE techniques combined with tissue culture protocols and can edit more than one gene at a time, thus speeding up the trait development process.

The company focuses on crops that are already well-established in Argentina, such as soybean, sorghum, rice, cotton, and alfalfa.

BioHeuris has molecular biology labs and plant growth facilities at Centro Científico Tecnológico de Rosario (Argentina), where it operates the Heurik synthetic biology and Swap GE technology platforms. A laboratory in St. Louis (Missouri, United States) is located at the Helix Center and is scaling-up the plant GE and protein evolution research pipelines.

The company has partnerships with Santa Rosa Semillas, Grupo Don Mario, and ACA to develop management systems for high-yield soybean varieties. A partnership with Tobin, a leading sorghum seed breeding and production company, involves editing elite lines to bring new hybrids to international markets more rapidly and efficiently. A development program with Itá Caabó, part of the Adecoagro group and one of the main food and renewable energy companies in South America and the largest rice breeder and producer in Argentina, aims to optimize integrated management of rice through GE of elite varieties and hybrids. With Gensus, the Argentine cotton seed company, BioHeuris is developing herbicide-resistant cotton varieties.

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