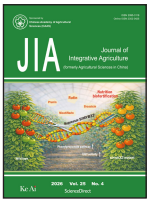
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REVIEW

Global trends in the commercialization of genetically modified crops in 2024

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Highlights

- The study systematically analyzes the spatial distribution pattern and regional evolution driving mechanism of global genetically modified (GM) crops in 2024.
- The global planting area of GM crops reaches 209.8 million hectares, with developing countries accounting for 54.0% and their growth rate continuing to outpace that of developed countries.
- The study provides multidimensional empirical support and decision-making basis for the optimal allocation of agricultural biotechnology resources and the formulation of food security strategies.

Abstract

The ongoing commercialization of genetically modified (GM) crops continues to enhance global grain yields, improve crop quality, and reduce pesticide usage. These technological advancements have effectively propelled agricultural production systems toward sustainable transformation. Specifically, GM crops address core challenges such as pest infestations, weed proliferation, and arable land constraints, emerging as a pivotal new productive force in agriculture. This study systematically examines the global spatial distribution patterns of GM crops in 2024 and provides an in-depth analysis of the driving forces and evolving regional trends, offering critical informational support and strategic guidance for innovation in agricultural science and technology. In 2024, the global GM crop cultivation area reached 209.8 million hectares, a 1.7% year-on-year increase. GM *Glycine max* (soybean) and *Zea mays* (maize) dominated the landscape, accounting for 50.0 and 32.5% of the total area, respectively. Among them, maize with stacked traits of insect resistance and herbicide tolerance accounts for 92.5% of GM maize. The share of cultivation in developing countries expanded substantially, with Brazil and Vietnam emerging as regional growth drivers. Policy support and the diffusion of advanced technologies were identified as core driving forces. Concurrently, applications of gene-editing technology accelerated, and several countries approved novel traits such as drought tolerance and disease resistance, marking substantial progress in the commercialization of next-generation GM crops. This research provides multidimensional insights and strategic guidance to support global agricultural biotechnology development, promoting the transition of biotechnology breeding into the '4.0 era'.

Keywords: genetically modified crops, commercialization, global agriculture, cultivation area, biotechnology

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1. Introduction

Food security, as a foundational element of global stability and sustainable development, is increasingly threatened by natural disasters, regional conflicts, and climate change. In 2024, food insecurity reached critical levels, with over 295 million people across 53 countries and regions experiencing acute hunger — an increase of nearly 14 million compared to 2023. Traditional agricultural systems face structural constraints, including climate variability, diminishing arable land, and overreliance on chemical fertilizers and pesticides. These limitations have led to unstable yields and growing environmental degradation. Against this backdrop, the commercial application of genetically modified (GM) crops offers a viable pathway toward more sustainable global agriculture. By enhancing resistance to abiotic and biotic stresses — such as drought tolerance and insect resistance (IR) — and reducing dependence on chemical inputs, GM crops contribute to yield stability and improved environmental sustainability. Their commercialization has demonstrated significant economic and ecological benefits, including reduced production costs and lower carbon emissions (ISAAA 2024b). Using data from the International Service for the Acquisition of Agri-biotech Applications (ISAAA), the Global Agricultural Market Information Company (AgbioInvestor 2024), and publicly available governmental statistics, this study systematically reviews the global spatial distribution of GM crops in 2024, analyzes the underlying mechanisms driving this expansion — including the synergistic effects of policy incentives and technological innovation — and explores the regional evolution of commercialization patterns. The study offers empirical evidence and strategic insights to address global food security challenges and guide the optimal deployment of biotechnology resources. By examining key factors such as cultivation area expansion, technology diffusion, and public perception of GM crops, this research informs efforts to advance global agricultural science and innovation. Notably, findings indicate that the total GM crop cultivation area in 2024 reached 209.8 million hectares, with developing countries accounting for 54.0% of the total. Policy incentives and technological progress remain the primary drivers. Stacked-trait crops dominate recent technological advancements, while developments in gene editing, novel traits (including drought and disease resistance), and region-specific regulatory frameworks are actively reshaping the global agricultural biotechnology landscape.

2. Overview of GM crop applications in 2024

2.1. Global cultivation of GM crops exhibits sustained expansion

In 2024, 28 countries achieved commercial cultivation of GM crops, totaling 209.8 million hectares, which represents a 1.7% increase from 2023 (AgbioInvestor 2025). Since initial commercialization in 1996, the cumulative global planting area of GM crops has surpassed 3.5 billion hectares. The 2024 area marks approximately a 123-fold increase from the 1.7 million hectares recorded in 1996 and accounts for an estimated 13.5% of the world's total arable land (approximately 1.55 billion hectares).

As shown in Fig. 1, the planting area of GM crops in developing countries has demonstrated a steady upward trend, while that in developed countries has declined. Compared to 2023, the share of GM crop planting area in developing countries reached 54.0% in 2024, an increase of 0.4 percentage points, further widening the disparity with developed countries. This trend highlights the accelerating shift in global agricultural technology adoption toward developing regions.

Maize, soybean, cotton, and canola are the most extensively commercialized GM crops cultivated globally, with adoption rates of 33.7, 74.9, 78.4, and 24.3%, respectively, collectively accounting for 99.19% of the total global GM crops area. Driven by global market demand, the cultivation areas of GM soybean, wheat, and sugarcane have expanded significantly, whereas those of maize, sugar beet, alfalfa, and rice have declined. Notably, as a newly commercialized GM crop, GM wheat has shown sustained growth in planted area, while GM rice has been withdrawn from commercial production following the revocation of 'Golden Rice' approval in the Philippines (IRRI 2021).

GM crops combining insect resistance and herbicide tolerance (HT) have become dominant in commercial applications, accounting for the majority of global cultivation. Multi-gene stacking technologies are now widely adopted, enabling the combined-trait expression. Novel trait development follows a diversified trajectory, encompassing stress tolerance (e.g., drought- and herbicide-tolerant wheat in Argentina), disease resistance (e.g., gene-edited powdery mildew-resistant wheat in China), yield enhancement (e.g., gene-edited high-yield soybean in China), and quality improvement (e.g., high-oleic soybean in the European Union).

2.2. Global GM crop adoption: Geographical concentration and expansion trends

In 2024, 27 countries cultivated 10 GM crops worldwide, with planting patterns exhibiting high geographic concentration. The top five producing nations — the United States, Brazil, Argentina, India, and Canada — accounted for 90.6% of

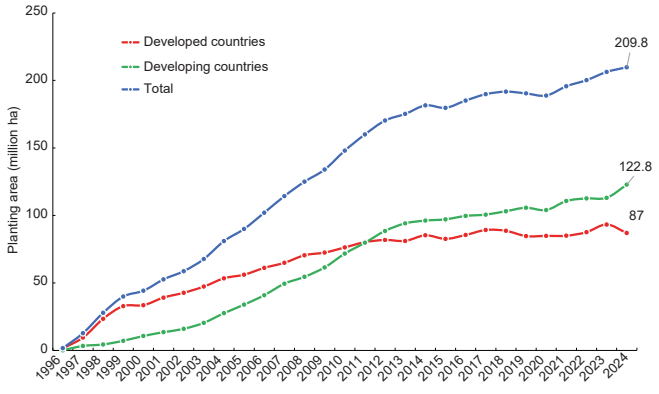


Fig. 1 Global genetically modified (GM) crop cultivation area and trends during 2014–2024 (Cheng *et al.* 2024; ISAAA 2024b; AgbioInvestor 2025).

the global GM crop area. The United States remained the world's largest producer of GM crops, with a total planting area of 75.4 million hectares (Fig. 2), representing a 1.3% year-on-year increase. In terms of crop distribution, GM maize, soybean, and cotton constituted 34.8 million hectares (50.9% of the global total), 33.5 million hectares (31.8%), and 4.5 million hectares, respectively (Fig. 3). Except for alfalfa, adoption rates for major GM crops in the United States exceeded 90%, indicating widespread adoption.

Brazil ranked second with a GM crop area of 67.9 million hectares, up 1.44% from the prior year. Its GM soybean area reached 45.7 million hectares — an increase of 4.7% year-on-year — and ranked first globally (Fig. 2). Notably, Brazil has emerged as the world's largest producer of gene-stacked GM soybeans (herbicide-tolerant and insect-resistant varieties), which constitute over 90% of national soybean production. Argentina ranked the third with 23.8 million hectares, up 8.3% year-on-year. The country's GM soybean area reached 16.2 million hectares, increasing by 12.7%, with an adoption rate of 68.1%. GM maize occupied 6.9 million hectares, declining by 3.6%, but its adoption rate reached 99%, predominantly involving gene-stacked varieties, which underscores the strong reliance on high-performance cultivars.

As shown in Fig. 2, China recorded 3.5 million hectares of GM crops, a 17.9% increase, primarily driven by the accelerated commercialization of GM maize and soybean. Vietnam planted 0.43 million hectares of GM crops, entirely GM maize, representing a sharp 93.2% year-on-year growth, indicating rapid uptake of GM technology in Southeast Asia. In contrast, India and Pakistan cultivated only GM cotton, with areas of 11.2 and 1.9 million hectares, respectively, decreasing by 7.1 and 16.7% year-on-year, highlighting regional disparities in adoption trends (CY Futures 2025).

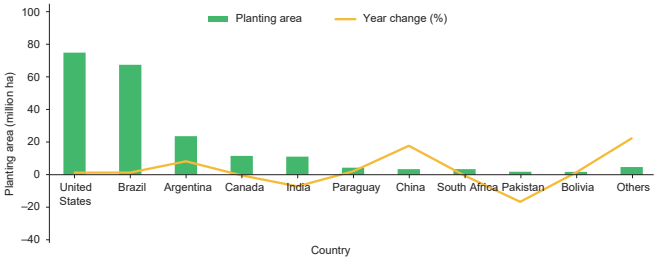


Fig. 2 Genetically modified (GM) crop planting area by country in 2024 (AgbioInvestor 2025).

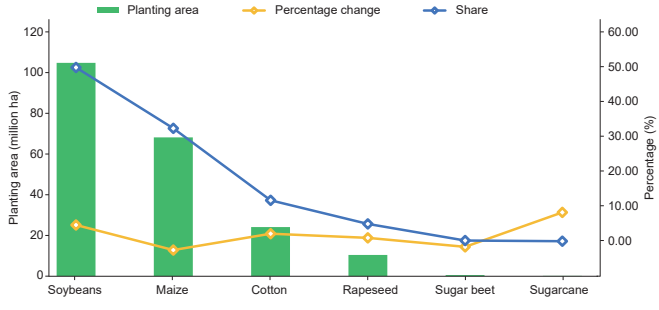


Fig. 3 Comparison of planting characteristics of major genetically modified crops.

3. Global approval of GM new varieties is active

In 2024, the global regulatory landscape for GM crops remained dynamic, with newly approved transformation events predominantly featuring stacked traits — combinations of IR and HT. This trend reflects the ongoing advancement of GM technology toward the integration of multifunctional traits. Regionally, China and the European Union were particularly active in regulatory approvals. China made significant progress in authorizing new transformation events for maize and soybean, emphasizing commercialization for domestic cultivation (Miao *et al.* 2024), whereas the EU focused on approvals for maize intended for import and processing. African nations such as Kenya and Nigeria, following recent policy shifts, advanced efforts to promote the commercial cultivation of drought-tolerant GM crops. By crop species, maize and soybean continued to account for the majority of newly approved transformation events, followed by cotton and canola. In terms of traits, stacked traits constituted a substantially larger share of approvals compared to single-trait events, which were primarily HT. Notably, emerging traits, including drought tolerance and disease resistance, began entering the regulatory approval pipeline (USDA Economic Research Service 2025).

Major regulatory jurisdictions — including the United States, Argentina, China, the European Union, and Australia — approved multiple GM crops for food, feed, processing, or cultivation. Approval activity was concentrated in these regions, reflecting their established biosafety frameworks. Across species, soybean and maize together represented the largest proportion of approved events, followed by cotton, canola, and other crops. Regarding traits, stacked-trait products dominated the global GM crop planting area, while single-trait events comprised a smaller fraction of total approvals. Additionally, several countries authorized GM crops incorporating novel traits such as drought tolerance, disease resistance, and reduced plant height, indicating a diversification of agronomic objectives.

3.1. Clear regulatory pathway for GM crops in the United States

In 2024, the United States Department of Agriculture (USDA) Animal and Plant Health Inspection Service (APHIS) maintained its regulatory oversight of GM crops, applying two distinct pathways based on risk assessments. The results showed that the GM products pose no greater plant pest or disease risk than conventional counterparts.

Exemption from regulation (no review required): Under the "SECURE rule", gene-edited crops that contain no foreign DNA and exhibit traits achievable through conventional breeding qualify for exemption.

In September and October 2024, APHIS announced the deregulation of one GM citrus variety, one GM pea, one GM potato, one gene-edited *Citrus sinensis* (sweet

orange), one gene-edited *Zea mays*, and three gene-edited *Thlaspi arvense* (field pennycress), thereby authorizing their unrestricted cultivation. Additionally, one gene-edited *Solanum lycopersicum* (tomato) and one gene-edited *T. arvense* met the exemption criteria and may be cultivated without regulatory oversight. As shown in Table 1, multiple GM products across various species — including the insect-resistant event MON95379, the herbicide-tolerant soybean event GMB151, and the drought-tolerant wheat event HB4® — successfully completed regulatory review, each utilizing distinct technological platforms to enhance stress resilience and product quality.

3.2. EU GM variety approval focuses on high yield and insect and disease resistance traits

In 2024, the European Commission authorized several GM crop events for food and feed import under Regulations (EC) No. 1829/2003 and No. 1830/2003. A total of seven events were approved — six in *Z. mays* and one in *Gossypium hirsutum* (Table 2). The approved traits primarily included HT and IR. Notably, these authorizations are restricted to import and processing and do not permit commercial cultivation. All products must comply with strict labeling and traceability requirements established by the European Commission (2024).

3.3. Approval of GM and gene-edited crops in China is advancing simultaneously

In 2024, the Ministry of Agriculture and Rural Affairs of China granted its first approvals for 19 GM crop transformation events, including 12 maize, 5 soybean, and 2 cotton events. The approved traits primarily included IR, HT, and stacked traits combining IR and HT, indicating China's transition into an accelerated phase of GM crop commercialization (MARAPRC 2024).

As shown in Table 3, China also approved nine gene-edited (GE) crop transformation events in 2024, covering maize and soybean varieties, with targeted traits such as yield improvement, stress tolerance, disease resistance, and quality enhancement.

The continuous strengthening of policy support from the Chinese government has propelled China's biological breeding industrialization into a phase of rapid development. Pilot data indicate that transgenic maize varieties exhibit significant yield-enhancing advantages, with single-crop yields increasing by 5.6 to 11.6%. As of 2024, the pilot planting area for transgenic maize and soybeans has reached approximately 10 million mu (about 0.67 million hectares), and further expansion is expected by 2025, marking a new phase in the large-scale promotion of modern agricultural biotechnology applications in China (ISAAA 2024a).

3.4. Brazil's GM approval focuses on maize and soybeans

On August 1, 2024, Brazil's National Technical Biosafety Commission (CTNBio) approved two *Z. mays* transformation events for commercial cultivation. The first event, MON87427×MON94804×MON95379×MIR162×MON88017, submitted by Bayer do Brasil Ltda., incorporates the *CP4epsps*, *Cry1B.868*, *Cry1Da_7*, *Cry3Bb1*, *GA20ox_SUP*, and *Vip3Aa* genes, conferring short stature, resistance to Lepidoptera and Coleoptera pests, and tolerance to glyphosate herbicide. The second event, DP910521, submitted by Corteva Agriscience do Brasil Ltda., contains the *cry1B.34* and *pat* genes, providing resistance to Lepidoptera pests and tolerance to glyphosate. In December 2024, Brazilian regulators approved Bayer's Intacta RR2 PRO®, a stacked-

Table 1 Representative R&D and approved traits of transformation events in the United States in 2024

Category	Name	Developer	Species	Approved traits
Maize	MON95379	Bayer	*Zea mays*	Resistance to Lepidoptera pests
	DP915635	Corteva	*Z. mays*	Glufosinate tolerance; resistance to Coleoptera pests
	Corteva maize	Corteva	*Z. mays*	Resistant to northern maize leaf blight, gray leaf spot, anthracnose stalk rot, and southern rust
Soybean	GMB151	BASF	*Glycine max*	Resistance to soybean cyst nematode and HPPD inhibitor herbicides
	TruVail™	Benson Hill	*G. max*	High protein content
	FAE1 and FAE8 knockout soybean	Inari Agriculture	*G. max*	Shortened growth period, increased seed size and quantity, enhanced root nodulation
	Amfora soybean	Amfora	*G. max*	High protein content
Wheat	HB4®	Bioceres Crop Solutions	*Triticum aestivum*	Expression of sunflower HB4 transcription factor (drought tolerance) and PAT enzyme (glufosinate tolerance)
Potato	BG25	J.R. Simplot	*Solanum tuberosum*	Expression of Rpi-amr3/Rpi-vnt1 (late blight resistance); RNAi suppression of *Vlnv* (low reducing sugar)
Field pennycress	CoverCress TT8	CoverCress Inc.	*Thlaspi arvense*	CRISPR editing of *TT8*/*FAE1* genes to reduce erucic acid and glucosinolate content
Tomato	Phytoform TOMATO	Phytoform Labs Ltd.	*S. lycopersicum*	CRISPR knockout of abscission zone gene to inhibit pedicel abscission
Rice	Os03g14669-identified rice	Hjelle Advisors & Amfora & Mississippi State University	*Oryza sativa*	High protein content

Data source: U.S. Department of Agriculture (http://www.aphis.usda.gov).

Table 2 Representative R&D and approved traits of transformation events in the European Union in 2024

Category	Event name	Developer	Species	Approved traits[1)]
Maize	MON89034×1507×NK603	Corteva/Bayer	*Zea mays*	Glyphosate tolerance and IR (expressing Bt Cry1A.105/ Cry2Ab2 proteins)
	MON89034×1507×MON88017×59122	Corteva/Bayer	*Z. mays*	Glufosinate tolerance and IR (expressing Bt Cry3Bb1 protein)
	MON810	Bayer	*Z. mays*	Glyphosate tolerance and IR (expressing Bt Cry1Ab protein)
	DP915635	Corteva	*Z. mays*	Glufosinate tolerance and resistance to maize rootworm (expressing Bt Cry34Ab1/Cry35Ab1 proteins)
	DP23211	Corteva	*Z. mays*	Glufosinate tolerance and IR (expressing Bt Cry3Aa protein)
	DP202216	Corteva	*Z. mays*	Glufosinate tolerance, yield enhancement (ZMM28)
Cotton	COT102	Syngenta Group	*Gossypium hirsutum*	Lepidopteran resistance (Vip3Aa19), hygromycin B resistance (aph4)

[1)] All approvals were based on scientific opinions issued by the European Food Safety Authority (EFSA), which concluded that these events are as safe as their conventional counterparts. The 2024 approvals reflect the European Union's ongoing emphasis on stacked-trait technologies, with most maize events incorporating combinations of herbicide tolerance (HT) and insect resistance (IR) traits to enhance pest management and reduce reliance on chemical inputs (European Commission 2024; USDA 2024).
Data source: European Commission website (https://eur-lex.europa.eu).

trait soybean event combining IR against Lepidoptera with HT. This event was initially approved in 2023 and is scheduled for expanded commercial rollout in 2025.

3.5. Argentina's GM approval covers the fields of grain, oil, and industry

On March 19 and 20, 2024, the Ministry of Agriculture, Livestock and Fisheries of Argentina issued approvals for two transformation events. T he first, *G. max* event BCS-GM151-6, was authorized for food, feed, and commercial cultivation. It carries the *cry14Ab-1.b* and *hppdPf4Pa* genes, which confer resistance to soybean cyst nematode and tolerance to HPPD-inhibiting herbicides. BCS-GM151-6 has also received regulatory approval in the United States and Canada. The second approved event was *Saccharomyces cerevisiae* SCY011, a GM yeast containing the *JA126PE096* gene for α-amylase synthesis, intended for use in fuel ethanol production. In October 2024, the Secretariat of Agriculture, Livestock and Fisheries of the Ministry of Economy approved GM maize DAS-1,131-1 for food, feed, and cultivation. Developed by Corteva, DAS-1131 expresses the *Cry1Da2* protein (from *Bacillus thuringiensis*), providing resistance to Lepidoptera pests and HT to glyphosate.

3.6. Australian OGTR approves commercial cultivation of GM crops

In 2024, Bayer's Bollgard 3 XtendFlex remained dominant in Australia's cotton sector. This variety combines resistance to Lepidoptera pests with tolerance to dicamba and glufosinate herbicides. Roundup Ready® (glyphosate-tolerant) and LibertyLink® (glufosinate-tolerant) cotton lines continued to serve as complementary options. Australia's Office OGTR approved three GM crops: GM banana QCAV-4, GM potato BG25, and GM canola MON-00073-7 — detailed as follows (Table 4).

3.7. Extension of GM crops in Africa to multiple categories

In 2024, several African countries achieved significant policy breakthroughs in the approval and commercialization of GM crops, advancing from regulatory reform to field implementation. Kenya and Nigeria served as regional benchmarks, promoting GM technology through judicial and legislative mechanisms.

Kenya implemented a key judicial confirmation following the October 2022 repeal of the national ban on GM imports and cultivation. This enabled the country to advance the commercial production of Bt cotton (*Gossypium hirsutum*), incorporating the *cry1Ac* gene to confer resistance to *Helicoverpa* armigera (African bollworm). Kenya also initiated multi-crop field trials, including Bt maize (event MON810 for resistance to stem borer) and vitamin A-biofortified sorghum containing the *psy1* and *crtI* genes, aimed at addressing nutritional deficiencies.

In Ghana, 2024 marked the regulatory approval of Ghana's first GM *Vigna unguiculata* (cowpea), developed by CSIR-SARI. This variety, resistant to *Maruca vitrata* (Maruca pod borer), represents the country's first commercial release of a GM cowpea. Earlier in the year, Nigeria's National Variety Release Committee (NVRC) approved the insect-resistant and drought-tolerant TELA maize (transformation event MON87460×MON89034), further facilitating the adoption of GM technology. However, delays in technology dissemination and intellectual property disputes have constrained the pace of large-scale implementation. In Burkina Faso, in 2024, Bt cotton was reapproved for the 2024–2033 cultivation period, with new varieties developed to overcome previous concerns related to fiber length (ISAAA 2024d).

3.8. Approval of GM organisms is being comprehensively promoted in other countries

On October 3, 2024, Health Canada and the Canadian Food Inspection Agency approved GM soybean MON94637 for food, feed, and cultivation. Developed by Bayer, this soybean event expresses Cry1A.2 and Cry1B.2 proteins from *Bacillus thuringiensis*, providing resistance to Lepidopteran pests. MON94637 had previously been approved in Brazil for food and feed uses. Health Canada also classified a gene-edited

Table 3 Representative R&D and approved traits of transformation events in China in 2024

Category	Event name	Developer	Species	Approved traits[1)]
Maize	Zheda Ruifeng 8×nCX-1	Hangzhou Ruifeng Bioscience Co., Ltd.	*Zea mays*	IR and HT
	Ruifeng 125×nCX-1	Hangzhou Ruifeng Bioscience Co., Ltd.	*Z. mays*	IR and HT
	LP026-2	Longping Biotech Hainan Co., Ltd.	*Z. mays*	IR and HT
	LW2-1	Longping Biotech Hainan Co., Ltd.	*Z. mays*	HT
	WYN17132	Zhejiang Xinan Chemical Industrial Group Co., Ltd.	*Z. mays*	HT
	WYN041	Zhejiang Xinan Chemical Industrial Group Co., Ltd.	*Z. mays*	IR and HT
	BBL2-2	Beijing Aoruijin Seed Industry Co., Ltd.; Biotechnology Research Institute, Chinese Academy of Agricultural Sciences; Beijing Boai Yuanshang Biotechnology Co., Ltd.	*Z. mays*	IR and HT
	ND207×CC-2	Beijing Liangyuan Biotechnology Co., Ltd.	*Z. mays*	IR and HT
	QY2569-42	Qingdao Qingyuan Seed Science Co., Ltd.	*Z. mays*	IR and HT
	ZZM032	China National Seed Group Co., Ltd.	*Z. mays*	IR and HT
	MZIR260	China National Seed Group Co., Ltd.	*Z. mays*	IR
	KJ1003	KJDalong (Beijing) Biotechnology Co., Ltd.	*Z. mays*	IR and HT
	Br2 gene mutant yield trait-improved maize 179AC19-13-13	Shandong Sunfong Biotechnology Co., Ltd.	*Z. mays*	Yield trait improvement
	ZmNL4 gene mutant yield trait-improved maize KN-NL4-2	Weimi Biotechnology (Hainan) Co., Ltd.; Huazhong Agricultural University	*Z. mays*	Yield trait improvement
Soybean	DBN9004×DBN8002	Beijing DaBeiNong Biotechnology Co., Ltd.	*Glycine max*	IR and HT
	DBN8205	Beijing DaBeiNong Biotechnology Co., Ltd.	*G. max*	IR and HT
	XP-2	Hangzhou Ruifeng Bioscience Co., Ltd.	*G. max*	HT
	WYN341GmC	Zhejiang Xinan Chemical Industrial Group Co., Ltd.	*G. max*	HT
	WYN029GmA	Zhejiang Xinan Chemical Industrial Group Co., Ltd.	*G. max*	HT
	Physiological trait-improved soybean 25T93-1	Shandong Sunfong Biotechnology Co., Ltd.	*G. max*	Physiological trait improvement
	Quality trait-improved soybean P16	Suzhou Qihe Biotechnology Co., Ltd.	*G. max*	Quality trait improvement
	GmLn gene mutant yield trait-improved soybean QH64112	Suzhou Qihe Biotechnology Co., Ltd.; Beijing Qihe Biotechnology Co., Ltd.	*G. max*	Yield trait improvement
	GmEl and *GmElLb* gene mutant physiological trait-improved soybean E001SYFT	China National Seed Group Co., Ltd.	*G. max*	Physiological trait improvement
Cotton	GGK2	Xinjiang Guoxin Seed Industry Co., Ltd.; Biotechnology Research Institute	*Gossypium hirsutum*	HT
	KJC017	KJDalong (Beijing) Biotechnology Co., Ltd.	*G. hirsutum*	HT
Wheat	*TaALS* gene mutant herbicide-tolerant wheat TaALS-4	Suzhou Qihe Biotechnology Co., Ltd.; Institute of Genetics and Developmental Biology, Chinese Academy of Sciences	*Triticum aestivum*	Herbicide tolerance
	TaMLO-A1, *TaMLO-B1*, *TaMLO-D1*, and *TaMLOX* gene mutant disease-resistant wheat MLO-KNRNP	Suzhou Qihe Biotechnology Co., Ltd.; Institute of Genetics and Developmental Biology, Chinese Academy of Sciences	*T. aestivum*	Disease resistance
Rice	*Wx* gene mutant quality trait-improved rice 118-9-15	Suzhou Qihe Biotechnology Co., Ltd.; Jiangsu Academy of Agricultural Sciences; Beijing Qihe Biotechnology Co., Ltd.	*Oryza sativa*	Quality trait improvement

[1)] IR, insect resistance; HT, herbicide tolerance.

potato — developed in the United States and engineered to reduce polyphenol oxidase levels, thereby delaying browning — as a non-novel plant product. Consequently, it does not require a premarket safety assessment and is anticipated to enter the Canadian market by 2025. Canada's major GM crops in 2024 continued to include canola, maize, soybean, and sugar beet.

In Japan, as of October 2024, a total of 334 gene-edited products have received regulatory approval for food and feed use — 201 for feed and 133 for food. Under Japan's Food Labeling Act, gene-edited products that do not contain foreign DNA are exempt from mandatory labeling and regulation. In May and July 2024, Japan's Ministry of Agriculture, Forestry and Fisheries approved gene-edited canola events MON94100 and RF3, and gene-edited maize events such as DP202216×NK603×DAS40278 for feed use and cultivation. As of 2024, seven gene-edited products had been submitted for domestic production and commercialization, with four already approved.

On December 25, 2024, the Saudi Food and Drug

Table 4 Representative R&D and approved traits of transformants and transformation events in Australia in 2024[1)]

Crop	Species	Transformant/ Transformation event	Trait description	Commercial significance[2)]
Cavendish banana	*Musa acuminata*	QCAV-4	Resistance to Fusarium wilt tropical race 4 (TR4/ Panama disease)	The world's first commercialized GM banana; approved for cultivation in Australia; first GM fruit crop in the country (ISAAA 2024b)
Potato	*Solanum tuberosum*	BG25	Low reducing sugar, reduced browning, and resistance to late blight	First GM potato approved for food use in Australia by FSANZ
Canola	*Brassica napus*	MON-ØØØ73-7	Glyphosate tolerance	Commercial cultivation no longer requires a license due to negligible risk

[1)] The TR4-resistant genetically modified (GM) banana serves as a model for addressing major food security challenges in tropical regions. Localized field trials have already commenced in the Philippines. Australia's established "single-trait review and multi-crop expansion" fast-track approval system may serve as a regulatory model for countries in the Asia-Pacific region. From a regional integration perspective, the GM canola breeding center in Western Australia supplies stress-tolerant germplasm to Southeast Asia (FSANZ2024).
[2)] ISAAA, International Service for the Acquisition of Agri-Biotech Applications; FSANZ, Food and Agriculture Organization of the United Nations.

Authority (SFDA) released two draft regulations: "General Requirements for GM Processed Food and Feed Products" and "General Requirements for Unprocessed GM Agricultural Products". The former applies to products containing, derived from, or produced using GM organisms, with labeling required when the GM component exceeds 1%.

From October to December 2024, the Ministry of Food and Drug Safety of Korea released the results of the 236th, 237th, 238th, and 239th reviews conducted by the GM Safety Review Committee. Based on the data submitted by applicants, the committee concluded that the GM canola events RF3 and MS8/RF3, developed by BASF, exhibit HT to glufosinate and possess fertility restoration traits. Additionally, GM maize events Bt11×MIR162×TC1507×NK603, Bt11×TC1507×NK603, and Bt11×MZIR098×DP-004114×NK603, developed by Syngenta, were determined to possess HT to both glufosinate and glyphosate, along with resistance to Lepidopteran insect pests. The GM canola event DP073496-4, developed by Corteva, was found to exhibit glyphosate tolerance. Furthermore, the committee reviewed the GM cotton event MON15947, developed by Bayer, which confers IR.

4. Policy and market acceptance: Global evolution of regulatory systems for GM crops

GM crops offer significant benefits for agricultural productivity and food security; however, commercialization remains constrained by variations in public perception and national regulatory approaches (Turnbull *et al.* 2021). To address these challenges, countries updated their regulatory frameworks in 2024 to better balance technological innovation with effective risk management. Key developments across countries and regions during this period reflect the following characteristics (Table 5).

4.1. Product-based tiered regulation

United States: Product-based tiered regulation. The principle of "substantial equivalence" continues to underpin the U.S. regulatory approach, which relies on a coordinated framework involving the USDA, EPA (Environmental Protection Agency), and FDA (Food and Drug Administration). Products developed using site-directed nuclease (SDN)-1 and SDN-2 techniques may be exempt from safety review under specific conditions, such as the absence of foreign DNA, while SDN-3 products remain subject to case-by-case review. In September and October 2024, the USDA announced regulatory exemptions for several gene-edited crops, including tomato and field pennycress, reinforcing the structured tiered model (FDA 2022; ISAAA 2024b).

Table 5 Regulatory stringency index by country

Country	Regulatory principle for gene editing	Degree of commercialization	Labeling requirements
United States	Substantial equivalence	High	Voluntary labeling
Brazil	Clear guidance	Medium	Mandatory labeling
China	Moderate caution	Partially open	Mandatory labeling
India	Gene editing guidelines	Medium-low	Mandatory labeling (no content-threshold exemption)
European Union	Precautionary principle	Very low	Mandatory labeling

Argentina: Regulatory leader in Latin American coordination. As the technical coordinator for MERCOSUR, Argentina's National Service for Agrifood Health and Quality (SENASA) classifies products developed using gene-editing technologies under the category of "innovative plant breeding". Biosafety assessments are only triggered for products that contain foreign DNA, streamlining the approval process for gene-edited crops.

4.2. Technology dichotomy regulation

European Union: Cautious openness and technological decoupling. In February 2024, the European Parliament voted in favor of the proposed "Precision Breeding Act", which aims to distinguish NGT1 crops (eligible for regulatory exemption) from NGT2 crops (regulated under the traditional GMO framework). Final enactment of this legislation is still pending approval by member states. Directive 2001/18/EC on GM organisms continues to apply to all products containing foreign DNA (AgbioInvestor 2024; European Parliament 2024).

4.3. Risk proportionate regulation

Japan: Agile regulation with risk-based classification. The Ministry of the Environment revised its "Regulations on the Use of Living Modified Organisms" to classify gene-edited products based on the presence of foreign DNA and the editing method used, including targeted mutagenesis or homologous recombination. In April 2024, the Consumer Affairs Agency implemented the "Guidelines for Labeling of Gene-Edited Foods", which mandate voluntary labeling for products with novel nutritional traits — such as the high-GABA tomato — thereby enhancing transparency for consumers (ISAAA 2024c).

United Kingdom: differentiated regulation after Brexit. Following Brexit, the United Kingdom passed the "Genetic Technology (Precision Breeding) Act" in 2023, eliminating GMO regulatory barriers to gene-edited crops whose modifications could be achieved through traditional breeding techniques. This legislation applies exclusively in England and emphasizes the principle of "proportionate risk regulation". Scotland, Wales, and Northern Ireland, however, continue to align with the European Union's precautionary regulatory framework, demonstrating regulatory divergence within the UK (HCL 2023).

4.4. Commercialization-oriented regulation

China: Regulatory innovation during commercialization. China's 2024 GM policy adopted a dual-track approach of "accelerating industrialization" alongside "refining regulation". Reforms in labeling systems, variety registration, and regulatory oversight are advancing the practical deployment of GM technology, while safety evaluations, end-to-end regulatory oversight, and enhanced public communication are used to address potential risks. The No. 1 Central Document of 2024 emphasized the national objective of "accelerating the expansion of bio-breeding industrialization". After completing a three-year pilot program, the commercialization of GM maize and soybean entered the demonstration stage in 2024, with both the number of participating provinces and total cultivation area increasing substantially.

4.5. Harmonization-focused regulation

Australia: Regulatory adjustment specifically for gene editing techniques. The Office of the Gene Technology Regulatory (OGTR) removed SDN-1 products from its definition of GMOs, exempting them from regulatory oversight. However, SDN-2 products remain subject to the "Gene Technology Act 2000", leading to inconsistencies with classifications used in the United States and Japan (AgriGrowth Tasmania 2025).

New Zealand: Regulatory reform to shift from process-based to risk-based. Previously, gene-editing technologies in New Zealand were tightly restricted under long-standing GMO regulations. In March 2024, the government announced a comprehensive regulatory reform, including plans to enact new legislation by the end of 2025 that would transition to a risk-based model. This change will end nearly 30 years of process-based classification for gene-edited products and facilitate their regulated use, aligning New Zealand with Australia and other jurisdictions (Bucholzer and Frommer 2022).

In 2024, global regulatory policy trends were shaped by two dominant trajectories. First, a general tendency toward regulatory relaxation emerged. Countries such as the United States, Brazil, and Australia formally exempted gene-edited crops from traditional GMO regulations when genetic modifications could be achieved through conventional breeding methods, thereby accelerating the deployment of these technologies (FAO 2023).

Second, a shift toward risk-based regulatory adjustment was observed. Notably, the European Parliament voted in February 2024 to adopt a more flexible framework for plants developed using new genomic technologies (NGTs) (European Parliament 2024). Looking ahead, national policies are expected to increasingly converge as countries seek to address the dual challenges of climate change and global food security (Ishii and Araki 2017; Turnbull *et al.* 2021).

5. Summary and outlook

The industrialized cultivation and commercialization of GM crops continued to expand significantly in 2024. Driven by policy support and market demand, the global grain trade pattern is shifting toward greater efficiency and regional integration. Functional gene research has expanded beyond single insect-resistant Bt genes to multidimensional traits, including high yield, disease resistance such as viral and fungal resistance, and nutritional enhancement such as high lysine and high vitamin A (Miao *et al.* 2024; AgbioInvestor 2025). Crop species have also extended from traditional bulk crops such as maize and soybean to emerging varieties, including wheat and canola. In 2024, China made notable progress, with planting areas steadily increasing and pilot projects expanding to eight provinces. These areas are expected to grow further in 2025, marking the entry of GM-related bio-breeding technologies into an accelerated phase of promotion.

By adopting no-till systems and reducing pesticide use, GM crops have become one of the most cost-effective pathways for agricultural emission reduction. According to available data, the current global production of GM crops helps reduce approximately 30 million tons of carbon dioxide emissions annually. Carbon reduction occurs via direct and indirect mechanisms. In the future, herbicide dependence should be minimized through multi-gene stacking technologies (e.g., combining insect resistance with drought tolerance) and by establishing carbon-trading agricultural models that incorporate no-till carbon sequestration into policy subsidy systems. Regarding public communication, it will be essential to promote a balanced, ethics-based narrative that emphasizes responsible innovation, integrating environmental benefits with social acceptance in coordinated development.

Bio-breeding technologies are undergoing significant iterative advancements, with gene-editing applications accelerating and achieving rapid translation from laboratory research to field implementation. In 2024, a French biotechnology company cultivated high oleic acid and pod-bursting-resistant *Brassica napus* using gene-editing techniques. Traits and crop types are exhibiting a clear trend toward diversification, with newly approved crops

demonstrating high adaptability. With stacked traits now dominant, these innovations provide diversified solutions for global markets and support sustainable agriculture and food security. Going forward, the deep integration of gene-editing technologies with conventional field-based breeding pipelines will optimize breeding efficiency, shorten research and development cycles, and expand market options through industry–academia–research collaboration, driving biotech breeding into the "4.0 era".

Looking ahead, the policy framework for GM and gene-edited crops worldwide will exhibit a clear convergence and industrialization orientation. Nations will aim to streamline approval processes, broaden the scope of trait exemptions, and promote regional regulatory mutual recognition to reduce trade barriers and enable global optimization of biotechnology resources. Industrial policies should further prioritize the development of multi-trait crops and the strategic implementation of science-based public communication. By leveraging policy incentives, innovative technologies such as gene editing and stress resistance can be integrated into resource-efficient and environmentally sustainable agricultural systems, ultimately fostering a coordinated development model that encompasses technological innovation, regulatory adaptation, and enhanced market acceptance.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that they did not use AI in the preparation and writing of this manuscript.

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