DOI 10.15302/J-SSCAE-2021.04.022

Overview of the Global Crop Seed Industry and Strategic Thinking on its Development in China

Zheng Huaiguo, Zhao Jingjuan, Qin Xiaojing, Jia Qian, Qi Shijie

Institute of Agricultural Information and Economics, Beijing Academy of Agriculture and Forestry Sciences, Beijing 100097, China

Abstract: The seed industry is a basic and core industry that is strategically important to a nation. Considering the national guidance opinions on fields such as seeds and cultivated land, industrialization of biological breeding, and the development of core technologies for germplasm resources, the seed industry has become a driving force for the rapid development of agriculture in China. In this study, we summarize the current status of the global crop seed industry in terms of germplasm resource protection and utilization, biological breeding technology development, and seed industry development. Moreover, we analyze the problems in China's seed industry from an international perspective. To promote the development of the seed industry, China should implement a national germplasm resource strategy to consolidate the foundation of its seed industry, implement a scientific and technological innovation strategy in the seed industry to achieve breakthroughs in original innovation, construct a seed industry system with Chinese characteristics to enhance industrial competitiveness, promote the role of enterprises in technological innovation, and modernize the supervision system to improve industrial advantages.
Keywords: international seed industry; crop seed industry; germplasm resources; biological breeding technology

1 Introduction

In a speech at the Twentieth Meeting of the Central Committee for Deepening Overall Reform on July 9, 2021, General Secretary Xi Jinping pointed out that the seed industry is the foundation of agricultural modernization; therefore, we must develop our national seed industry, raise the security of germplasm resources to a strategic level that concerns national security, and concentrate efforts on solving difficulties, making up weak links, strengthening advantages, controlling risks to achieve self-reliance in seed technology, and ensuring that our germplasm resources are independent and controllable [1]. The seed industry is a basic and core industry that is strategically important to a nation. Considering the national guidance opinions on fields such as seeds and cultivated land, industrialization of biological breeding, and the development of core technologies for germplasm resources, the seed industry has become a driving force for the rapid development of agriculture in China. Nowadays, the international seed industry has entered a period of opportunity with the aim of seizing the strategic position and economic growth point, showing the development trends of high technology, integration, and oligopoly. Agriculturally developed countries have entered the Breeding 4.0 era characterized by "Biotechnology + Artificial Intelligence + Big Data Information Technology." In addition, the merger and reorganization of seed enterprises worldwide is becoming increasingly intensive, resulting in the integration of modern biotechnology, bio-agrochemicals, and digital agriculture in the seed industry. As one of the cores of the seed industry, it serves as the

Received date: June 10, 2021; **Revised date:** July 21, 2021
Corresponding author: Zhao Jingjuan, associate researcher of Institute of Agricultural Information and Economics of Beijing Academy of Agriculture and Forestry Sciences. Major research field is seed industry strategy. E-mail: zjjaaa_zn@163.com
Funding program: Sub-program of Agricultural Professional Knowledge Service System of the Construction Program of China Knowledge Centre for Engineering Sciences and Technology (CKCEST-2021-1-1); Special Program of Science and Technology Innovation Ability Building of Beijing Academy of Agriculture and Forestry Sciences (KJCX20200203)
Chinese version: Strategic Study of CAE 2021, 23(4): 045–055
Cited item: Zheng Huaiguo et al. Overview of the Global Crop Seed Industry and Strategic Thinking on its Development in China. *Strategic Study of CAE*, https://doi.org/10.15302/J-SSCAE-2021.04.022

fundamental basis for ensuring the food security of a nation. Taking into consideration the vigorous developmental trend and the complex environment of the crop seed industry, a comprehensive understanding of the development and an in-depth analysis of the competitive landscape of the global crop seed industry are of positive significance in formulating development strategies for China's seed industry, promoting breakthroughs in key biological breeding technology, and planning the industrial layout of the seed industry in a forward-looking manner.

2 Overview of the global crop seed industry

2.1 Protection and utilization of global germplasm resources

Crop germplasm resources are not only the genetic resources of improved varieties but also the material base for breeding high-quality and high-yield crops. Therefore, governments and international organizations worldwide have attached strategic importance to the collection and conservation of crop genetic resources. According to statistics from the International Seed Federation, 7.4×10^6 germplasm resources and 1750 gene pools are available in the world, among which 130 gene pools have more than 1×10^4 germplasm resources. The United States, China, and India have the world's top three crop genetic resource pools. According to the 2021 data, the National Plant Germplasm System of the United States has reserved 600 419 resources in 16 204 species, 2553 genera, and 244 families [2], among which the number of germplasm resources from China accounts for about 28% of the inventory. The number of reserved crop germplasm resources in China's germplasm resource pool exceed 5.2×10^5, of which 76% are local resources and 24% are foreign resources [3,4]. The number of various crop germplasm resources reserved in the gene pool of the National Bureau of Plant Genetic Resources affiliated to the Department of Agriculture & Farmers Welfare in India exceeds 4.5×10^5, including 1.1×10^5 rice germplasm resources, approximately 4×10^4 wheat germplasm resources, 1×10^4 corn germplasm resources, 2.7×10^4 vegetable germplasm resources, 6.1×10^4 oil germplasm resources, and 6.1×10^4 bean germplasm resources [5].

The United States has established a plant germplasm system led by the nation, with members including federal and state government organizations, research institutions, and private organizations [6]. The National Plant Germplasm System, which systematically collects germplasm resources throughout the world for conservation, identification, and evaluation, and records relevant information on crop germplasm resources, has distributed approximately 2.5×10^5 documents to national and international clients, including public, private, and non-governmental organizations and sectors.

2.2 Development of global biological breeding technology

In recent years, advances in biotechnology and computer technology have driven the rapid development of breeding technology, and agriculturally developed countries have entered the Breeding 4.0 era characterized by "Biotechnology + Artificial Intelligence + Big Data." Transgene technology, gene editing technology, genomic selection breeding, and genomics have become the core frontiers of international biotechnology breeding research.

2.2.1 Transgene technology

The research and development of transgene technology have been promoted from single- to multi-gene transformation, for example, from the transformation of a single exogenous functional gene to the transformation of multiple genes, including regulatory genes. From the perspective of technological application, the first generation of transgenic crops resistant to insects, diseases, and herbicides has gradually evolved into transgenic crops with resistance to stress (drought, cold, salt, and alkali), quality improvement, nutrition improvement, and biomedicine. Taking the lead in transgene technology, the United States has entered the commercial application stage. China is generally a follower in terms of transgene technology while playing the leading role in some aspects.

2.2.2 Gene editing technology

Gene editing technology based on the CRISPR/Cas system has been a major breakthrough and a research hotspot in the field of life science in recent years. From the perspective of technological research and development, the United States and China are in leading positions. In terms of technology application, China is basically at the same scenario as foreign countries, and even reaches the advanced international level in some aspects. For example, China's research on gene editing technology in major food crops (rice and wheat) is in a leading position in the world [7]. In 2021, researchers at the Wyss Institute for Biologically Inspired Engineering at Harvard University, USA invented the Retron Library Recombineering, a gene editing tool that can generate up to millions of mutants, "code" mutant bacterial cells, and search the entire library simultaneously. This tool can be used with higher

DOI 10.15302/J-SSCAE-2021.04.022

editing efficiency when the clustered regularly interspaced short palindromic repeats are toxic or not feasible [8].

2.2.3 Genomic selection breeding

With the rapid development of genome sequencing technology and computer science, genomic selection breeding has greatly improved the prediction of complex traits such as crop yield and quality. In the future, it is expected to be the core method for heterosis prediction and selection of high-yield and good-quality varieties in crop breeding [9]. From the perspective of technology applications, genomic selection breeding has been researched in depth in corn, rice, and other food crops, but less in horticultural crops. International seed giants such as Bayer AG (Monsanto) and Corteva Agriscience (Dow DuPont) have realized the large-scale application of related technologies in crops such as corn, and the United States is a pacemaker for this technology. Germany, France, and other countries have also taken the lead in the relevant research. However, China is still in the initial stages of genomic selection breeding research.

2.2.4 Genomics

Rapid development of genome sequencing technology has promoted breakthroughs in crop genome research. Crop genome research was initiated early in China, and China has completed the genome sequencing of important crops such as rice, wheat, corn, and cucumber and preliminarily mastered the functional traits of the genes of these crops, taking the international lead in terms of the research level [10]. In addition, China has developed genotype identification methods based on high-throughput genome sequencing and has carried out genome association analysis and functional research on agronomic traits in rice and corn. At present, China is in an internationally leading position in terms of functional genome research on rice. As the first country to apply second-generation sequencing technology in vegetable genome research, China has mapped the complete genome sequence and variation maps of cucumber, tomato, Chinese cabbage, cabbage, watermelon, and other vegetables and fruits [11]. China is at the same level as developed countries in view of big data mining of important agronomic trait genes using genomics.

2.3 Industrialization of global biotechnology breeding

2.3.1 Transgenic crops

From 1996 to 2019, the accumulated planting area of transgenic crops worldwide reached 2.7×10^9 hm^2. In 2019, transgenic crops were grown in 71 countries and regions. The United States gains the most economic benefits from transgenic crops being the largest planting area for transgenic crops. In 2019, the planting area reached 7.15×10^7 hm^2, and the planted transgenic crops included corn, soybean, cotton, alfalfa, rape, beet, potato, papaya, pumpkin, and apple, and the average application rate of transgenic soybean, corn, and cotton reached 95%. China's planting area of transgenic crops was approximately 3.2×10^6 hm^2, only 0.48% of that of the United States, and the main varieties planted included cotton and papaya (Table 1). In regard to economic benefits, the countries planting transgenic crops earned a total of USD 224.9 billion from 1996 to 2018, among which the United States gained USD 95.9 billion, accounting for 42.64% of the global total, and China gained USD 23.2 billion, accounting for 10.32% of the global total. Except for the United States, the top countries in terms of economic benefits are Argentina (USD 28.1 billion), Brazil (USD 26.6 billion), and India (USD 24.3 billion) [12].

2.3.2 Gene-edited crops

The United States is the most advanced country in terms of the industrialization of gene-edited crop varieties. SU Canola sulfonylurea herbicide-resistant rape is the world's first commercialized gene-edited crop that was commercially planted in 2015 with an area of 4000 hm^2 in the United States. In 2016, the United States approved the planting of mushroom varieties, in which pieces of browning-related deoxyribonucleic acid (DNA) were cut using genome editing techniques. To date, more than 150 new varieties of gene-edited plants have been designated as unregulated by the United States Department of Agriculture (USDA), and commercial planting of such varieties is allowed in the United States, including high-oleic soybean, powdery mildew-resistant wheat, camelina with improved oil content, and camellia with high oil content. To date, the USDA has invested and made public 23 gene-edited crops, among which three crops were developed by multinational companies, Dow AgroSciences and DuPont Pioneer (currently Dow DuPont), and the rest were from startups such as Calyxt, Yield10, and BensonHill Biosystems. As some startups seize the opportunity for gene-editing technology and advance their patent deployment, the licensing and transfer of intellectual property between large multinational seed companies and small- and medium-sized technology companies has become an important strategy for the property ownership of gene editing technology [13]. In 2018, the United Kingdom approved experimental planting of gene-edited

camelina with high omega-3 polyunsaturated fatty acids. In 2020, Japan approved the sales application of Japan's first gene-edited food, a kind of tomato rich in the ingredient that suppresses the rise in blood pressure (gamma-aminobutyric acid), indicating that gene-edited products could be sold in the market.

Although China has obtained a series of internationally leading new materials and varieties in applied research on gene-edited crop breeding, including tobacco, rice, corn, sorghum, soybean, watermelon, cucumber, tomato, banana, and poplar, no gene-edited crops have been approved for sale in the market.

Table 1. Transgenic crops and planting areas in 2019.

Rank	Country	Planting area ($\times 10^6$ hm^2)	Varieties of transgenic crops
1	United States*	71.5	Corn, soybean, cotton, alfalfa, rape, beet, potato, papaya, pumpkin, and apple
2	Brazil*	52.8	Soybean, corn, cotton, and sugar cane
3	Argentina*	24.0	Soybean, corn, cotton, and alfalfa
4	Canada*	12.5	Rape, soybean, corn, beet, alfalfa, and potato
5	India*	11.9	Cotton
6	Paraguay*	4.1	Soybean, corn, and cotton
7	China*	3.2	Cotton and papaya
8	South Africa*	2.7	Corn, soybean, and cotton
9	Pakistan*	2.5	Cotton
10	Bolivia*	1.4	Soybean
11	Uruguay*	1.2	Soybean and corn
12	Philippines*	0.9	Corn
13	Australia*	0.6	Cotton, rape, and safflower
14	Myanmar*	0.3	Cotton
15	Sudan*	0.2	Cotton
16	Mexico*	0.2	Cotton
17	Spain*	0.1	Corn
18	Colombia*	0.1	Corn and cotton
19	Vietnam*	0.1	Corn
20	Honduras	<0.1	Corn
21	Chile	<0.1	Corn and rape
22	Malawi	<0.1	Cotton
23	Portugal	<0.1	Corn
24	Indonesia	<0.1	Sugar cane
25	Bangladesh	<0.1	Eggplant
26	Nigeria	<0.1	Cotton
27	Eswatini	<0.1	Cotton
28	Ethiopia	<0.1	Cotton
29	Costa Rica	<0.1	Cotton and pineapple

Note: Data are sourced from the International Service for the Acquisition of Agribiotech Applications (ISAAA). * represents a country planting transgenic crops with an area greater than 5×10^4 hm^2.

2.3.3 Biological breeding technology and product regulation

Policies for the regulation of biological breeding technology and its products are important factors that affect the research and development of biological breeding technology and its industrialization for a nation. Internationally, there are two main groups. Countries of the first group, represented by the United States, implement a product-oriented regulatory system for biotechnology products and adhere to the principle of substantial equivalence and case analysis [14–16]. For gene-edited crops (without the introduction of foreign genes), they considered that variations that can be obtained by natural or traditional breeding methods are non-transgenic organisms that require no regulation. Canada [17], Brazil [18,19], Argentina [20,21], Chile [22], Colombia [23], Israel [24], Japan [25,26], Australia [27] and other countries adopt similar policies. India, Bangladesh, the Philippines, Nigeria, Kenya, Paraguay, Uruguay, Norway, and other countries refer to similar practices [28]. Countries of the second group, represented by the European Union (EU), implement a technical means-oriented regulatory system for biotechnology products and believe that all organisms obtained by biotechnology should be subject to strict safety evaluation and regulation as transgenic organisms [29]. In 2018, the Court of Justice of the EU ruled that organisms produced by technologies such as recombinant DNA, cell

DOI 10.15302/J-SSCAE-2021.04.022

fusion, and even radiation mutations were regarded as transgenic organisms and were subject to corresponding regulations. However, academics and industry insiders in the EU and its member states have called for the relaxation of restrictions on the industrialization of gene-edited products [30]. France regards gene-edited crops as non-transgenic organisms [31]. The United Kingdom has also expressed that it would adopt a more relaxed regulatory policy for gene-edited crops after Brexit [32]. New Zealand has adopted a regulatory policy similar to that adopted by the EU [33].

As for transgenic crops, China has always taken the attitude of "ensured safety, independent innovation, bold research, and careful promotion," strictly controlled the whole process of research, test, production, processing, and operation, and intensively monitored the laboratory research and field trial stages of transgenic agricultural products with potential risks. At present, China is the only country that adopts mandatory qualitative labeling according to the catalogue and requires that the production and operation of transgenic food should be marked significantly. No clear regulatory policy for gene-edited crops has been issued in China [34]. Policy documents such as the *Work Plan for the Regulation of Agricultural Transgenic Organisms in 2021* and the *Notice on Encouraging the Original Innovation of Agricultural Transgenic Organisms and Regulating the Transition, Transfer, and Breeding of Biological Materials* have released important signals that China will prepare for comprehensive industrialization on the basis of strict safety evaluation of agricultural transgenic organisms.

2.4 Trade of the global crop seed industry

According to statistics (Table 2), global seed exports totaled USD 13 195 million in 2019, and the top three countries in terms of seed exports were the Netherlands, the United States, and France, with a total export of USD 6295 million, accounting for about 47.71% of the global total in 2019. China's seed exports amounted to USD 207 million in 2019, accounting for approximately 1.57% of the global total, ranking 11th. The top three exports were vegetable seeds (USD 116 million), rice seeds (USD 63 million), and herbal flower seeds (USD 17 million).

Table 2. Top 11 seed exporters in 2019.

Rank	Country	Export volume ($\times 10^8$ t)	Export amount (USD 100 million)
1	Netherlands	10.97	27.54
2	United States	21.50	20.02
3	France	8.70	15.39
4	Germany	2.28	6.66
5	Denmark	1.82	4.96
6	Hungary	2.55	3.63
7	Italy	0.83	3.43
8	India	3.64	2.89
9	Chile	0.32	2.81
10	Belgium	3.85	2.67
11	China	0.24	2.07

Note: The data are sourced from the UN Comtrade Database.

According to statistics (Table 3), global seed imports totaled USD 14.657 billion in 2019, and the Netherlands ranked 1st with a seed import of USD 1.094 billion, accounting for approximately 7.46% of the global total. China's seed imports amounted to USD 443 million, accounting for approximately 3.02% of the global total, ranking 11th. The top three imports were vegetable seeds (USD 224 million), perennial ryegrass seeds (USD 47 million), and herbal flower seeds (USD 39 million). China has a seed trade deficit of USD 236 million. By comparing import and export data, it was shown that the Netherlands, the United States, France, Germany, Italy, and Belgium are not only major seed exporters but also major seed importers, with active trade and highly open markets.

2.5 Global multinational seed companies

With the acceleration of economic globalization and market integration, competition for the market share of multinational companies in the seed industry is becoming increasingly fierce. The global market share of a country where large multinational companies in the seed industry are located reflects the country's industrial competitiveness. In 2019, four Chinese enterprises (Syngenta Group, Yuan Longping High-tech Agriculture Co., Ltd., Beidahuang Kenfeng Seed Industry Co., Ltd., and Jiangsu Provincial Agricultural Reclamation and

Development Corporation) were among the top 20 companies in terms of global sales. The top 20 companies included one in the United States (Corteva Agriscience), three in Germany (Bayer AG, BASF SE, and KWS Group), four in the Netherlands (Rijk Zwaan, Enza Zaden, Bejo, and Barenbrug Group), four in France (Limagrain Group, Florimond Desprez, RAGT Semences, and Euralis Group), two in Japan (Sakata Seed Corporation and Takii & Co., Ltd.), and one in India (Advanta Seeds). Bayer AG and Corteva Agriscience have always been the front-runners in the seed industry, with their total sales accounting for 60% of the total sales of the top 20 companies, which have obvious advantages in transgene technology, gene editing technology, and digital agriculture. The Syngenta Group, BASF SE, Limagrain Group, and KWS Group constitute the second tier, with total sales accounting for approximately 24% of the total sales of the top 20 companies. Although the remaining 14 companies only account for 16% of the sales [35], they own distinctive businesses, such as the grass and lawn grass seed business of DLF and Barenbrug, the vegetable seed business of Sakata Seed Corporation and Rijk Zwaan, the flower seed business of Takii & Co., Ltd., the rice seed business of Yuan Longping High-tech Agriculture Co., Ltd., and the wheat seed business of Jiangsu Provincial Agricultural Reclamation and Development Corporation, are the backbones of the global seed industry. A new pattern of "two super companies, four strong companies, and differentiated development" has been formed in the global seed industry (Table 4).

Table 3. Top 11 seed importers in 2019.

Rank	Country	Imported volume ($\times 10^8$ t)	Imported amount (USD 100 million)
1	Netherlands	8.01	10.94
2	Pakistan	21.00	9.21
3	United States	5.59	8.78
4	Germany	3.21	7.39
5	France	1.90	6.86
6	Italy	7.09	6.06
7	Nigeria	2.85	5.96
8	Malaysia	22.74	5.93
9	Belgium	17.34	5.74
10	Spain	3.67	5.62
11	China	0.94	4.43

Note: The data are sourced from the UN Comtrade Database.

Table 4. Sales of the top 20 companies in 2019.

Rank	Company	Country	Sales (USD 1 million)
1	Bayer AG	Germany	10 667
2	Corteva Agriscience	United States	7590
3	Syngenta Group	China	3083
4	BASF SE	Germany	1619
5	Limagrain Group	France	1491
6	KWS Group	Germany	1263
7	DLF Seeds Ltd.	Denmark	779
8	Sakata Seed Corporation	Japan	587
9	Takii & Co., Ltd.	Japan	484
10	Yuan Longping High-tech Agriculture Co., Ltd.	China	450
11	Rijk Zwaan	Netherlands	440
12	Enza Zaden	Netherlands	379.4
13	Florimond Desprez	France	357
14	Bejo	Netherlands	327.9
15	Barenbrug Group	Netherlands	263
16	RAGT Semences	France	239
17	Euralis Group	France	233
18	Advanta Seeds	India	231
19	Beidahuang Kenfeng Seed Industry Co., Ltd.	China	188
20	Jiangsu Provincial Agricultural Reclamation and Development Corporation	China	177

Note: The data are sourced from annual reports of the multinational seed companies.

DOI 10.15302/J-SSCAE-2021.04.022

2.6 Analysis on the competitiveness of international seed industry

Benchmarking against strong seed industry countries such as the United States, the Netherlands, Germany, France, Australia, the United Kingdom, Canada, Japan, and Brazil, the trade competitiveness index, business competitiveness index, and industry scale index are used as evaluation indices to analyze and evaluate the competitiveness of the international seed industry from two aspects: market and industry entities [36,37].

The trade competitiveness index represents a country's ability to participate in international market competition, and is represented by the trade competition index, revealed comparative advantage index, international market share, and market openness [38]. The business competitiveness index is represented by the share of sales of the country in which one or more of the top 20 companies belong to or if they belong to in the market value of the global seed industry, which reflects the competition strength of a country as an entity of the seed industry in the international market. The industry-scale index is represented by the share of the value of a country's seed market in the value of the global seed market, which reflects the contribution of the seeds produced in the country to the global seed industry. It eliminates the differences in international trade caused by different scales and domestic seed market demands, and also reflects the satisfaction of domestic seed market demands in the country.

The results (Table 5) show that the industry competitiveness index of China's seed industry is 0.302, ranking fifth after the United States (0.678), the Netherlands (0.466), France (0.353), and Germany (0.318), at the medium level.

Table 5. Ranking of seed industry competitiveness indexes of 10 countries.

Rank	Country	International trade competitiveness index	Business competitiveness index	Industry scale index	Industry competitiveness index
1	United States	0.416	0.560	1.000	0.678
2	Netherlands	1.000	0.104	0.112	0.466
3	France	0.598	0.171	0.199	0.353
4	Germany	0.266	1.000	0.030	0.318
5	China	0.008	0.288	0.603	0.302
6	Brazil	0.212	0.000	0.145	0.143
7	Canada	0.124	0.000	0.104	0.091
8	Japan	0.056	0.079	0.051	0.059
9	United Kingdom	0.114	0.000	0.001	0.046
10	Australia	0.066	0.000	0.000	0.026

Note: Data are calculated according to the index system established in this study.

3 Problems in China's seed industry

3.1 A low proportion of germplasm resources of foreign origins, and obviously insufficient accurate identification of germplasm resources

Developed countries collect global genetic resources as part of their national strategy. They strictly control the export of core genetic resources and focus on the collection of foreign germplasm resources. For example, the United States collected germplasm resources under different ecological conditions from many countries as early as World War I and World War II, and became the country with the largest amount and the largest number of species of germplasm resources preserved in the world [39]. Germplasm resources originating from foreign countries account for approximately 72% of the inventory in the germplasm resource pool of the United States. In contrast, although China is rich in germplasm resources, most are domestic resources. The resources originating from foreign countries only account for 24% of the inventory, which results in insufficient genetic diversity of the germplasm and a shortage of excellent and characteristic resources. Therefore, China has a disadvantaged position in the seed industry. In addition, the proportion of resources accurately identified in China was very low. Among the 5.2×10^5 preserved germplasm resources, less than 1.5×10^4 are accurately identified, and China lacks accurate identification of agronomic traits and resistance genes. Owing to a lack of identification, resources cannot be explored and utilized. In China, the utilization rate of crop germplasm resources is only 3.0% to 5.0%, and the effective utilization rate is only 2.5% to 3.0%. Therefore, it is urgent to establish a whole-chain organization system for germplasm resource utilization, gene discovery, research and development, product development, and industrial applications.

3.2 Active research and development in the field of biotechnology breeding, but lack of original innovative technology

According to the core collection search data of Web of Science, 87 830 publications were issued in the field of biotechnology breeding worldwide from 2015 to 2019, including 25 987 publications issued by the United States and 21 620 by China, ranking 1st and 2nd in the world, respectively, accounting for 29.5% and 24.6% of the total publications in the world. Therefore, the United States and China form the first group of basic research on biotechnology breeding. According to the data searched from the global patent database of Derwent Innovation, there were a total of 23 133 patent applications in the field of biological breeding technology worldwide from 2015 to 2019. The United States and China ranked 1st and 2nd in the world. The United States filed 11 849 patent applications, accounting for 51.2% of the global total, while China filed 6338 (27.28%). China is also an important technology research and development force in the field of global biological breeding technology, although there is still a gap between it and the front-runners of the industry.

Although China has an advantage in terms of research and development scale, there is still a gap between China and the United States in terms of the influence of publications. China continues to catch up in basic research. The United Kingdom, Germany, the Netherlands, Canada, Australia, and France have a small number of publications, but the influence of such publications is stronger than that of China, making them potential competitors.

In terms of technology research and development, the United States takes the lead and has strong technological research and development capabilities, with large numbers of patent applications and high-quality patents. China is technologically active and carries out frequent research and development activities, yet it has unsatisfactory overall patent quality as a technological follower. Germany and Australia are China's potential competitors with considerable competitive strengths, generally holding high-quality patents despite the small number of applications.

In general, China lacks independently innovated original technology despite its global dominance in the field of biotechnology breeding. Taking CRISPR/Cas-based gene editing technology as an example, although Chinese researchers have improved the safety and efficiency of the original gene editing technology and obtained certain independent intellectual property rights, the problems of follow-up research and development and insufficient original innovation remain in the majority. There is a problem seriously constraining the commercial application on a large scale, as the core technologies of gene editing in use originate from the United States, and the patents of such core technologies are largely held by Alderson Broaddus University and Corteva Agriscience.

3.3 Less competitive seed industry, with no scientific and technological advantages transformed into industrial strengths

The development of China's seed industry is clearly lagging behind progress in biological breeding technology. The scientific and technological advantages of biotechnology breeding are far from being transformed into industrial strengths, attributed to both the industry's own issues and the system, mechanism, and regulatory policies.

Judging from the seed industry itself, since joining the International Union for the Protection of New Varieties of Plants, China has witnessed a dramatic increase in the number of variety rights applications, which has surpassed the European Union to take the 1st place since 2017 [38]. In addition, China's number of licenses surpassed that of the United States since 2014, taking the 2nd place after the European Union. Despite the large number of varieties, their homogeneity is comparatively serious, compounded by the shortage of globally competitive products, thus discouraging the transformation of scale advantages into industrial advantages. The seed industry can only be thriving when the enterprises are technically strong. China's seed enterprises have been developing rapidly in recent years, but a large gap between them and the top international enterprises still remains. Insufficient investment in the research and development of enterprises is the main reason for weak innovation capacity. It often takes more than a decade or even decades of effort, at a high cost, before the birth of a superior crop variety. In consequence, the research and development of high-performance seeds has been the "patent" of the international giants in the seed industry. According to the annual report of Bayer AG, its research and development investment in 2020 was EUR 7.126 billion, and that of Corteva Agriscience was USD 1.142 billion. Yuan Longping High-tech Agriculture Co., Ltd., the leader of the seed industry in China, invested only CNY 411 million in research and development, significantly less than international giants.

With respect to system and mechanism, China is committed to the seed industry system reform and has issued framework documents, including the *Opinions of the State Council on Accelerating the Development of Modern Crop Seed Industry* and the *Opinions of the General Office of the State Council on Deepening the Reform of the*

DOI 10.15302/J-SSCAE-2021.04.022

Seed Industry System and Improving the Capacity of Innovation, with the aim of establishing commercial breeding systems. As talents, resources, and technologies required for seed breeding are largely limited to universities and research and development institutions, enterprises are severely incompetent in research and development and often resort to copying the development models of foreign countries, so it takes a long time before the production of desired results.

Regarding regulatory policies, the outdated regulation of genetic modification and new biotechnology also hinders the industrialization of biological breeding in China. The prevailing regulation governing the regulation of new technologies and products is the *Regulations on Administration of Agricultural Genetically Modified Organisms Safety*, issued in 2001 and revised in 2017. There are no clear provisions on whether biological products produced by new technologies, such as gene editing, are agricultural transgenic products and whether and how they should be regulated. Unclear definitions and imperfect regulations may significantly limit the use of genome editing and other new technologies in agriculture; thus, China may miss opportunities to surpass its competitors in terms of biotechnology.

4 Reflections and suggestions on the development of China's seed industry

4.1 Implementing a national germplasm resources strategy to consolidate the development foundation of the seed industry

The protection and utilization of germplasm resources should be set as a national strategy, and a national-led germplasm resource conservation system should be established. By coordinating the efforts of various sectors of society, including administrative departments, scientific research institutions, universities, and private enterprises and research institutes, China should strengthen the conservation of endangered germplasm resources and wild varieties on the one hand, and actively introduce foreign germplasm resources through industrial exchanges among seed enterprises and globalization to solve the key problem of germplasm resources by research and development innovation on the other hand. Efforts should be made to optimize operational mechanisms and administration systems, develop medium- and long-term national planning for the conservation of biological diversity, set up a special national fund to support the construction of germplasm banks and the accurate identification of germplasm resources, discover a number of high-performance germplasm and genes, and transfer the germplasm resources and results of proven technology to seed enterprises to better serve their commercial research and development.

4.2 Implementing a scientific and technological innovation strategy in the seed industry to achieve breakthroughs in original innovation

China should attach high importance to the research and development of alternative frontier technology in response to the disadvantageous situation in which agriculturally developed countries have patented key genes and superior genetic traits of germplasm resources related to gene editing technology. It is suggested to develop a special project for innovative and exploratory research on the seed industry, with financial policies appropriately favoring original and innovative research; strive to develop new gene editing systems/tools and obtain intellectual property protection to get the upper hand at seed industry development; devote greater efforts to utilize the information technology and big data in industry research and development; better the layout of high-throughput phenotyping, genomic selection breeding, and other core biological breeding technologies; and lower the dependence on imported equipment such as high-throughput accurate and efficient molecular marker detectors; minimize follow-up research and development of technologies for which foreign companies already hold core patents and waste scientific and technological resources caused by low-level redundant research.

4.3 Constructing a seed industry system with Chinese characteristics to enhance the industry competitiveness

In-depth reform of the seed industry system is suggested to implement the strategy of decoupling research institutions with enterprises and build a commercial breeding system with the least possible delay. Given the fact that the talent, resources, and technologies of China's seed industry are largely limited to scientific research institutions, and the seed enterprises are still weak in technical research and development, it is unwise to aimlessly copy foreign practices, but to build up a seed industry system with Chinese characteristics, that is, a seed industry innovation system based on industry–university–research institute innovation consortium. Considering the successful experience of the National Agricultural Science & Technology Innovation Alliance in terms of operational mechanism, the industry–university–research institute model and the main interest distribution model,

research institutions and universities with strong research strengths and a solid foundation should be selected to form an innovation consortium with leading enterprises of the seed industry; the government and enterprises should jointly fund the research and development investment at different stages with different focuses, tackle key technological problems in the seed industry, and breed and introduce new varieties of high performance to the market. Therefore, the overall competitiveness of China's crop seed industry can be improved rapidly through institutional innovation.

4.4 Strengthening the seed enterprises and promoting their role in technological innovation

As strong enterprises will bring forth a thriving industry, high-quality development of enterprises should serve as a driving force for the seed industry. First, through mergers and acquisitions, China should cultivate Chinese giants of the seed industry and pool the resources of high-end talents, advanced technologies, and research and development capacity so that the comprehensive innovation efficiency and added value of the industry may be improved on an ongoing basis, and redundant construction and overcapacity as a result of disorderly competition may be avoided. Second, since the technical threshold for seed research and development has decreased owing to the rapid development of gene editing and other emerging technologies, support for high-tech start-ups in the biological seed industry should be reasonably intensified in terms of policy, financing, and taxation, thus encouraging these enterprises to seize the initiative in the research and development of biological seed technology.

4.5 Modernizing the supervision system to transform technological advantages into industrial advantages

Product-oriented regulatory policies have a role in turning the research and development advantages of developed countries into industrial superiority. To turn China's leading-edge biotechnology into product, industrial, and competitive advantages over time, it is recommended to introduce a clear and forward-looking regulatory policy that is different from that of transgenic organisms for gene editing technology. For the industrialization of transgenic crops, under the premise of fully evaluating the safety of transgenic products and whether China is competitive enough in the international market, regulatory agencies should introduce detailed planning and supporting regulations against time, issue clear timetables to motivate research institutions and enterprises, and eliminate obstacles to the industrialization of biotechnology breeding. Thus, the development of the biological seed industry may advance after modernizing regulatory policies.

References

[1] Xinhua News Agency. Xi Jinping chaired the twentieth meeting of the Central Committee for deepening the reform, emphasizing the overall planning and guiding the construction of the new development pattern, promoting the revitalization of the seed industry, and promoting the ecological environment protection and sustainable development of the Qinghai Tibet Plateau [EB/OL]. (2021-07-09)[2021-07-20]. http://www.xinhuanet.com/2021- 07/09/c_1127640160.htm. Chinese.

[2] USDA. U.S. national plant germplasm system [EB/OL]. (2021-06-06)[2021-06-07]. https://npgsweb.ars-grin.gov/gringlobal/query/summary.

[3] Seed Industry Management Department of Ministry of Agriculture and Rural Affairs, National Agricultural Technology Extension Service Center, Science and Technology Development Center of Ministry Agriculture and Rural Affairs. Crop seed industry development report in China 2020 [M]. Beijing: China Agricultural Science and Technology Press, 2020. Chinese.

[4] The total amount of germplasm resources preserved in China exceeded 520000, ranking second in the world [J]. Agricultural Science-Technology and Information, 2021 (8): 81. Chinese.

[5] NBPGR. Status of collections at National Genebank (NGB), ICAR-NBPGR [EB/OL]. (2021-06-30)[2021-07-15]. http://www. nbpgr.ernet.in/Research_Projects/Base_Collection_in_NGB.aspx.

[6] Protection and Utilization Platform of Agricultural Germplasm Resources in Jiangsu Province. Conservation status and development direction of crop germplasm resources [EB/OL]. (2009-01-09)[2021-06-01]. http://jagis.jaas.ac.cn/CO_show.aspx?id=78&class=5. Chinese.

[7] Hao L F, Chen H Y. Interview with experts in gene editing field [J]. Chinese Journal of Biotechnology, 2021, 37(1): 342–350. Chinese.

[8] Sohu.com. Harvard scientists create new gene editing tools [EB/OL]. (2021-05-21)[2021-06-18]. https://www.sohu.com/a/464162722_120393261. Chinese.

[9] Liu C, Meng H W, Cheng Z H. Plant genome-wide selection breeding technical principle and research progress [J]. Molecular Plant Breeding, 2020, 18(16): 5335–5342. Chinese.

[10] Jiang J K. China's agricultural genome research leaps to the forefront of the world [J]. China Vegetables, 2015 (12): 24.

DOI 10.15302/J-SSCAE-2021.04.022

Chinese.

[11] The research and utilization of cucumber, tomato, cabbage and other vegetables genomics in China is at the international leading level [J]. Rural Work Communication, 2020 (24): 16. Chinese.

[12] International Service for the Acquisition of Agri-biotech Applications. Global status of commercialized biotech/gm crops in 2019 [J]. China Biotechnology, 2021, 41(1): 114–119. Chinese.

[13] Zou W N, Song M. Analysis on the development trend and competitive situation of plant gene editing technology based on patent information [J]. Journal of Agricultural Biotechnology, 2020, 28(6): 1060–1072. Chinese.

[14] Liu Q. Studies on American regulatory mechanism for GMOs [J]. Journal of Anhui Agricultural Sciences, 2014, 42(36): 12829–12832. Chinese.

[15] USDA. Secretary perdue issues USDA statement on plant breeding innovation [EB/OL]. (2018-03-28)[2021-06-01]. https://www.usda.gov/media/press-releases/2018/03/28/secretary-perdueissues-usda-statement-plant-breeding-innovation.

[16] Wang J. Yang Y P. Review on supervision current situation of new plant breeding techniques regulatory in major countries [J]. Journal of Agricultural Science and Technology, 2019, 21(5): 1–7. Chinese.

[17] USDA. Canada: Agricultural biotechnology annual [EB/OL]. (2020-02-11)[2021-06-01]. https://www.fas.usda.gov/data/canadaagricultural-biotechnology-annual-3.

[18] Zhan J T, Xu Y J, Jiang A L. Analysis and enlightenment of the supervision system of transgenic technology industry in Brazil： passive innovation of system and technology monopoly [J]. Science and Technology Management Research, 2018, 38(3): 63–68. Chinese.

[19] Nepomuceno A L, Fuganti-pagliarini R, Felipe M S S, et al. Brazilian biosafety law and the new breeding technologies [J]. Frontiers of Agricultural Science and Engineering, 2020, 7(2): 204.

[20] Yuan S, Han T F. Regulatory policy on genetically modified in Latin America [J]. Soybean Science & Technology, 2019 (4): 66–67. Chinese.

[21] Whelan A I，Lema M A. Regulatory framework for gene editing and other new breeding techniques (NBTs) in Argentina [J]. GM Crops Food, 2015, 6(4): 253–265.

[22] USDA. Chile: Agricultural biotechnology annual [EB/OL]. (2020-03-18)[2021-06-07]. https://www.fas.usda.gov/data/chileagricultural-biotechnology-annual-3.

[23] USDA. Colombia: Agricultural biotechnology annual [EB/OL]. (2020-02-11)[2021-06-07]. https://www.fas.usda.gov/data/colombia-agricultural-biotechnology-annual-5.

[24] USDA. Israel: Agricultural biotechnology annual [EB/OL]. (2020-11-23)[2021-06-07]. https://www.fas.usda.gov/data/israelagricultural-biotechnology-annual-4.

[25] USDA. Japan: Agricultural biotechnology annual [EB/OL]. (2020-04-01)[2021-06-07]. https://www.fas.usda.gov/data/japanagricultural-biotechnology-annual-5.

[26] Liu X J, Wang X J, Wang Z X. Research advances and regulation policy of CRISPR-Cas system in plants [J]. Current Biotechnology, 2021, 11(1): 1–8. Chinese.

[27] USDA. Australia: Agricultural biotechnology annual [EB/OL]. (2020-12-09)[2021-06-07]. https://www.fas.usda.gov/data/australia-agricultural-biotechnology-annual-5.

[28] USDA. India: Agricultural biotechnology annual [EB/OL]. (2020-02-11)[2021-06-07]. https://www.fas.usda.gov/data/indiaagricultural-biotechnology-annual-3.

[29] USDA. European Union: Agricultural biotechnology annual [EB/OL]. (2020-12-31)[2021-06-07]. https://www.fas.usda.gov/data/ european-union-agricultural-biotechnology-annual-0.

[30] Wang H Y, Liu X, Xue H, et al. Improve safety management and promote the development of technology and industry for gene edited crops [J]. Plant Physiology Journal, 2020, 56(11): 2317– 2328. Chinese.

[31] USDA. France: Agricultural biotechnology annual [EB/OL]. (2021-01-14)[2021-06-07]. https://www.fas.usda.gov/data/franceagricultural-biotechnology-annual-5.

[32] USDA. United Kingdom: Agricultural biotechnology annual [EB/OL]. (2020-12-22)[2021-06-07]. https://www.fas.usda.gov/data/ united-kingdom-agricultural-biotechnology-annual-5.

[33] USDA. New Zealand: Agricultural biotechnology annual [EB/OL]. (2020-12-18)[2021-06-07]. https://www.fas.usda.gov/data/ new-zealand-agricultural-biotechnology-annual-4.

[34] Kang G Z, Li G Z, Xu H X. Development and status of transgenic technology in China [J]. Modern Agricultural Science and Technology, 2017 (22): 27–29. Chinese.

[35] NOVOSEED. Top 20 of global seed industry in 2019 (4 in China) [EB/OL]. (2020-05-04)[2021-03-01]. https://mp.weixin.qq.com/s/ IOF-Xi91Y4zMfXACgq1x2w. Chinese.

[36] Wang L. Research on international competitive power of Chinese seed industry in the background of global integration [D]. Beijing: Chinese Academy of Agricultural Science (Doctoral dissertation), 2014. Chinese.

[37] Wang L, Liu L J, Song M. Analysis of international competitive ability of seed industry in China based on the market share [J]. Scientia Agricultura Sinica, 2014, 47(4): 796–805. Chinese.

[38] Zou W N. Analysis of global biotechnology breeding technology and industrial competition based on patent data mining [D]. Beijing: Chinese Academy of Agricultural Science (Master’s thesis), 2020. Chinese.

[39] Xu F H, Zhang L, He Y, et al. Learn from the experience of developed countries to strengthen the protection and utilization of germplasm resources in China [J]. Seed World, 2014 (12): 1–3. Chinese.