Managers’ attitudes toward gene-editing technology and companies’ R&D investment in gene-editing: the case of Chinese seed companies

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ABSTRACT
The Chinese government has issued a series of new policies to make it easier to industrialize gene-edited crops. However, whether technological advantages will eventually translate into industrial advantages and whether farmers will soon have access to gene-edited varieties partly depends on seed companies’ willingness to produce and sell gene-edited varieties to farmers and to invest in developing their own gene-edited varieties. This study utilizes data from a survey of 111 seed companies collected in 2019 before the implementation of new regulations. This study provides empirical evidence on whether gene-edited crops will be available to farmers. The results show that the number of companies conducting research on gene-edited crops is limited, mostly to large companies. Approximately 55% of seed companies would consider developing and selling gene-edited crops modified by SDN-1 and SDN-2 site-directed nuclease genome editing without external genetic material, whereas 46% support crops modified by SDN-3, which require gene replacement or foreign deoxyribonucleic acid (DNA) insertion and are regulated as genetically modified organisms (GMOs). The regression results show that large companies and companies with well-educated researchers are more likely to support and develop gene-editing technology. Past GM investment experience and collaboration with public institutions in gene-editing research increases the probability of company investment in gene editing R&D. These results suggest that gene-edited cultivars are more likely to be produced and sold to farmers in the future than GMOs, and that gene-edited agricultural products could have a significant market share of the seed market in the future.

1 Introduction
The last three decades have witnessed a revolution in plant genetics, such as in genetically modified (GM) and gene-editing technologies. GM technology has been considered the most important technology since the Green Revolution, and plays a significant role in sustainable production system in the agricultural sector. In 2019, the global planted area of GM crops is 190.4 million hectares, which is a 112-fold increase compared to the 1.7 million hectares planted in 1996. Brookes and Barfoot reveal that the estimated economic gain of GM products from 1996 to 2018 is $224.9 billion. However, because external deoxyribonucleic acid (DNA) in genetically engineered products is randomly inserted into recipient genomes without predetermined its exact location, some scientists believe that it may be potentially harmful to human health. Most consumers are concerned about the safety of GM foods.

The concept of “new breeding techniques” (NBTs) has emerged with the rapid development of genetic engineering techniques and DNA sequencing methods over the past 15 years. It refers to gene-editing techniques in which DNA is inserted, modified, replaced, or deleted in the genome of a living organism at a predetermined location. These new techniques include zinc fingers, transcription activator-like effector nucleases (TALENs), and the most widely used clustered regularly interspaced short palindromic repeats (CRISPR)/Cas system. Advocates of NBTs hope that some of the varieties developed by these techniques will not be considered GM products and will not require regulation of genetic modification. It is worth noting that gene-
editing technology can produce the same product as mutants obtained by conventional mutagenesis which does not require regulation as a GMO. Because the precision with which NBTs can place new DNA or surplus unwanted genes, they result in far fewer unintended mutations than current GMOs or conventional breeding.\textsuperscript{6,14,15} A body of literature indicates that the benefit of gene-editing includes increased crop yields, disease resistance, and improved climate adaptation.\textsuperscript{16–18} Gene-editing has the potential to revolutionize biotechnology as a more acceptable tool, especially in agriculture. However, whether it can be successfully translated into crops and products in agriculture ultimately depends on government regulatory policies, stakeholder acceptance, and agribusiness investment.

In response to the rapid development of agricultural biotechnology and the continuing demand by scientists for the prompt establishment of safety regulations, China’s Ministry of Agriculture and Rural Affairs initiated an official safety evaluation guideline policy regarding gene-edited crops in early 2022. Under this policy, GM-free gene-edited crops, while still subject to GMO regulations, entail simplified safety assessments for food safety and the environment compared to GM crops. This new policy complements the regulations issued in 2001 on the safety of GMOs. Notably, this new policy aims to promote the development of biological breeding technology R&D and stimulate biotechnology investment in China’s agricultural sector, making it possible for China to approve gene-edited crops.

Although the new policy provides an opportunity for the development of China’s gene-edited crop industry, whether the policy will successfully promote biological breeding R&D and whether farmers will enjoy the benefits of gene-edited crops is yet to be determined by the attitude and investment of domestic agricultural companies. They are the linkages between market demand and technological innovation and are most sensitive to changes in cutting-edge technology.\textsuperscript{19} If agricultural companies believe that the commercialization of gene-edited crops will reduce existing sales and lead to lower expected profits, they will strongly oppose the adoption of gene-edited crops and products, and will take note of R&D investments in market NBT products. Thus, it is difficult for farmers to obtain gene-edited technology-improved seeds.\textsuperscript{20–23} Therefore, a better understanding of Chinese companies’ attitudes toward the application of gene-editing technology and companies’ investments in gene-editing technologies not only helps to clarify whether farmers will soon have access to trait-improved varieties but also to elevate the discussion of biotechnology R&D and future commercialization of gene-edited crops in China.

Recent studies on attitudes toward the use of gene technology in agriculture have focused on consumers and social media. The results of these studies suggest that the public is more accepting of gene-edited food products than GM products, but both are inferior to conventional products.\textsuperscript{24–28} Studies on the attitudes of the Chinese public have mainly focused on discussions on bioethics, such as designer babies.\textsuperscript{29–32} Only Ortega et al.\textsuperscript{18} examined Chinese consumers’ attitudes toward gene-edited foods and found that, although consumers oppose the use of biotechnology in food, they are more accepting of gene-edited food. No literature has been conducted on Chinese agricultural companies’ acceptance and investment in gene-editing technology.

This study aims to examine the attitudes of Chinese seed company managers toward gene-editing technologies, how many seed companies have invested in gene-editing, and the major factors that influence attitudes and companies’ investment decisions for the following reasons. First, gene-editing technology is likely to be used industrially in crop breeding in China because of its efficiency, low cost, safety, and fewer ethical issues.\textsuperscript{33–35} China is a leading country in the use of biotechnology development and conventional plant breeding to ensure food security.\textsuperscript{36–38} Second, agribusiness managers decide whether their companies will develop or sell gene-edited improved seeds as alternatives to existing seeds. Most Chinese consumers lack knowledge and understanding of gene-editing technology and have negative perceptions of GM products in China.\textsuperscript{37,38} Managers may be influenced by this information and tend to oppose gene-editing technologies. Third, seed companies are also important technological innovators. The Chinese government hopes that a greater number of seed companies will engage in gene-editing
research and increase their investment in production and marketing. It is clear that ensuring China has strong domestic R&D capability is a prerequisite for the industrialization of gene-editing.39

Our results will offer empirical evidence regarding whether gene-edited crops will soon be available to farmers and provide new insights for the Chinese government to decide on policies for crop varieties improved by gene-editing technologies.

2 Literature Review

2.1 Stakeholders’ Attitudes toward Gene-Edited Food and Products

Several researchers have examined the factors influencing consumers’ and farmers’ perceptions of biotechnology.40,41 In general, the key determinants for consumers are trust in institutions,42 information assessment,43 perceived risks and benefits,44 perceived behavioral controls,41 quality perception45 and health effects of the product.46 For farmers, the key factors are factual sources of information on food technology47 and perceived hazards and benefits.48 The literature on managers’ biotechnology perceptions is limited.

A number of studies have demonstrated the importance of biofortified crops and have indicated that public perception and acceptance of crops with biofortified crops differ by trait. GM, gene editing, and other biotechnologies have been rapidly adopted by farmers in developing countries, and are accepted by consumers with traits such as resistance to pests and diseases,49 herbicide tolerance,50 high yield and quality,51 high nutrient content,52 and drought tolerance.53 Thus, it promises to improve worldwide food productivity, enhance food supply and affect farmers’ income and financial access to food.54,55 A study on consumer perceptions of GM bananas in Uganda showed that small farms and larger households would reduce the demand for bananas with disease resistance, but large farms and high income would increase the demand for bananas with nutritional benefits.56 Moreover, the elderly and women are less likely to purchase bananas solely for improved taste. Clear communication concerning the nutritional benefits of GM or biofortified foods has been found to increase the acceptance of such foods.41 De Steur et al.57 revealed that female rice consumers in China, are willing to pay a 33.7% premium for folic acid biofortified rice because of the health benefits.

Empirical studies have also investigated consumer perceptions of transgenic versus gene-edited products, and have concluded that consumers are more accepting of gene-edited products than transgenic products, but less accepting of gene-edited products than non-bioengineered products.58–61 Moreover, consumers advocate food labeling and traceability for transgenic products to make information transparent.62 For example, most European and Australian consumers regard GM foods as unsafe and negative.63,64 Approximately 45% of US consumers consider GM technology unsafe, and more than 80% support mandatory GM labeling policies.65 Gene-editing attitude literature on consumers and farmers found that although CRISPR foods are not commercialized in Costa Rica, 80.9% of local consumers accept gene-editing improved crops and nearly half are willing to consume gene-edited products.66 A multi-country survey showed that 56% of US consumers are willing to consume CRISPR foods, versus 51% of Australian consumers, 47% of Canadian consumers, 46% of Belgian consumers, and 30% of French consumers.68 Nearly 70% of Italian farmers have a positive attitude toward CRISPR/Cas9 rice.17 Early studies regarding Chinese public attitudes toward biotechnological food have found that over 57% of Chinese consumers accept transgenic foods for consumption. However, recent studies have documented new evidence that consumers are increasingly opposing transgenic products.67,68 For instance, Zhao et al.69 found that nearly 40% of Chinese consumers accept GM-labeled foods. The proportion of Chinese consumers willing to buy transgenic products has decreased to less than 30%.37 The latest literature shows that 45% of Chinese consumers accept that gene-edited plant products are commercialized in the market, and 36% are neutral.18 Deng et al.70 found that 66% of company managers opposed the adoption of GM crops and 61% opposed GM foods in China. Few studies have explored the attitudes of company managers in different industries toward GM technology.21,70 However, these studies failed to
investigate the attitudes of agricultural company managers toward gene-editing food.

2.2 Agricultural R&D Investment and Policies in Gene-Editing

The Chinese government has invested heavily in agricultural biotechnology to ensure that Chinese biotechnology can dominate production areas involving food security, while being able to compete with developed countries. Major funding sources for agricultural biotechnology research are the 863 Program, the 973 Program, the National Science and Technology Major Project, and other sources including funding from international programs and the National Natural Science Foundation of China. From 1986 to 2000, the “863” high-tech development program allocated a total of 1.3 billion RMB to support biotechnology. Since then, the Chinese government has implemented major projects such as the “973” development program and “GMOs breeding” to strengthen investments in biotechnology research. It should be noted that the share of government investment in biotechnology R&D from the public sector has been maintained at approximately 80%.

Since the enactment of the Seed Law in 2001, the Chinese government has proposed the establishment of a commercial breeding system led by private seed companies and has encouraged seed companies to explore the frontiers of biotechnology, such as genetic modification, gene-editing, and gene mining through some policies or regulations. These measures include the enactment of intellectual property protection laws, facilitating agricultural technology cooperation between the public sector and seed companies, increasing financial investment in seed companies that conduct R&D investments, and mergers and acquisitions of overseas competitive research institutions and companies. Studies of Chinese chemical and pesticide industry companies found that both chemical and pesticide companies in China have invested in GM technology R&D because of positive profit expectation and government policies that promote private sector R&D investment.

China has invested substantially in gene-editing research. It ranks second in the world in terms of publications and patents on genome editing technology. However, China has not yet commercialized any gene-edited crops, suggesting the need to develop specific policies and regulations for gene-edited products, a more efficient approval process, and a labeling system for gene-edited technology products. The new GMO regulatory issued in 2021 emphasizes accelerating the R&D application of advanced biological breeding parallel to regulation, which indicates the Chinese government’s determination to promote biological breeding. Subsequently, the guidelines for the safety evaluation of gene-edited crops for agricultural use introduced in 2022 further indicates that gene-editing will be a major research direction for agricultural business in the future. Whether crop varieties can be applied to agricultural production through gene-editing should be discussed in next research.

3 Materials and Methods

3.1 Conceptual Framework and Econometric Method

One of the major purposes of this study is to analyze the major factors affecting the attitudes of seed company managers regarding gene-editing technology. The choice model has been used extensively to analyze consumer attitudes toward biotech foods and producer choices for adopting GM crops. Following the modeling approach to stakeholders’ choice of GM products, we define a function to model managers’ attitudes toward gene-editing based on the random indirect utility theory proposed by Lancaster. The utility derived by the manager choosing an alternative i can be expressed as \( U_i \). The manager will choose to support gene-editing when the utility of supporting gene-editing technology is at least as great as it does not support it. It can be represented as:

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1 The references are from some government documents: “The Decision on Accelerating the Cultivation and Development of Strategic Emerging Industries” promulgated in 2010; “The Opinions of the State Council on Accelerating the Development of Modern Crop Seed Industry” promulgated in 2011; “The National Development Plan for Modern Crop Seed Industry (2012-2020)” promulgated in 2012; “The Opinions of the General Office of the State Council on Accelerating the Transformation of the Agricultural Development Mode” promulgated in 2012; and “The Essentials of Promoting the Development of Modern Seed Industry in 2020” promulgated in 2020.
\[ U(Gene\ editing; X; \varepsilon) \geq U(Anti - gene\ editing; X; \varepsilon) \]  

where \( Gene\ editing\) represents the support for gene-editing. \( X \) is a vector of related factors. The utility of a manager’s attitudes (either in favor of gene-editing or against it) is influenced by specific economic factors such as company size and company R&D investment. Then Equation (2) can be obtained:

\[ U_i = \beta_0 + \beta_1 Edu_i + \beta_2 Soe_i + \beta_3 Size_i + \beta_4 R&D_i + \beta_5 List_i + \beta_6 M&A_i + \varepsilon_i \]  

where \( U_i \) is the utility of the manager when choosing \( i \). This means that the choice of \( i \) gives them the maximum utility. Based on the results of genome modification and double-strand break (DSB) repair outcomes, gene editing technologies can be classified into three main categories.\(^2\) The corresponding choices in the survey are as follows: (1) whether they support the development and sale of gene-edited seeds; (2) whether they are willing to exploit and offer crop seeds improved by gene-editing techniques with base-pair knockout, substitution, or addition (SDN-1); (3) whether they are willing to exploit and offer crop seeds improved by gene-editing techniques with pre-designed mutations, sequence optimization, allelic substitutions and gene substitutions are derived only from the gene pool of the species (SDN-2); and (4) whether they support crop seeds improved by inserting genes from other species at the target position of the genome (SDN-3). \( Edu_i \) is the proportion of researchers with a bachelor’s degree or above, \( Soe_i \) represents a dummy variable for whether a company is state-owned, and \( Size_i \) is company size measured by its register capital. \( R&D_i \) represents the average R&D investment of the seed company during 2016–2018. \( List_i \) and \( M&A_i \) are dummy variables representing a company listed on the stock exchange and a company that experienced a merger or acquisition during the period 2016–2018, respectively. Assuming that the random disturbance terms are independently and identically distributed, the probability that the manager considers and develops crops improved by these technologies can be expressed as follows:

\[ P(Support = 1) = \frac{\exp\{\mu_i\}}{\sum_{j=0}^{1} \exp\{\mu_j\}} = \frac{\exp\{\mu(\beta_0 + \beta_1 Edu_i + \beta_2 Soe_i + \beta_3 Size_i + \beta_4 R&D_i + \beta_5 List_i + \beta_6 M&A_i)\}}{\sum_{j=0}^{1} \exp\{\mu(\beta_0 + \beta_1 Edu_i + \beta_2 Soe_i + \beta_3 Size_i + \beta_4 R&D_i + \beta_5 List_i + \beta_6 M&A_i)\}} \]  

Because seed company managers’ attitudes toward gene-editing are recorded as a binary variable in the questionnaire (1 = support, 0 = oppose), a probit model was used for econometric estimation.

The other major purpose of this study is to analyze the factors influencing seed companies’ decisions regarding gene-editing R&D investment. The profit-maximizing company will invest in R&D until the marginal cost of R&D equals the company’s expected marginal revenue, and the company makes timely adjustments based on the risk and time lag between the cost and realized benefit.\(^78\) David et al.\(^79\) proposed a conceptual framework to measure the impact of various factors on R&D investment decisions, in which the marginal rate of return is modeled as a function of technology opportunities and potential market demand, and the marginal cost of capital is modeled as a function of the company’s R&D costs. Following Pray and Fuglie\(^78\) and David et al.,\(^79\) we propose a generic formulation of a company’s biotechnology R&D activities, which can be expressed as follows:

\[ ID = F(DEM, TOP, COST, X, \beta, \varepsilon) \]  

where \( DEM \) represents the demand for technological innovation in a potential market segment or industry, indicated by the percentage of revenue from the sales.
of major food crop seeds in a company’s operating revenue (Share). Given the difficulty of industrializing major GM food crops in the short term, the increased revenue of a company’s major food crop seeds suggests an increased potential market demand for seeds of major food crops improved by gene-editing technologies. TOP indicates a technological opportunity to generate innovation (e.g., innovations by other companies in the industry or advancements in science and technology). Companies’ experience with R&D investments in GM technology, denoted by GMi, is included. Biotechnology investment experience may influence companies’ investment decisions on biotechnology R&D. When a company has some understanding of biotechnology, it may make it easier to assess the value of new research tools such as gene editing and to generate new products using it. Dummy variables that characterize state-owned companies are also included because state-owned seed companies are usually formed from the components of government research institutions which increases their likelihood of conducting research using new technologies. COST represents the R&D cost of developing new technologies (e.g., the state of applied science and the time and cost of regulatory approval), including R&D collaboration between companies and the public sector (e.g., universities and government research institutions), which helps companies reduce the cost of searching for scientific talent and acquiring frontier knowledges and share the risks and costs to some extent, denoted by Coop. Eq. (4) can be written as:

\[
ID_i = \beta_0 + \beta_1 \text{DEM}_i + \beta_2 \text{TOP}_i + \beta_3 \text{COST}_i + \beta_4 X_i + \epsilon_i
\] (5)

where IDi represents whether the seed company invested in gene-editing R&D, with 1 indicating R&D investment, and 0 otherwise. Xi is the control variable that may influence the decision to invest in gene-editing R&D, including the company’s own characteristics, \( \beta \) is the parameter corresponding to the variable, and \( \epsilon \) is the standard error. Eq. (5) can be expressed as:

\[
ID_i = \beta_0 + \beta_1 \text{Share}_i + \beta_2 \text{Edited}_i + \beta_3 \text{GM}_i + \beta_4 \text{Coop}_i + \beta_5 \text{List}_i + \beta_6 \text{M&A}_i + \beta_7 \text{Soe}_i + \beta_8 \text{Size}_i + \epsilon_i
\] (6)

Most studies use the probit model to characterize linear probabilities because the curves of the probit model are symmetric around the 0.5 point on the y-axis. The event probability rises to a probability of 0.5 and then decreases toward an asymptote of 1. However, in extreme value events, the probability of an event tends to one faster than it tends to zero because the extreme value distribution is left-skewed.80 This property corresponds to the case of rare events, as is the case with only eight of the 111 companies conducting gene-editing research in our survey. Therefore, we use cloglog regression, which is a family of generalized linear models, but has an advantage over the probit model of being asymmetric around the y-axis inflection point 1−1/e. The probability that a seed company will invest in gene-editing R&D is expressed as follows:

\[
P(ID_i = 1) = 1 - \exp\{-\exp(\beta_0 + \beta_1 \text{Share}_i + \beta_2 \text{Edited}_i + \beta_3 \text{GM}_i + \beta_4 \text{Coop}_i + \beta_5 \text{List}_i + \beta_6 \text{M&A}_i + \beta_7 \text{Soe}_i + \beta_8 \text{Size}_i)\}
\] (7)

3.2 Data

The data used were derived from a survey of technology R&D activities conducted in 2019 for 111 seed companies in China (Table 1). The survey provided an appropriate context for this study by considering two factors. First, market concentration in the Chinese seed industry is relatively low, and a large number of seed companies are geographically dispersed. Second, unlisted companies lack formal information on biotechnology R&D, whereas listed companies rarely choose to disclose specific biotechnology R&D information. In addition to registered patents that can be observed, the biotechnology R&D progress of seed companies is difficult to capture.

The R&D activities of Chinese seed companies were assessed through a field survey that included multistage sampling (Fig. 1). First, seed companies with registered capital of not less than 10 million RMB were chosen from a nationwide sample of 5,200 companies to ensure a representative sample; then 2,000 seed companies remained after
screening, and the total seed revenue of these 2,000 companies (70.5 billion RMB) account for approximately 84% of the total market that includes 5,200 companies (83.5 billion RMB) in 2017. Secondly, companies with revenues from crop seed products such as maize, cotton, rice, and soybeans, which accounted for more than 50% of their total operating revenues, were selected to ensure that the surveyed companies were in the seed business, then there are 1,038 companies left. Thirdly, 200 companies of these 1,038 companies were randomly selected to further narrow the field. Fourthly, a stratified selection procedure was employed to randomly select 100 out of 200 companies. The 200 companies were classified into ten groups based on their total seed sales revenue, from the highest to the lowest. Ten companies were chosen randomly from the 20 companies in each group, with the remaining 10 companies serving as an alternative sample for the same group. Some companies were not available for the survey, therefore, the researchers contacted other alternative companies in the same group. Finally, 115 companies were interviewed and 4 questionnaires were excluded because significant information was missing, leaving 111 valid questionnaires.

The seed companies were surveyed through face-to-face interviews and e-mail between July 2019

Table 1. Definition and summary statistics of variables.

| Variable name | Description | Mean  | S.D.  | Min  | Max  |
|---------------|-------------|-------|-------|------|------|
| **Dependent variable** | | | | | |
| Edit_Att | The attitudes of managers toward gene-editing (Support = 1; Oppose = 0) | 0.58 | 0.50 | 0.00 | 1.00 |
| SDN-1_Att | The attitudes of managers toward SDN-1 (Support = 1; Oppose = 0) | 0.55 | 0.50 | 0.00 | 1.00 |
| SDN-2_Att | The attitudes of managers toward SDN-2 (Support = 1; Oppose = 0) | 0.35 | 0.50 | 0.00 | 1.00 |
| SDN-3_Att | The attitudes of managers toward SDN-3 (Support = 1; Oppose = 0) | 0.46 | 0.50 | 0.00 | 1.00 |
| ID | Making investment in gene-editing R&D | 0.07 | 0.26 | 0.00 | 1.00 |
| **Independent variable** | | | | | |
| AverageR&D | Company’s average annual investment in gene-editing R&D in 2016–2018 (Million RMB) | 0.09 | 0.43 | 0.00 | 2.46 |
| GM | Experience in GM R&D investment | 0.05 | 0.23 | 0.00 | 1.00 |
| Share | The proportion of total sales revenue of maize and rice in the total sales revenue of the company | 0.61 | 0.43 | 0.00 | 1.00 |
| Coop | Gene-editing R&D collaborations with universities and research institutions | 0.08 | 0.27 | 0.00 | 1.00 |
| Edu | The share of researchers with bachelor degree or above | 2.61 | 1.14 | 1.00 | 4.00 |
| a | = 0–20%; b = 20–40%; c = 40–60%; d = above60% | | | | |
| Editedu | The share of researchers who specialized in gene = editing R&D with a master's degree or above | 3.91 | 15.67 | 0.00 | 90.00 |
| **Control variables** | | | | | |
| Size | Registered capital of the company (Million RMB) | 79.25 | 160.97 | 10.00 | 1316.97 |
| Stateowned | Whether the company is state-owned | 0.13 | 0.33 | 0.00 | 1.00 |
| (Soe = 1; others = 0) | | | | | |
| List | Whether the company is listed on stock exchange | 0.09 | 0.29 | 0.00 | 1.00 |
| (Listed = 1; others = 0) | | | | | |
| M&A | Whether the company has undergone a merger and acquisition in 2016–2018 | 0.29 | 0.46 | 0.00 | 1.00 |
| (Yes = 1; No = 0) | | | | | |

Figure 1. Flow diagram of the companies surveyed in this study.
and March 2020. To interview the leading seed companies in the industry, we contacted the Ministry of Agriculture and provincial seed associations to help us conduct the survey. In this survey, respondents from 27 provinces were distributed across different regions in China. This study is the first to examine gene-editing R&D activities in Chinese seed companies and it may provide a valuable reference for understanding the investment in gene-editing R&D by Chinese seed companies.

4 Empirical Results

4.1 Seed Company Managers’ Attitudes toward Gene-Editing Technology

Since company managers might have different attitudes toward gene-edited products improved using different approaches, the attitudes toward three types of gene-editing techniques, namely SDN-1, SDN-2, and SDN-3, are collected.

Figure 2 shows the variation in managers’ attitudes across different gene-editing technologies. Most seed company managers have a positive attitude toward gene-editing technologies. Of the 111 seed companies, 58% (n = 64) of the managers are willing to adopt and sell seeds of crops improved through gene-editing, which is much higher than both the percentage of Chinese seed managers who believe that GM foods are safe (23%) and the percentage of managers (46%) willing to adopt GM crops. This is in line with the results of previous studies on stakeholders’ perceptions of transgenic and gene-edited foods, indicating that the public is more supportive of gene-edited products than GM products.

More than half the managers would consider developing and selling crop seeds modified by SDN-1 and SDN-2 without the addition of external genetic material, while less than half of the managers would consider introducing crop seeds modified by SDN-3 that requires gene replacement or foreign DNA insertion. Specifically, SDN-1 and SDN-2 receive equivalent support, accounting for 55% of the cases, followed by SDN-3 with only 46%. Namely, 61 out of 111 company managers support SDN-1 and SDN-2, while only 51 out of 111 company managers support SDN-3. There are two possible explanations for this finding. First, the biological mechanisms of SDN-1 and SDN-2 are distinct from those of SDN-3, as SDN-3 requires an entire gene as a template and results in gene replacement or foreign DNA insertion, its outcomes are comparable to transgenic and cisgenic. As seed companies’ managers know that most Chinese consumers are concerned about GM products, they would not be interested in developing and promoting the seed products developed by SDN-3, which consumers might reject. Second, most countries have more stringent regulatory requirements and scrutiny procedures for SDN-3 than SDN-1 and SDN-2, which may increase the cost of access to local and global markets for products developed by SDN-3, resulting in diminished expected revenue and less support for SDN-3 among seed company managers.

In summary, as Gao et al. revealed, communication about GM food safety among stakeholders such as officials, the scientific community, consumers, industry, and the media is not yet well-developed. There is a huge debate and concern regarding GM food safety in China, which has led

\[\text{\textsuperscript{3}}\text{For example, Argentina enacted the regulation of gene-edited crops in 2018, which prescribed SDN-1 as non-GM and SDN-3 as GM, with no regulatory standards for SDN-2. In Australia, SDN-1 is exempted from existing GMO regulations, while SDN-1 and SDN-2 are exempted in Canada. In addition, Brazil and Argentina have regulated the application of SDN-3, but not of SDN-1 and SDN-2 that involves any recombinant DNA.}\]
to overall concerns about biotechnology. The existing doubts about food biotechnology pose a significant challenge to the commercial viability of such products. However, gene-editing offers more targeted and effective modifications than other non-GM technologies and is, therefore, more precise and predictable than older transgenics that do not use gene editing to improve the efficiency of genetic engineering. A growing body of recent research suggests that crops produced by gene editing may be more acceptable to the public than those produced by techniques that introduce foreign DNA into the genome. These emerging public perceptions may drive the extent to which gene editing contributes to improved global crop and food security. Particularly, consumer concerns about the insertion of exogenous genetic material through gene editing or genetic engineering may be critical in shifting attitudes and supporting SDN-1 and SDN-2 gene-edited crops, because crops without foreign genetic material are more readily accepted by the public and less costly to regulate.

4.2 Seed Companies’ R&D Investment in Gene-Editing

The questionnaire surveyed the seed companies about how much they had invested in gene-editing technology R&D and the year when companies started to conduct gene-editing research, as well as their R&D investment in that year.

The results show that only a few seed companies with higher register capital conduct gene-editing research. As Fig. 3 shows, among the 111 seed companies, only 7.2% (n = 8) invest in gene-editing R&D, which indicates the huge market potential and technological opportunity for Chinese seed companies to invest in gene-editing technology R&D in the future. The first of the surveyed companies that started investing in gene-editing R&D was in 2013, the year Chinese scientists published the world’s first studies demonstrating CRISPR/Cas genome-editing in crop. Most companies started to invest in gene-editing technology R&D between 2013 and 2016 (Fig. 4). Their total R&D investment in gene-editing has leapt from 1 million RMB ($0.14 million) to 13.96 million RMB ($1.94 million) during 2013–2016.

Figure 5 shows the total R&D investment and researchers in gene-editing technology research from 2013 to 2018. Total R&D investment in gene-
the total number of researchers undertaking gene-editing R&D continued to increase between 2013 and 2018, from 10 to 64, a more than fivefold increase. It is worth noting that researchers undertaking gene-editing R&D are well-educated. The first company that invested in gene-editing R&D in 2013 employed 10 researchers, all of whom held a master’s degree or above. As more companies invest in gene-editing R&D, more researchers are involved, including those with a master’s degree or below. However, the percentage of those with a master’s degree or above remains above 60% in the period 2013–2018.

In general, the number of companies investing in gene editing R&D is limited. Insufficient confidence in R&D is mainly due to the expensive development costs and ambiguity and non-consistency of global regulation. Many countries, including China, have been strictly regulating GMOs, and preparing such regulatory packages has been costly, which has significantly impacted innovation and commercialization. Terazono et al. noted that the development times for GM and gene-edited crops are 13 and 5 years, and commercialization costs are $150 million and $10 million. Ams et al. suggested that the time required for gene-editing development of traits is much less than GM and the cost is reduced significantly. The new Chinese government guidelines for the safety assessment of gene-edited crops will shorten development time. This reduction in the expected cost of gene-editing is vital for crop development and competition.

### 4.3 Major Factors Affecting Seed Company Managers’ Attitudes toward Gene-Editing

Table 2 reports the results of the determinants of seed company managers’ attitudes toward gene-editing technologies. We use four different dependent variables indicating different gene-editing technology types: manager’s attitudes toward gene-editing technologies (first column) and manager’s attitudes toward SDN-1, SDN-2, and SDN-3 (second–fourth columns). We use the probit model to formulate the attitudes estimation separately.

The results in Table 2 show that the ownership of the seed company significantly affects the company manager’s general attitude toward different types of gene-editing techniques. In
Table 2. Estimation results of factors affecting seed company managers’ attitudes toward gene-editing.

| Variables | Edit_Att | SDN-1_Att | SDN-2_Att | SDN-3_Att |
|-----------|----------|-----------|-----------|-----------|
| Stateowned | −1.862*** | −1.810*** | −1.661*** | −1.515** |
|           | (0.560)  | (0.569)   | (0.516)   | (0.591)   |
| Edu       | 0.405*** | 0.408***  | 0.490***  | 0.283**   |
|           | (0.130)  | (0.129)   | (0.130)   | (0.126)   |
| Size      | 0.008**  | 0.008**   | 0.006*    | 0.009**   |
|           | (0.004)  | (0.004)   | (0.003)   | (0.004)   |
| List      | 0.865    | 0.923     | 0.382     | 1.113*    |
|           | (0.644)  | (0.647)   | (0.556)   | (0.635)   |
| M&A       | 0.143    | 0.091     | 0.238     | 0.061     |
|           | (0.318)  | (0.317)   | (0.315)   | (0.312)   |
| AverageR&D| −0.767   | −0.653    | −0.650    | −0.519    |
|           | (0.526)  | (0.518)   | (0.518)   | (0.519)   |
| Constant  | −1.153***| −1.226*** | −1.350*** | −1.296*** |
|           | (0.357)  | (0.362)   | (0.359)   | (0.364)   |
| Observations | 111     | 111       | 111       | 111       |

Note: Values within parentheses under coefficient represent standard error; ***, **, and * represent 1%, 5%, and 10% statistical significance, respectively.

particular, state-owned seed company managers are more negative toward gene-editing technology than non-state-owned company managers, and they tend not to support the three types of gene-editing technologies. This finding suggests that state-owned companies are more conservative and cautious regarding the development and sale of gene-edited seeds. This might be due to the fact that the government had not expressed strong support for gene-editing and that they must be regulated as GMOs under the regulations issued in 2001. Notably, this survey was conducted in 2019, and their attitudes may change under the new gene-editing safety evaluation.

The proportion of researchers with a bachelor’s degree or above in seed companies has a significant positive effect on managers’ attitudes toward gene-editing technologies. That is, the more the researchers with a bachelor’s degree or above, the more supportive their managers are for gene-editing technologies and the more they are in favor of all three technologies. This is probably because more educated researchers have a better understanding of the complexity of the benefits and risks associated with gene-editing, along with its promising applications, which is consistent with previous literature investigating the determinants of attitudes toward other biotechnologies.  

Company size also has a significant effect on seed company managers’ attitudes toward gene-editing and SDN-3. Specifically, managers in companies with more registered capital are more likely to support gene-editing and the other three technologies. Previous research has shown that many large companies that are often leaders in their industries intend to position themselves as leaders in gene-editing. Their proactive attitudes toward gene-editing reflect their continuous pursuit of a dominant position in the development and application of emerging gene-editing technologies to maintain profits and control.

Managers from listed companies are more supportive of SDN-3 than those from unlisted companies, perhaps because they have more experience with GMOs. Being listed also has a positive but not significant effect on SDN-1 and SDN-2. Other variables, such as recent mergers and acquisitions or a company’s R&D investment, do not contribute significantly to the manager’s propensity for gene-editing technology.

4.4 Major Factors Influencing Seed Companies’ Decision on Gene-Editing R&D Investment

Table 3 shows the estimation results of the factors driving seed companies’ decisions to invest in gene-editing R&D using the cloglog model. The first column in Table 3 shows the baseline results for control variables, such as companies’ characteristics, while the second and third columns show the effect on the baseline estimates when core variables are added. The fourth column shows the main estimates for all explanatory variables.

The estimation results indicate that the proportion of the sales revenue of maize and rice in the
total sales revenue of the company has a significant positive effect on the company’s investment in gene-editing R&D. The higher the proportional revenue of the seeds of these major crops, the more likely it is that the company will invest in gene-editing R&D. This might be because it is difficult to industrialize improved products using GM technology in China in the short term due to the lack of legal safeguards, such as the complex approval process for industrialization and the pending safety evaluation system, as well as public concerns about GM technology.88–90 Although China has approved safety certificates of the production of a few crops, such as insect-resistant rice and high-phytase maize, these crops can only be used for processing and not for production. Furthermore, according to the Administrative Measures for the Identification of Agricultural GMOs, a catalog of principles for mandatory labeling issued in 2002, crops such as soybeans and maize are subject to a strict policy of labeling GM food.33,69 Therefore, gene-edited crops that most private research work on are major food crops that might be more acceptable to consumers than GMOs.

Collaborations between seed companies, universities, and government research institutions increase the probability of seed companies conducting gene-editing R&D. This finding is in line with previous research suggesting that R&D collaboration positively affects biotechnology R&D expenditure.39 Collaboration between the public and private sectors can be effective in converting progress in basic science into commercial opportunities.91 Previous studies have suggested a silo effect in biotechnology R&D in the Chinese public sector.92 Breeding resources and technologies are mainly from universities and research institutions with an advantage in technology R&D.19,93 The top 10 institutions in China for gene-editing technology patent applications are universities and research institutions.94 Therefore, technological cooperation among universities, research institutions, and companies should be encouraged to promote the flow of germplasm resources and mature technological achievements for seed companies, to avoid duplication of research and help companies conduct commercial R&D, and accelerate the industrial application of gene-editing in agriculture.

Notably, the previous experience of seed companies with GM R&D investments is significantly and positively associated with their decision to undertake gene-editing R&D investments. This finding is consistent with previous research findings that companies with previous R&D experience are likely to undertake R&D, which is particularly relevant for seed companies because biotechnology companies are highly scientific and embedded in a science and technology-driven field.39,95 Therefore, seed

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Table 3. Estimation results of factors affecting seed companies’ gene-editing R&D investment decision.

| Variables | Model1 | Model2 | Model3 | Model4 |
|-----------|--------|--------|--------|--------|
| Share     | 1.120**| 1.541* | 1.120**| 1.541* |
|           | (0.502)| (0.822)| (0.502)| (0.822)|
| Editedu   | 0.006  | 0.005  | 0.000  | −0.004 |
|           | (0.008)| (0.008)| (0.006)| (0.006)|
| Size      | 0.013***| 0.013***| 0.020***| 0.022***|
|           | (0.004)| (0.004)| (0.004)| (0.004)|
| List      | −1.284 | −1.320 | −1.702 | −1.399 |
|           | (1.293)| (1.279)| (1.352)| (1.316)|
| M&A       | 0.343  | 0.314  | −1.570 | −2.240 |
|           | (1.859)| (1.843)| (1.606)| (1.602)|
| Stateowned| 0.496  | 0.861**| 1.046  | 2.113**|
|           | (0.393)| (0.406)| (0.810)| (0.880)|
| GM        | 0.457***| 0.441***| 0.512***| 0.582***|
|           | (0.122)| (0.128)| (0.131)| (0.126)|
| Coop      | 3.404***| 3.949***| 3.404***| 3.949***|
|           | (0.988)| (0.848)| (0.988)| (0.848)|
| _cons     | −6.358***| −7.093***| −7.414***| −8.920***|
|           | (1.612)| (1.861)| (1.492)| (1.652)|
| Observations | 111 | 111 | 111 | 111 |

Note: Values within parentheses under coefficient represent robust standard error; ***, **, and * represent 1%, 5%, and 10% statistical significance, respectively.
companies with experience in transgenic R&D are more likely to create new biotechnologies based on the strengths derived from the technological accumulation of past R&D efforts, as their managers have confidence in gene-editing technologies. In addition, gene-editing can be used to increase the production of GMOs, which also provide companies an incentive to invest in some gene-editing research.

We also found a significant positive effect of company size on gene-editing R&D investment decisions. Large companies show a greater propensity to support gene-editing and a higher probability of investing in gene-editing R&D. The Schumpeterian hypothesis proposes that large companies benefit from greater economies of scale, risk sharing, and innovation input support, therefore, they are more proactive in R&D innovation. This is especially true for small and medium-sized companies in the biotechnology field, as they cannot compete with large companies in terms of production capacity and diffusion, and R&D costs effectively limit the size of the projects in which companies can invest in R&D. As a result, larger seed companies are more engaged in gene-editing R&D investments.

Note that seed company ownership of state-owned firms is significantly and positively associated with seed companies’ decisions to invest in gene-editing R&D, which is consistent with previous findings that state-owned companies are more likely to engage in biotechnology R&D activities. This implies that Chinese state-owned seed companies may be an important source of gene-editing R&D. Although state-owned seed company managers remain prudent about gene-editing, the companies are more likely to invest in gene-editing R&D. Chinese state-owned seed companies now have research centers that previously served as government institutions, which increases the likelihood that they will develop and invest in new biotechnologies.

5 Discussion and Conclusions

Gene-editing, as a new breeding technology, shows promise for complementing transgenics and, in some cases, replacing both transgenics and conventional breeding for agricultural crop improvement. With food security as a top priority for the Chinese government, Chinese scientists having already made great progress in developing and approving gene-editing technology, and the Chinese government has identified advanced biological breeding as an important future development direction and has specifically introduced new policies for assessing the safety of gene-editing, as well as gene-editing industrialization. However, whether the technological advantages of gene-editing will eventually be converted into industrial advantages and whether farmers will have access to seeds improved through gene-editing technology partially depends on policy regulation, stakeholder attitudes, and companies’ investments. This study aims to examine the attitudes of Chinese seed company managers toward gene-editing and R&D investment in gene-editing by using survey data of 111 seed companies collected in 2019. This is the first quantitative study on R&D investments and the attitudes of agricultural companies in gene-editing technology in China.

The results show that only 7% of the companies (mainly large companies) are engaged in gene-editing research. The total R&D investments by seed companies engaged in gene-editing increase elevenfold from 2013 to 2018 (from $0.14 million to $2.01 million). Most seed company managers (58%) support the development of gene-editing technology in China. Approximately 55% of seed managers would consider developing and marketing gene-edited crop seeds that do not contain foreign genetic material, whereas 46% support the introduction of gene-edited crop seeds with foreign genes.

The regression results show that large companies and those with more well-educated researchers are more likely to support and develop gene-editing technology. Companies with a greater proportion of seed sales of major food crops (maize and rice), experience in GM R&D investments, gene-editing R&D collaborations, and state-owned companies are more likely to invest in gene-editing R&D. This suggests that large and state-owned companies are proactive in conducting research to secure a competitive advantage within emerging gene-editing technologies. Past biotechnology investment experience and public-sector collaborations in gene-editing R&D have enabled companies to accumulate R&D-related
experience and access breeding resources to facilitate their gene-editing R&D investments. Given that the consumption of GM food crops remains unpopular with consumers, companies are increasingly investing in developing genetically-edited food crops that may be more popular with consumers.

Important factors that seed companies need to consider are difference in technical processes, costs and timelines of developing transgenic or gene-edited crops. Gene-editing precision offers a more attractive R&D cost economics and a higher probability of success. It also has a faster time to market if it is not regulated as a GMO and less R&D risk. Until recently, there is little evidence that seed companies that have invested in transgenic R&D have captured satisfactory returns from these investments. Consequently, profit-oriented companies will invest in gene-editing R&D in their subsequent investment choices. Moreover, the biotechnology industry is one in which innovation is driven by a combination of scientific innovation, entrepreneurial management and experienced investment. The finding that firms with experience investing in transgenic R&D are more likely to invest in gene-editing R&D supports the argument that these firms are attempting to maximize profits. They have greater knowledge of the potential of genetic modification to improve crops and they are choosing research tools that may reduce the cost of regulations and that are most likely to be acceptable to consumers.

In summary, this study highlights the fact that Chinese seed companies view gene-editing technology as an attractive research and development tool. Most seed company managers in this study indicate that they are willing to consider breeding and selling gene-edited cultivars as soon as gene-editing technology is permitted by the government and regulations for commercialization are in place. Although the attitudes of some state-owned company managers toward gene-editing remain cautious, it has not prevented significant growth in gene-editing R&D investments by state-owned and private seed firms.

Based on the findings of this study, policymakers should consider the following policy options. First, government policies need to ensure that the regulatory system for gene-editing is science-based and that modifications of plant genomes create plants that are safe for human and animal consumption and do not create hazards for agriculture and the environment. Most scientists consider modern gene-editing which does not add foreign genetic material to be safer and countries such as Argentina and the United States exempt these crops from the regulations for GMOs. A regulatory framework that is effective in the long run for controversial and important biotechnologies needs to balance the interests and preferences of both producers and consumers. An important tradeoff is between strict regulations with considerable compliance costs and the widespread use of controversial technologies. An overly stringent and burdensome regulatory framework may result in higher costs for companies, which will limit the benefits to companies offering relatively easy-to-use technologies and restrict small agricultural production players that may be interested in obtaining improved crops.

Second, policy options are greater investments to instill public confidence in biotechnology, beginning with science education programs that emphasize the fundamentals of biotechnology. Research has shown that knowledge improves stakeholder attitudes toward gene-editing, so it is important to make gene-editing widely known to the public.

Finally, the government should promote collaboration between the public sector and seed companies to encourage them to conduct cutting-edge biotech research in important areas related to food security. This can be achieved by integrating the resources and competencies of universities, research institutions, and seed companies. Through these measures, farmers, consumers, and agribusiness will benefit from the rapid development of gene-editing technology.

This study has some limitations. First, our survey was conducted before the outbreak of the COVID-19 pandemic. In general, the attitude of company managers toward gene-editing technology and biological research may have changed. In addition, the investment of seed companies in gene-editing technology may have changed in response to high food prices and fluctuations in prices in the agricultural supply chains due to the pandemic and increased occurrences of extreme climate events. In addition, the new policy on safety assessment of agricultural
gene-edited plants in China may have changed attitudes and investments. Nevertheless, this research provides guidance on how industry responds to the technological opportunities that gene-editing presents. It may also provide guidance on how other related industries, especially, livestock producers, food manufacturing, and medical firms will respond, as well as guidance on the policy options that might be suitable to stimulate their use of biotechnology. Future research could focus on the impact of new regulations on gene-editing and genetic engineering on seed firm research and innovation as well as their response to price and health shocks.

Acknowledgments

This work was supported by the National Natural Science Foundation of China under Grant [72003012], the National Natural Science Foundation of China under Grant [71661147002].

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the National Natural Science Foundation of China [72003012]; National Natural Science Foundation of China [71661147002].

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