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Comprehensive evaluation of new sorghum varieties and their light-simple and efficient production technology: a case study of Ji Niang No. 2

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The revitalization of the seed industry is of increasing significance in ensuring food security and promoting the high-quality development of modern agriculture. A series of superior sorghum varieties have been cultivated in China with the support of the National Technical System of Millet & Sorghum Industry to promote the high-quality development of the sorghum industry. In this paper, Ji Niang No. 2, the major achievement of the National Technical System of Millet & Sorghum Industry, is taken as the research object. Based on the field survey data in North China in 2023, STEM systematic evaluation method was adopted to evaluate Ji Niang No.2 and its supporting planting technology comprehensively. The results show that the comprehensive score of Ji Niang No. 2 and its supporting light-simple and efficient production technology is 85 points which accounts for 85%, making the whole promotion feasible. Specifically, it is scientifically feasible, due to its significant increase of planting area during a long promotion period, all-round and multi-level project support, excellent achievement accumulation. It is technically feasible because of its remarkable demonstration performance. It is economically feasible because of its remarkable effect of yield increase, revenue increase, water saving and fertilizer saving. It is feasible in terms of model both farmers and agricultural management departments give a high evaluation to Ji Niang No. 2 planting mode. Based on these findings, recommendations are proposed to support government policy formulation, benefiting not only China's sorghum industry but also expanding to other countries worldwide.

KEYWORDS

sorghum, Ji Niang No. 2, production technology, STEM system, comprehensive benefit, comprehensive evaluation

1 Introduction

Sorghum, the world's fifth largest crop (Mundia et al., 2019), is widely utilized in brewing, feed, food, and sugar industries (Bakari et al., 2023), showcasing significant development potential (Liu et al., 2019). Currently, sorghum is primarily cultivated in tropical, subtropical and temperate regions of Asia, Africa, Americas and Europe. In the last decade, the global sorghum area harvested as a whole has shown a trend of first decline and then stable fluctuation. As shown in Figure 1, the global sorghum area harvested dropped from 44.66 million hectares in 2014 to the lowest value of 39.26 million hectares in 2019, and then remained fluctuating at the level of 39.8-41.3 million hectares. Although China's sorghum planting area is only about 700,000 hectares, accounting for a relatively small proportion of the world's sorghum planting area, China's sorghum per unit yield is relatively high, reaching 4818.2kg/hectare, compared with main sorghum production countries such as Sudan, Nigeria, India, Niger, Burkina Faso, America, Ethiopia, Mali, Mexico, etc.

Sorghum has been cultivated for thousands of years in China, predominantly in the Northeast, North China, and Southwest regions, covering 80% of the country's planting area (Jiang et al., 2024). With the improvement of the quality of life and the change of consumption concepts, the edible status of sorghum has gradually been marginalized (Singh et al., 2024), and sorghum has gradually withdraw from the status of staple food and become a minor crop. However, since 2011, driven by the development of the liquor industry, China's sorghum area harvested have shown an overall fluctuating growth trend, and it has increased from 453.6 thousand hectares in 2011 to 733.0 thousand hectares in 2023. The development of sorghum industry has therefore attracted more attention from researchers (Sawatzky, 2024; Yan et al., 2018; Rocha et al., 2023).

In recent years, in order to avoid competing with the main crop[1], sorghum, as a drought-tolerant and barren-tolerant minor cereals, is widely planted on marginal land such as arid land and saline-alkali land (Porcuna-Ferrer et al., 2024; Martínez and Andree, 2024). Factors such as low production efficiency and backward management measures have become the key problems restricting the development of sorghum industry (Zou, 2023; Shu et al., 2020). To solve the key problems, different studies were done by specialist all over the world. On the one hand, some specialists conduct research from the perspective of breeding. For example, Okot et al. (2022) collected data from 210 farmers across seven districts in Sierra Leone in 2019 and analyzed the sorghum production constraints and farmers' preferred sorghum traits to guide breeding in Sierra Leone. One the other hand, more specialists conduct research from the perspective of cultivation. Abit (2010) evaluated the differential response of grain sorghum hybrids to application of mesotrione and quizalofop at various rates and application timings and determine the physiology of tolerance of grain sorghum hybrids to mesotrione. Lee et al. (2019) studied the suitable sowing and harvesting dates of sorghum in the mountain of Yeongnam, South Korea. Affoh et al. (2023) explored the effect of meteorological factors such as rainfall, temperature, sunshine, wind speed, and relative humidity on the yield of sorghum.

In China, under the supporting of China's National Technical System of Millet & Sorghum Industry in recent years, a number of sorghum varieties with dwarfed, high quality, earlier maturation period characteristics has been breeded, and it also matches a series

1 For different countries, the main crop refers to different crops. For example, in China, it mainly refers to rice, wheat, corn, soybean, which occupy an absolutely important position in China's agricultural production to ensure the national food security.

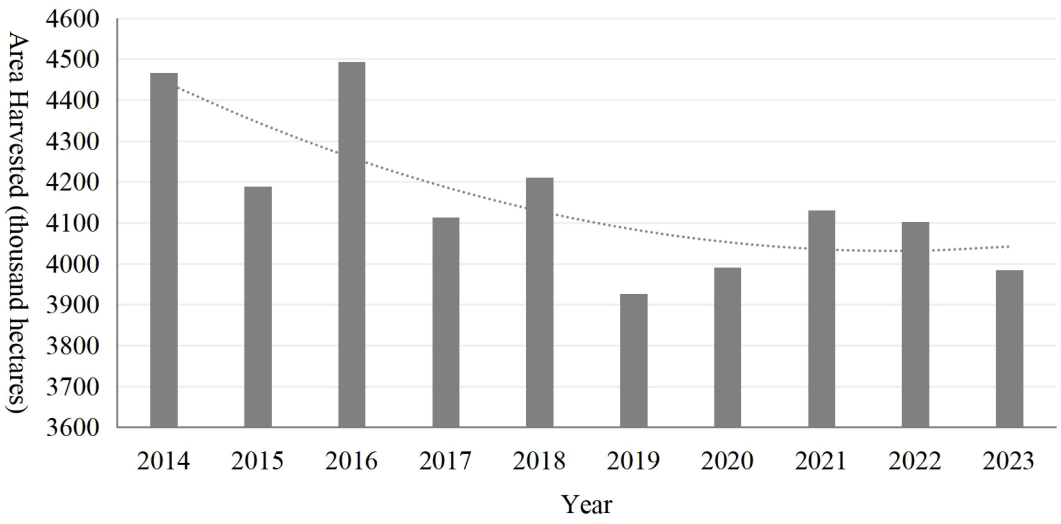

FIGURE 1
Global sorghum area harvested from 2014 to 2023. Data source: FAO Stat.

of cultivation technology for demonstration to improve its promotion effect. Among them, Ji Niang No. 2 is one of high-quality sorghum varieties cultivated by China's National Technical System of Millet & Sorghum Industry. Its excellent qualities such as aphid resistance, lodging resistance, good yield, strong adaptability, high starch content, glutinous, etc. and its matching simple and efficiency cultivation technology makes it achieve high yield and stable production, widely been recognized by growers and distillery. Its planting area has reached more than 187.00 thousand hectares. Therefore, it is meaningful to analyze and evaluate the comprehensive benefits of Ji Niang No.2, in order to promote the further development of sorghum breeding and planting technology and provide technical support for the high-quality development of sorghum industry.

However, existing research on sorghum development mainly focuses on cultivation techniques, brewing, and other individual aspects. Jeong and Shim (2016) evaluated the effect of green manure on the chemical properties of topsoil and sorghum yield, finding that sorghum cultivation using green manure might sequester carbon in soils. However, the yield of sorghum cultivated with green manure was not different from that cultivated with chemical fertilizers, suggesting that the mixture of hairy vetch and manure barley can be a useful chemical fertilizer alternative in sorghum cultivation. Eom et al. (2015) compared quality characteristics and physiological activities of Korean traditional wines fermented by adding puffed sorghum powder, showing that physiological activity and quality characteristics of fermented wines containing puffed sorghum powder contribute to value-added improvement of sorghum processing. Moreover, existing research on sorghum varieties mainly involves Cheongpung (Geonsik et al., 2019), Sodamchal (Kim et al., 2017), and others, whereas there is little research on the sorghum variety Ji Niang No. 2 in China.

Therefore, this paper comprehensively considers the scientificity and extension effect of subject technology, economic, ecological, and social effects of the technology, and constructs a secondary index evaluation system from four aspects: scientific feasibility, technical feasibility, economic ecological feasibility, and model feasibility, to comprehensively evaluate the green and efficient production technology of the variety of sorghum Ji Niang No. 2 based on investigation data in North China in 2023.

2 Experical design and data sources

2.1 Plant material and production technology

Ji Niang No. 2 is a sorghum hybrid variety of aphid resistant which is breeded by Hebei Branch Center of the National Sorghum Improvement Center, Millet Research Institute of Hebei Academy of Agriculture and Forestry Sciences, supporting by the National Technical System of Millet & Sorghum Industry during China's "13th five-year plan" period[2]. Its average growth period is 115 days for that sowed in spring, and that is 105 days for that sowed in summer. Its plant height is 177.7 cm, ear height is 32.7 cm, weight of grain per ear is 69.7 gram, thousand kernel weight is 24.1 gram. The total starch content of its kernels is 73.16%, the amylopection content is 95.8%, the tannin content is 1.33%, and the crude fat content is 3.89%.

The Matching production technology of Ji Niang No. 2 includes "seed coating formulations of chemical herbicide and herbicide method for sorghum fields", "pesticide free control technology for major pests", "simplified cultivation technology for spring and summer sowing sorghum", "pesticide reduction production technology for sorghum" and "sorghum green cultivation technology". The specific production technology is as follows:

Growers of Ji Niang No. 2 purchase Ji Niang No. 2 sorghum seeds to sow from the regular brand company (Hebei Fengyuan Seed Industry Co., Ltd). Before sowing, the growers make rotary tillage, harrowing and other pre-sowing preparation on the cultivated land when the soil moisture and temperature status is suitable, and the cultivated depth is 20-25cm. When sowing, sorghum accurate seeders are used to sow seeds with equidistant row of 50-60cm, sowing rate per hectare is 7.5 kg, sowing depth is 3-4cm, and applies 600kg/hectare of compound fertilizer with 20% nitrogen content, 10% phosphorus content and 10% potassium content. After sowing, in terms of water and fertilizer management, Ji Niang No. 2 no longer applies fertilizer after seeding, and relies on natural precipitation to obtain the water needed for its growth during the whole growth period. In terms of weed management, chemical weeding of metolachlor or sperimetolachlor is carried out before seedling emergence, and chemical weeding of dichloroquinolac, 2methyl4 chloride or chlorofluoropyloxyacetic acid is further carried out for land parcels with serious weeds after seedling emergence. In terms of pest management, Trichogramma biological control method is used to prevent the persecution of common corn borer, cotton bollworm and other pests on the growth of Ji Niang No. 2.

2.2 Experimental design and evaluation indicators

An effective agricultural technology evaluation system should reflect the dual characteristics of scientific research and production practice, including scientific research investment and support, technology extension and technology application, so as to evaluate the feasibility of the technology. Based on this, this paper organized 10 synchronous online structured interviews with relevant experts, enterprises and business entities in North China, the main planting area of Ji Niang No. 2. Based on the scientific research and practice characteristics of Ji Niang No. 2 and its supporting light-simple and efficient production technology, and the principles of measurability, relevance and operability in the selection of indicators, the feasibility analysis of the agricultural technology evaluation system for Ji Niang No. 2 and its supporting light-simple and efficient production technology is divided into four primary categories of feasibility—scientific, technical, economic

2 China's "13th five-year plan" period refers to the years from 2016 to 2020.

ecological, and model feasibility—each assessed across seventeen sub-indicators as shown in Table 1. This evaluation framework is referred to as the STEM system for short. This comprehensive method enabled a rigorous evaluation of the technology's compliance with scientific principles, its effectiveness demonstrated in production settings, the economic and ecological benefits relative to existing agricultural practices, and its adaptability and potential for broader implementation.

2.2.1 Scientific feasibility

This involves assessing whether the core technology adheres to scientific principles and laws. The more support of scientific and technological projects the agricultural technology obtains, the higher scientific feasibility in theory and practice it has; Longer years of demonstration and promotion, more intellectual property rights and awards at all levels indicate that it has been verified by scientific experimental methods and gain acceptance of science and technology management departments and experts. Therefore, there are five secondary indicators in scientific feasibility.

2.2.2 Technical feasibility

This involves assessing the recognition degree of the subject technology in scientific research and practice. The existing demonstration scale and users' recognition of technology reflect the effect of the main technology in production practice from an objective point of view, that is, whether it is widely recognized by growers; The level and number of on-site observation meetings and whether it is listed as the main promotion technology reflect the recognition and support of the main technology from the perspective of experts of scientific research and development and promotion and agricultural management departments. Therefore, there are five secondary indicators in technical feasibility.

2.2.3 Economic ecological feasibility

This mainly evaluates the economic and ecological benefits generated by the subject technology. Compared with the original local sorghum planting structure or technical model, the increase rate of yield and output value of Ji Niang No. 2 and its supporting production technology can effectively reflect the progress of the

TABLE 1 Evaluation index system for Ji Niang No. 2 and its light-simple efficiency production technology.

Primary Indicator	Secondary Indicator	Evaluation Criteria and Score
A. Scientific Feasibility20	A1. Number of years the main technology has been promoted	1 year (1), 2 years (2), 3 years (3), 4 years or more (4)
	A2. Whether the main technology has received project support	No funding received (0), Enterprise commissioned project (1), City-level project (2), Provincial-level project (3), National-level project (4)
	A3. Whether the main technology has obtained intellectual property	No (0), In progress (2), Yes (4)
	A4. Number of intellectual property rights obtained	1-2 (1), 3-4 (2), 5-6 (3), 7 or more (4)
	A5. Level of awards received for the main technology	None (0), City/department level awards (1), Provincial level awards (2), National level awards (4)
B. Technical Feasibility30	B1. Existing demonstration scale	No demonstration (0), Over 1,000 acres (1-4), Over 10,000 acres (5-7), Over 100,000 acres (8)
	B2. Acceptance level of surveyed technology users	Not accepted (0), Needs improvement (3), Generally accepted (5), Accepted (8)
	B3. Number of field observation sessions organized	None (0), 1-8 (2), 9-18 (3), 19-27 (4), More than 27 (5)
	B4. Level of field observation sessions organized	Organized (0), County level (2), City level (3), Provincial level (4)
	B5. Whether listed as a main push technology or included in promotion and transformation plans at various levels	Not included (0), County level (2), City level (3), Provincial level (4), National level (5)
C. Economic Ecological Feasibility30	C1. Grain yield increase effect	Negative (0), 1%-10% (2), 11%-20% (3), 21%-30% (4), Over 30% (6)
	C2. Income increase effect	Negative (0), 1%-10% (2), 11%-20% (3), 21%-30% (4), Over 30% (6)
	C3. Comparative benefit	Negative (0), 1%-10% (2), 11%-20% (3), 21%-30% (4), Over 30% (6)
	C4. Water saving effect	Negative (0), 1%-10% (2), 11%-20% (3), 21%-30% (4), Over 30% (6)
	C5. Fertilizer saving effect	Negative (0), 1%-3% (2), 4%-6% (3), 7%-9% (4), Over 10% (6)
D. Model Feasibility20	D1. Acceptance by technology users recommended to use the technology	Not accepted (0), Needs improvement (3), Generally accepted (6), Accepted (10)
	D2. Acceptance by local industry departments	Not accepted (0), Needs improvement (3), Generally accepted (6), Accepted (10)

main technology. The regional adaptability of the subject technology can be effectively reflected by comparing the increase rate of the output value with that of the alternative crop maize. The comparison of water saving and fertilizer saving with corn, an alternative crop, can effectively reflect the friendliness of the main technology to the local ecological environment. Therefore, there are five secondary indicators in economic ecological feasibility.

2.2.4 Model feasibility

This examines whether the technology is recommended by industry stakeholders, recognized by local agricultural departments, and is adaptable with promising prospects for wider dissemination. Therefore, two secondary indexes are set up from two aspects: the recognition degree of management subjects and agricultural authorities.

2.2.5 Comprehensive evaluation

The score of the four first-level indicators of scientific feasibility, technical feasibility, economic ecological feasibility and model feasibility respectively is the sum of the scores of the corresponding second-level indicators. They are expressed by the Equations 1, 2, 3 and 4 respectively. The proportion of the above each first-level indicator is the ratio between the obtaining score of the corresponding first-level indicator and the total score of the corresponding first-level indicator. They are expressed by the Equations 5–8.

$$Score_A = Score_{A1} + Score_{A2} + Score_{A3} + Score_{A4} + Score_{A5} \quad (1)$$

$$Score_B = Score_{B1} + Score_{B2} + Score_{B3} + Score_{B4} \quad (2)$$

$$Score_C = Score_{C1} + Score_{C2} + Score_{C3} + Score_{C4} + Score_{C5} \quad (3)$$

$$Score_D = Score_{D1} + Score_{D2} \quad (4)$$

$$Proportion_A = Score_A / SumScore_A \quad (5)$$

$$Proportion_B = Score_B / SumScore_B \quad (6)$$

$$Proportion_C = Score_C / SumScore_C \quad (7)$$

$$Proportion_D = Score_A / SumScore_D \quad (8)$$

The score of the comprehensive evaluation result is the sum of the scores of the four first-level indicators of scientific feasibility, technical feasibility, economic ecological feasibility and model feasibility, which is expressed by Equation 9. The Proportion of the comprehensive evaluation result is the ratio of the comprehensive evaluation result score in the total score of 100, expressed by the Equation 10. The score of each indicator is shown in Table 2.

$$Score_{comprehensive} = Score_A + Score_B + Score_C + Score_D \quad (9)$$

$$Proportion_{comprehensive} = Score_{comprehensive} / 100 \quad (10)$$

2.3 Data sources

The data in this paper is mainly from the sampling survey of farmers who plant Ji Niang No.2 in North China carried out by the industrial economic team of China's National Technical System of Millet & Sorghum Industry. The reason of choosing North China area is that it is the main promotion area of Ji Niang No.2.

The project team designed a questionnaire firstly according to the research needs, randomly selected 35 farmers for pre-investigation before the formal investigation, and modified and improved the questionnaire according to the pre-investigation results. In the formal investigation, according to the planting area distribution of Ji Niang No.2 in North China, the survey samples of farmers were randomly and proportionally selected in different provinces or municipalities of North China. The project team finally obtained the survey data of 118 farmers, including 81 farmers in Hebei Province, 21 farmers in Henan Province, 9 farmers in Shandong Province and 7 farmers in Tianjin municipality. Among these farmers, 11 farmers grew less than 3.3 hectares of Ji Niang No. 2, accounting for 9.3%; 18 farmers grew 3.3-6.7 hectares of Ji Niang No. 2, accounting for 15.3%; 87 farmers grew 6.7–20 hectares of Ji Niang No. 2, accounting for 73.7%; 2 farmers grew more than 20 hectares, accounting for 1.7%. The planting scale ratio of this survey sample is basically consistent with the actual planting scale ratio, so the survey data are representative.

At the same time, in order to make the evaluation more objective and comprehensive, 5 members of Ji Niang No.2 R&D team and 10 leaders or staffs of Hebei Fengyuan Seed Industry Co., Ltd which is the only sales company of Ji Niang No.2 seed were

TABLE 2 Overall score of Ji Niang No. 2 and its light-simple efficiency production technology.

Indicator	Score	Evaluation Result and Standards
Scientific Feasibility	20	1. Not feasible (<60%); 2. Feasible after improvement (60%-69%); 3. Generally feasible (70%-79%); 4. Feasible (≥80%)
Technical Feasibility	30	1. Not feasible (<60%); 2. Feasible after improvement (60%-69%); 3. Generally feasible (70%-79%); 4. Feasible (≥80%)
Economic Ecological Feasibility	30	1. Not feasible (<60%); 2. Feasible after improvement (60%-69%); 3. Generally feasible (70%-79%); 4. Feasible (≥80%)
Model Feasibility	20	1. Not feasible (<60%); 2. Feasible after improvement (60%-69%); 3. Generally feasible (70%-79%); 4. Feasible (≥80%)
Total	100	1. Not feasible (<60%); 2. Feasible after improvement (60%-69%); 3. Generally feasible (70%-79%); 4. Feasible (≥80%)

interviewed; 35 sorghum research experts, 50 grassroots staffs of agricultural departments and 120 growers of other sorghum varieties were randomly selected to chat and interview in the research area.

The above survey and interview data were sorted out to obtain the data required for STEM system evaluation and analysis in this paper. Among them, the scientific feasibility index data comes from the interview and supporting data of 5 members of Ji Niang No.2 R&D research team and 10 leaders or staffs of Hebei Fengyuan Seed Industry Co., Ltd. the technical feasibility index data comes from the survey data of 118 growers of Niniang No.2, interview data of 35 sorghum research experts and 10 leaders or staffs of Hebei Fengyuan Seed Industry Co., Ltd. The economic feasibility index data comes from the survey data of 118 growers of Niniang No.2. The model feasible index data comes from the survey and interview data of 118 growers of Niniang No.2, 35 sorghum research experts, 50 grassroots staffs of agricultural departments and 120 growers of other sorghum varieties.

3 Results

In this paper, STEM systematic evaluation method is adopted to analyze and evaluate the comprehensive benefits of Ji Niang No. 2 and its supporting light-simple and efficient production technology. The evaluation results are as follows.

3.1 Scientific feasibility

3.1.1 Years of promotion

According the investigation and interview, although Ji Niang No. 3 was officially registered in April 2018, it had already begun a large-scale promotion journey through the variety identification system in 2016 before the new variety registration system was implemented in the sorghum planting field in 2017. Its promotion area shows a steady increase year by year since 2016, as shown in Figure 2. The promotion area of Ji Niang No. 2 increased from 4.3 thousand hectares in 2016 to 45.3 thousands of hectares in 2023, with a compound annual growth rate of 40.0%.

Ji Niang No. 2 is favored for its stable production performance, meeting the urgent need of distilleries for a reliable supply of raw materials, making it indispensable sorghum variety for many distilleries. According to the sales data performance, it can be predicted that in the next 5–10 years, Ji Niang No. 2 will still firmly occupy a place in the sorghum market, be welcomed by the majority of growers and distilleries, and have a very considerable development potential. Therefore, it is rated to 4 points in this second-level indicator evaluation.

3.1.2 Support for research and development

According to the investigation and interview, Ji Niang No. 2 has received a number of project support in terms of variety promotion and technology demonstration, with a total funding of more than 1.5 million RMB, as shown in Table 3 (3 representative support projects are listed).

In 2019, the sub-project of National Key Research and Development Program of China “research and demonstration on efficient green cultivation technology of summer-sown sorghum” which is carried out around Ji Niang No. 2 was successfully approved, funding 0.55 million RMB. This project provides a solid guarantee for deeply exploring the planting potential of Ji Niang No. 2 in summer sowing scene and optimizing the green cultivation technology system, and helped the scientific research team to overcome many technical problems.

In 2021, in the process of promoting the transformation of agricultural scientific and technological innovation achievements of Ji Niang No. 2, the Ji Niang No. 2 R&D team (Millet Institute of Hebei Academy of Agriculture and Forestry Sciences) together with Hebei Fengyuan Seed Co., Ltd declared Agricultural Scientific and Technological Achievements Transformation Fund Project in Hebei Province “efficient seed production and pilot plant demonstration of Ji Niang No. 2 which is a aphid-resistant sorghum hybrid variety”. This project was successfully approved

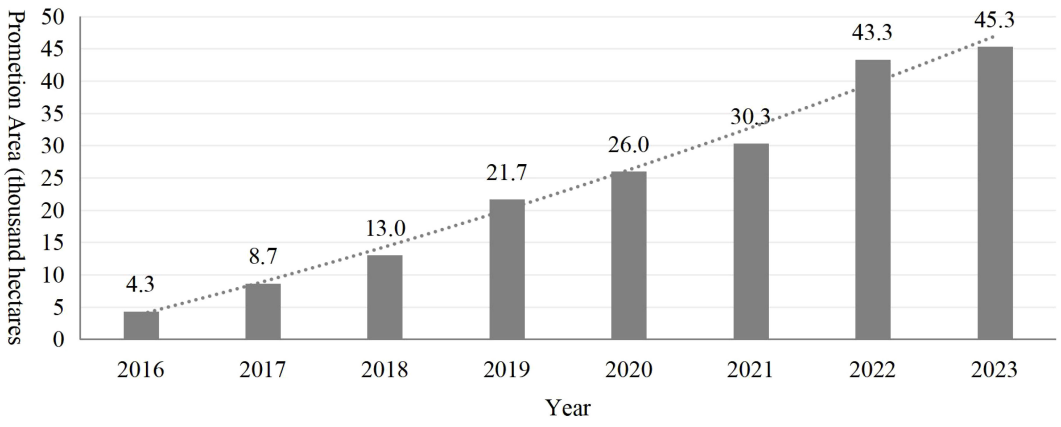

FIGURE 2
Promotion area of Ji Niang No. 2 from 2016 to 2023. Data source: Interviews with Hebei Fengyuan Seed Industry Co., LTD.

TABLE 3 Representative project support for Ji Niang No. 2.

Year	Project Type	Project Name	Project Funding
2019	Sub-project of National Key Research and Development Program of China	Research and demonstration on efficient green cultivation technology of summer-sown sorghum	0.55 million RMB
2021	Agricultural Scientific and Technological Achievements Transformation Fund Project in Hebei Province	Efficient seed production and pilot plant demonstration of Ji Niang No. 2 which is a aphid-resistant sorghum hybrid variety	0.30 million RMB
2022	Science and Technology Demonstration Pilot Project in Hebei Province	Demonstration center of Green, high-quality and efficient production technology of brewed sorghum (Fucheng County, Hengshui City, Hebei Province)	0.12 million RMB

and funded 0.3 million RMB. In addition, in order to ensure the smooth progress of the project and realize the demonstration and promotion of Ji Niang No. 2 in larger scope and deeper level, many sectors of society responded positively, supporting special funds of 0.6 million RMB to inject strong impetus into its development.

In 2022, Science and Technology Demonstration Pilot Project in Hebei Province "demonstration center of Green, high-quality and efficient production technology of brewed sorghum (Fucheng County, Hengshui City, Hebei Province)" focused on the green and high-quality production practice of Ji Niang No. 2 in the specific region Hengshui City, refined every link from planting to harvesting, and tailored demonstration samples for the planting of Ji Niang No. 2.

It is not difficult to find its all-round and multi-level development advantages by examining the obtained project support system of Ji Niang No. 2 from a macro perspective. There's National Key Research and Development Program of China which enable its technological innovation from the top-level design; there's all kinds of provincial projects, such as Achievements Transformation Funds Project, Science and Technology Demonstration Pilot Project, focusing on regional characteristics to promote the landing of the achievement of Ji Niang No. 2; there's practical measures which focus on the transformation of achievements, demonstration and promotion to ensure the scientific research achievement of Ji Niang No. 2 from the laboratory to the field, benefiting the vast number of farmers and industrial upstream and downstream. In conclusion, Ji Niang No. 2 deserves 4 points in this second-level indicator evaluation.

3.1.3 Intellectual property and recognition

In terms of agricultural scientific and technological innovation and intellectual property protection, Ji Niang No. 2 has shown outstanding achievements. According to the investigation and interview, the number of intellectual property rights related to Ji Niang No. 2 reaches 5, and they are shown in Table 4. With its profound technical heritage and extensive application value, these achievements fully demonstrate the outstanding achievements of The R&D research team and Hebei Fengyuan Seed Industry Co., Ltd, and also indicate the broad prospects of the future of Ji Niang

TABLE 4 Intellectual property rights related to Ji Niang No. 2.

Time	Type of Intellectual Property Right	Name of Intellectual Property Right	Effectiveness
Mar. 2016	Patent for invention	A breeding method for aphid resistant sorghum	This method laid a solid breeding technical foundation for the aphid resistance of Ji Niang No. 2, ensured its insect resistance in the field from the source, reduced the harm of aphids, ensured the stable yield, injecting strong impetus for the sustainable development of sorghum industry.
Apr. 2018	National registration certificate	Sorghum variety of Ji Niang No. 2	The registration of this sorghum variety has opened a new chapter in the large-scale promotion of Ji Niang No. 2.
Apr. 2019	Paper publishing	Breeding and cultivation technology of aphid-resistant waxy sorghum hybrid Ji Niang No.2	This paper systematically describes the breeding process, technical points and cultivation tips of Ji Niang No. 2, which provides a valuable knowledge sharing platform for researchers and growers and promotes the exchange and dissemination of sorghum planting technology.
Sep. 2020	Local standard of Hebei province	Technical regulation for Pesticide-free prevention and control of major pests of sorghum	The standard focuses on sorghum pest prevention and control. Relying on cutting-edge scientific research results and a large number of field practices, it provides green and scientific pest prevention and control operation guidelines for Ji Niang No. 2 and even the entire sorghum planting industry, and effectively promotes the transformation of sorghum planting into an eco-friendly model.
Apr. 2021	Patent for invention	A seed coating and a seed weeding method used for chemical weeding of sorghum fields	The invention directly addresses the problem of weeding in the sorghum planting process, and provides an efficient and environmentally friendly solution for the field management of Ji Niang No. 2 through the ingenious design of the seed coating formula and matched weeding methods, which greatly improves the planting efficiency and reduces the cost of labor and pesticides.

No. 2, providing strong support for the sustainable development of Ji Niang No. 2. Therefore, it obtaining 7 points altogether in the corresponding second-level indicators of evaluation.

3.1.4 Awards for the core technology of Ji Niang No. 2

In the journey of agricultural science and technology research and industrial promotion, focusing on many difficult problems in the development process of sorghum industry, such as the scarcity of high-quality varieties of aphid resistant and high-yield, the difficulty of accurately connecting scientific research results with market demand, and the lack of mature large-scale planting operation mechanism and service system, the results of "Breeding and application of Ji Niang Series of aphid-resistant hybrids" declared mainly by Ji Niang No. 2 and its green and efficient production technology successfully won the second prize of the Youth of Hebei Academy of Agriculture and Forestry Sciences, due to its the "last kilometer" of sorghum from the field to the market, such as the excellent quality of aphid resistance and high yield, the establishment of the first pesticide-reduction green sorghum production base, and the inoculation of a sorghum trading company which opened the "last kilometer" of sorghum from the field to the market. The award is an honor at the bureau level and is awarded 1 point in this second-level indicator evaluation in accordance with established evaluation rules.

3.2 Technical feasibility

3.2.1 Demonstrated and scale

Depending on its outstanding stable yield characteristics and excellent quality performance, Ji Niang No. 2 has been recognized by the majority of sorghum growers and has been rapidly promoted in Hebei Province, Tianjin City, Shandong Province, Henan Province and other places. Through in-depth and detailed investigation, it is known that in the past five years from 2018 to 2023, Ji Niang No. 2 has achieved excellent demonstration results in Hengshui, Xingtai and Cangzhou cities, with an accumulative demonstration area of more than 1.9 million hectare. Through the demonstration, Ji Niang No. 2 and its matched light-simple and efficient production technology quickly won high praise in the vast number of farmers. Among them, the performance of Hengshui Fucheng County and Jing County in Hengshui City is the brightest. The average annual planting scale of Ji Niang No. 2 in these two regions is stable at about 6.7 thousand hectare, which has formed a regional planting advantage and provided solid support for local agricultural efficiency and farmers' income. Based on such excellent demonstration results, this second-level indicator is awarded 8 points according to relevant evaluation criteria.

3.2.2 Acceptance among users

According to the survey data of the 118 farmers of Ji Niang No. 2, 87% of the growers believe that the sorghum variety of Ji Niang No. 2 and its efficient production technology are the main varieties and technologies for the development of the current sorghum industry, and show clearly that its production effectiveness exceeds 50 RMB/hectare. These 87% growers have a high enthusiasm for planting, and express that they shall still plant Ji Niang No. 2 in the future. However, 10% of the growers are wait-and-see and maintain a neutral attitude, thinking that there will be new varieties to promote. Therefore, this second-level indicator is worth 8 points.

3.2.3 Field observation events

From 2016 to 2023, a total of 14 sessions of variety and technology on-site observation meetings of Ji Niang No. 2 were organized, including 5 sessions above the provincial level, 8 sessions at municipal level and 1 session at county level, as shown in Table 5. Through different levels of on-site observation, the popularity of Ji Niang No. 2 has been expanded, which is of great significance for the future promotion and planting. Therefore, this item evaluation is worth 7 points.

3.2.4 Promotion programs

Among the surveyed areas, Ji Niang No. 2 has been the main sorghum variety in Hengshui City for six consecutive years from 2018 to 2023. The main varieties and technologies are the recognition of the Agricultural and Rural Bureau in Hengshui city on the varieties and technologies in the region, believing that these varieties and technologies can bring economic income to farmers. Therefore the recognition of Ji Niang No. 2 as the main variety and technology by Agricultural and Rural Bureau in Hengshui city is a high approval degree. Also, considering the high recognition in Hengshui City only, this item evaluation is worth 3 points.

3.3 Economic ecological feasibility

3.3.1 Yield increase

Compared with the original sorghum varieties, the ratio of yield increase per unit area in a technology implementation cycle was analyzed. According to the investigation of 118 growers of Ji Niang No. 2 in North China, it is found that the yield increase of farmers planting different scale of Ji Niang No. 2 is different. Therefore, here the yield increase effect of growers of different planting scale is analyzed. As shown in Table 6, growers with a planting scale of 6.7-20.0 hectares have the largest yield increase 23.0%, increased by 1470 kg/hectare; then the yield increase of the other three planting scale (less than 3.3 hectares, 3.3-6.7 hectares, more than 20.0 hectares) of growers is respectively 22.1%, 21.2% and 20.9%. Given that the yield increase of growers with a planting scale of more than 20.0 hectares comes near 21%, and their proportion of all growers is very small, only 1.7%. The score of this second-level indicator is worth 4 points.

Considering that varying environmental conditions (e.g., drought, saline soil) might affect the adaptability and yield stability of sorghum, the regional heterogeneity was analyzed. In

TABLE 5 On-site observation meetings related to Ji Niang No. 2 from 2016 to 2023.

Time	Place	The number of participants	Observation content	Level
2016.7.15	Fucheng County	23	City level	Sorghum trichogramma prevention and control technology of Ji Niang No. 2 on-site observation
2016.9.26	Fucheng County	52	City level	New sorghum variety of Ji Niang No. 2 on-site observation
2017.8.23	Fucheng County	120	Provincial level	Sorghum pesticide free production technology of Ji Niang No. 2 on-site observation
2017.8.30	Huanghua County	66	City level	New brewing sorghum variety of Ji Niang No. 2 on-site observation
2017.9.8	Huanghua County	89	Provincial level	Light-simple and efficient production technology of Ji Niang No. 2 on-site observation
2018.8.12	Ningjin County	78	Provincial level	New sorghum variety of Ji Niang No. 2 on-site observation
2018.8.28	Fucheng County	78	Provincial level	Aphid resistant sorghum variety of Ji Niang No. 2 & trichogramma pesticide free planting model on-site observation
2019.9.7	Gaocheng County	45	City level	New sorghum variety of Ji Niang No. 2 on-site observation
2021.9.3	Yuanshi County	51	City level	Sorghum production technology of Ji Niang No. 2 on-site observation
2021.9.4	Baixiang County	38	City level	New sorghum variety of Ji Niang No. 2 on-site observation
2021.9.12	Jing County	31	City level	Production technology of Ji Niang No. 2 and rape on-site observation
2022.9.9	Zhuolu County	48	County level	Sorghum variety of Ji Niang series on-site observation
2022.9.16	Xingtang County	45	City level	Sorghum mechanized production of Ji Niang No. 2 on-site observation
2023.9.13	Guangping County	120	Provincial level	Variety test promotion station of Ji Niang No. 2 on-site observation

Huanghua city, where there's mostly saline-alkali land, the average yield increase rate of Ji Niang No. 2 is 13.5%, compared with the original sorghum varieties. In Taihang Mountain with mostly drought land, the average yield increase rate is 12.8%. However, the average yield increase in other regions is 25.6%.

3.3.2 Revenue enhancement

Compared with the original sorghum variety, the increase rate of production value per unit area in a technology implementation cycle was analyzed. In the above analysis, it is pointed out that the yield increase of farmers planting different scale of Ji Niang No. 2 is different. Meanwhile, it is also found that the planting cost and sales price of Ji Niang No. 2 are not very different. So the revenue enhancement of growers of different scale is also different. From the perspective of planting scale, as shown in Table 7, the revenue enhancement of the four different planting scales (less than 3.3 hectares, 3.3-6.7 hectares, 6.7-20.0 hectares, more than 20.0 hectares) is respectively 27.6%, 26.2%, 28.4% and 26.3% respectively, which are all greater than 21%, so this item gets 4 points.

Considering that varying environmental conditions (e.g., drought, saline soil) might affect the adaptability and yield stability of sorghum, the regional heterogeneity was analyzed. In Huanghua city, where there's mostly saline-alkali land, the average revenue enhancement rate of Ji Niang No. 2 is 16.0%, compared with the original sorghum varieties. In Taihang Mountain with mostly drought land, the average revenue enhancement rate is 15.8%. However, the average yield increase in other regions is 29.3%.

3.3.3 Comparative financial advantage

Compared with its alternative crop corn, the increase rate of production value per unit area in a technology implementation cycle was analyzed. Similarly, according the investigation data, the farmers of the same planting scale have not very different revenue increase when comparing Ji Niang No. 2 with corn. From the

TABLE 6 Yield increase of Ji Niang No. 2 sorghum v.s. original sorghum.

No.	Planting Scale (hectare)	Yield of Ji Niang No. 2 (kg/hectare)	Yield of Original Sorghum (kg/hectare)	Increase (%)
1	<3.3	7530	6165	22.1
2	3.3-6.7	7620	6285	21.2
3	6.7-20.0	7875	6405	23.0
4	>20.0	7575	6266	20.9

Increase = (Yield of Ji Niang No. 2 - Yield of Original Sorghum) / Yield of Original Sorghum *100%.

TABLE 7 Revenue enhancement of Ji Niang No. 2 sorghum v.s. original sorghum.

No.	Planting Scale (hectare)	Revenue of Ji Niang No. 2 (RMB/hectare)	Revenue of Original Sorghum (RMB/hectare)	Increase (%)
1	<3.3	31440	24645	27.6
2	3.3-6.7	31800	25200	26.2
3	6.7-20.0	32925	25635	28.4
4	>20.0	31635	25131	26.3

Increase = (Revenue of Ji Niang No. 2 - Revenue of Original Sorghum) / Revenue of Original Sorghum *100%.

perspective of planting scale, As shown in Table 8, the revenue enhancement of the four different planting scales (less than 3.3 hectares, 3.3-6.7 hectares, 6.7-20.0 hectares, more than 20.0 hectares) is respectively 38.0%, 39.4%, 42.3% and 37.6% respectively, which are all significantly greater than 21% when comparing Ji Niang No. 2 with corn, so this second-level indicator is worth 6 points.

3.3.4 Water-saving effects

Compared with corn, the rate of water resource savings per unit area was analyzed. Considering transpiration efficiency, sorghum is more drought-resistant than corn, but in actual production, to ensure yield, the watering conditions for sorghum and corn are generally the same. The water-saving rate was calculated based on the proportion of households that did not water at all in relation to the total sample size. Therefore, out of the 118 surveyed Ji Niang No. 2 planting households, 31 did not water their crops, which represents 26.3% of the total sample size used to calculate the water-saving rate. This second-level indicator scores 4 points.

3.3.5 Fertilizer-saving effects

Compared with corn, the rate of fertilizer saving per unit area in a technology implementation cycle was analyzed. According the investigation of the 118 growers of Ji Niang No. 2 and local growers of corn, there seems to be some consultation between the growers of the same scale in a same place, and the fertilizer amount between them is not much different. In terms of the fertilizer saving effect of farmers of different scales, as shown in Table 9, the fertilizer saving rate of the growers with planting scale of less than 3.3 hectares is 8.9%, which is between 7% and 9%; the fertilizer saving rate of the growers with planting scale larger than 20.0 hectares is 4.9%, which is between 4% and 6%; the fertilizer saving rate of the growers with planting scale between 3.3 hectares and 6.7 hectares is respectively 16.3% and 12.8%, which are greater than 10%. The fertilizer saving rate of farmers with different planting scales are located in different scoring ranges, and further average values should be obtained. Taking the middle value of the four planting scales as the weight, the weighted average value is 10.7%, which is greater than 10%, so this second-level indicator is worth 6 points.

3.4 Model feasibility

3.4.1 Acceptance of recommended technology

Technical recommendation plays an important role in the promotion of Ji Niang No. 2. For 8 consecutive years of promotion from 2016 to 2023, the scientific research team and relevant promotion personnel spare no effort to carry out the recommendation activities of Ji Niang No. 2 and its matched planting technologies through diversified and effective forms, such as investigation, interview, discussion and consultation. Through the data collection and analysis of 506 farmers who were recommended Ji Niang No. 2 and its matched technology, it was found that approximately 83.3% of participants accepted Ji Niang No. 2, reflecting that the excellent performance of Ji Niang No. 2 in practical application has been widely recognized. It is qualified at the acceptance level according to the assessment standards. This second-level indicator scores 9 points.

3.4.2 Industry adoption

In 2023, the local agricultural management departments reported complete acceptance of Ji Niang No. 2 and its associated technologies. Underlying reasons are further analyzed. Labor saving is the most recognized reason. As high as 74% of respondents list

TABLE 8 Comparative financial advantage of Ji Niang No. 2 sorghum vs. corn.

No.	Planting Scale (hectare)	Revenue of Ji Niang No. 2 (RMB/hectare)	Revenue of Corn (RMB/hectare)	Increase (%)
1	<3.3	31440	22785	38.0
2	3.3-6.7	31800	22815	39.4
3	6.7-20.0	32925	23145	37.6
4	>20.0	31635	22995	39.3

Increase = (Revenue of Ji Niang No. 2 - Revenue of Corn) / Revenue of Corn *100%.

TABLE 9 Comparative fertilizer-saving effect of Ji Niang No. 2 sorghum vs. corn.

No.	Planting Scale (hectare)	Fertilization of Ji Niang No. 2 (kg/hectare)	Fertilization of Corn (kg/hectare)	Saving (%)
1	<3.3	615	675	8.9
2	3.3-6.7	540	645	16.3
3	6.7-20.0	510	585	12.8
4	>20.0	585	615	4.9

Saving = (Fertilization of Corn - Fertilization of Ji Niang No. 2) / Fertilization of Corn *100%.

labor saving as the reason for recognition, believing that both in weeding, fertilization and in pest prevention and control, Ji Niang No. 2 and its matched advanced planting technology makes the planting process more efficient and saves a lot of labor cost and time cost for farmers.

At the same time, production effectiveness is also undoubtedly the outstanding highlight. According to the data, 65% of the respondents choose the production effectiveness as the reason for recognition. This means that more than half of the respondents have actually witnessed the excellent performance of Ji Niang No. 2 in increasing production. Ji Niang No. 2 has brought real economic benefits to farmers, which has become the key factor of its popularity.

Meanwhile, simplicity and utility cannot be ignored. 55.9% of the respondents point out that Ji Niang No. 2 and its matched planting technologies is convenient and easy to operate, and there isn't so high technical threshold in the links of sowing, field management and harvest, greatly facilitating the majority of farmers. Especially for novice farmers who lack professional and technical knowledge, it is undoubtedly the best choice.

With such superior recognition, Ji Niang No. 2 has no doubt gained 10 points in this evaluation. These 10 points carry the authority recognition of the agricultural authorities, embody the practical praise of farmers, and inject great power into the future of Jizhong 2 in the agricultural field to expand the territory and continue to lead the sorghum planting industry, indicating its broader development prospects.

3.5 Comprehensive evaluation

Based on the analysis of each level of evaluation indicators and comparing them to target values, the scores for Ji Niang No. 2 and its supporting technologies were calculated, as shown in Table 10. According to the assessment, scores below 60% are considered infeasible; 60% to 69% are essentially feasible after improvements; 70% to 79% are basically feasible; and 80% and above are feasible. After calculations, the comprehensive score for the Ji Niang No. 2 model using light-simple and efficient production technology is shown in the Table 10.

The score of scientific feasibility is 16 points, accounting for 80%, which shows in the feasible stage; the score of technical feasibility is 26 points, accounting for 86.7%, which shows in the feasible stage; the score of economic feasibility is 24 points, accounting for 80%, which shows in the feasible stage; the score of model feasibility is 19 points, accounting for 95%, which shows in the feasible stage. Comparing the evaluation results, the comprehensive score of Ji Niang No. 2 using light-simple and efficient production technology is 85 out of 100, making the whole promotion feasible.

4 Discussion and conclusions

4.1 Conclusion

Our comprehensive assessment using the STEM system to evaluate the scientific, technical, economic ecological and model feasibility of Ji Niang No. 2 has been done. We have confirmed that Ji Niang No. 2 is a high quality sorghum variety researched by China's National Technical System of Millet & Sorghum Industry. It is of high and stable yield in various regions of China. Compared with the original sorghum varieties in the same planting place, the average increase rate of yield and production value of Ji Niang No. 2 is respectively 21.8% and 27.1%. Meanwhile, compared with its alternative crop corn in the same planting place, its average increase rate of production value is 39.3%, and its average saving rate of water and fertilizer is respectively 26.3% and 10.7%. Moreover, Ji

TABLE 10 Overall scores for Ji Niang No. 2 and its supporting technology.

Indicator	Score	Evaluation Result and Standards
Scientific Feasibility	16/20	80% 1. Not feasible 2. Feasible after improvement 3. Generally feasible 4. Feasible ✓
Technical Feasibility	26/30	86.7% 1. Not feasible 2. Feasible after improvement 3. Generally feasible 4. Feasible ✓
Economic Ecological Feasibility	24/30	80% 1. Not feasible 2. Feasible after improvement 3. Generally feasible 4. Feasible ✓
Model Feasibility	19/20	95% 1. Not feasible 2. Feasible after improvement 3. Generally feasible 4. Feasible ✓
Total	85/100	85% 1. Not feasible 2. Feasible after improvement 3. Generally feasible 4. Feasible ✓

Niang No. 2 and its light-simple and efficient production technology has been accepted by sorghum growers and agricultural management departments. For example, Ji Niang No. 2 has been the main sorghum variety in Hengshui City for six consecutive years from 2018 to 2023. The planting enthusiasm of Ji Niang No. 2 is high among sorghum growers, because about 90% of growers have expressed that they will continue to plant Ji Niang No. 2 in the future according to our survey data.

4.2 Discussion

This paper comprehensively evaluated the new sorghum variety researched in China, Ji Niang No. 2, and filled up the research gap in previous studies. As there is a lack of research on comprehensive evaluation of Chinese sorghum varieties and their supporting production technologies in previous studies.

The research and development institution of Ji Niang No. 2, Hebei Academy of Agriculture and Forestry Sciences, is located in North China. And the main promotion area of sorghum variety of Ji Niang No. 2 is mainly distributed in North China. Therefore, this paper takes North China as the research scope to conduct comprehensive evaluation. This plays an important role in the adjustment of planting structure and the strategy of rural revitalization in the North China Plain. However, Ji Niang No. 2 has wide adaptability and can adapt to a variety of natural conditions and soils, so it can be sown in major sorghum producing areas such as Northeast and Northwest China. In the future, our research team will further communicate with seed companies to discuss the promotion prospects of Ji Niang No. 2 in other regions. It will further inject great power into the future of Ji Niang No. 2 and continue to promote the development of sorghum planting industry.

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4.3 Development recommendations

The above attributes not only enhance Ji Niang No. 2’s appeal but also bolster its role in sustainable agricultural practices. Given the positive outcomes of the STEM system evaluation, the following recommendations are proposed to further elevate the impact and success of Ji Niang No. 2 sorghum:

1. Optimize Planting Techniques: Relying on the patents, technical standards of Ji Niang No. 2 and its supporting production technology, the main technology of Ji Niang No. 2 should be optimized continually and promote more efficient planting technologies, such as rational fertilization, irrigation, disease and pest control.
2. Expand Market Reach: Ji Niang No. 2 sorghum products are of high quality because it doesn’t apply chemical pesticides due to its anti-aphid characteristics and trichobia biological control of pest. It is suggested to strengthen the deep processing and development of Ji Niang No. 2 sorghum products, so as to improve its added value and market competitiveness, which is conducive to strengthening brand construction and improving the popularity and reputation of sorghum products.
3. Policy Support: As Ji Niang No. 2 has higher production value and higher efficiency than the original sorghum planting mode and corn in sorghum production area of North China, its economic benefits are significant. It is suggested that the government of areas suitable for sorghum production should increase support for the Ji Niang No. 2, such as providing financial subsidies, tax incentives, etc., to continue to reduce production costs and improve farmers’ planting enthusiasm and promote the development of sorghum industry.
4. Environmental Protection: Ji Niang No. 2 plays an important role in water saving, fertilizer saving and pesticide reduction. It is suggested that in the process of the development of the sorghum industry, the protection and sustainable development of the ecological environment should be taken as the background to strengthen the promotion of Ji Niang 2 and its supporting production technologies to reduce the use of chemical fertilizers and pesticides and prevent environmental pollution.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

ML: Conceptualization, Methodology, Validation, Writing – original draft. HL: Formal Analysis, Validation, Deep analysis, Writing – review & editing. SL: Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing. HZ: Software, Visualization, Writing – review & editing. WZ: Validation, Writing – review & editing. YZ: Investigation, Writing – review & editing. ZZ: Resources, Writing – review & editing.

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Conflict of interest

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References

Abit, M. J. M. (2010). *Grain Sorghum response to postemergence applications of mesotrione and quizalofop* . (PHD Thesis). Kansas State University, Manhattan, Kansas, USA.

Affoh, R., Zheng, H. X., Zhang, X. B., Yu, W., and Qu, C. H. (2023). Influences of meteorological factors on maize and sorghum yield in Togo, West Africa. *Land* 12 (1), 123. doi: 10.3390/land12010123

Bakari, H., Djomdi,, and Ruben, Z. F. (2023). Sorghum (Sorghum bicolor L. Moench) and its main parts (By-products) as promising sustainable sources of value-added ingredients. *Waste Biomass Valor* 14, 1023–1044. doi: 10.1007/s12649-022-01992-7

Eom, H. J., Noh, J. K., Choi, S. Y., and Soo, H. N. (2015). Quality characteristics of Korean traditional wines with puffed sorghum. *J. Korean Soc. Food Sci. Nutr.* 44, 1219–1225. doi: 10.3746/jkfn.2015.44.8.1219

Geonsik, Y., Lee, J.-W., Hwang, S.-G., Kim, I.-J., Hong, S.-T., Choe, M.-E., et al. (2019). "Cheongpung"- early maturing sorghum (Sorghum bicolar L.) variety with high yield and machine harvesting-adaptability. *Korean J. Breed. Sci.* 51, 434–439. doi: 10.9787/KJBS.2019.51.4.434

Jeong, G. H., and Shim, K. B. (2016). Effects of green manure on soil properties and grain yield of sorghum. *Korean J. Crop Sci.* 61, 290–296. doi: 10.7740/kjcs.2016.61.4.290

Jiang, Y. X., Yan, H. D., Su, D. F., Jiao, S. J., Wang, L. M., Ma, Z. J., et al. (2024). Comprehensive evaluation of nitrogen efficient utilization of sorghum hybrids. *J. Agron.* 14, 7–15. doi: 10.11923/j.issn.2095-4050.cjas2023-0079

Kim, J.-I., Choe, M.-E., Jeong, T.-U., Kim, K.-Y., Ko, J. Y., et al. (2017). Semi-dwarf grain sorghum (Sorghum bicolor L. Moench) variety 'Sodamchal' with waxy endosperm. *Korean J. Breed. Sci.* 49, 41–46. doi: 10.9787/KJBS.2017.49.1.41

Lee, H.-j., Joo, Y.-h., Lee, S.-S, Paradipta, D. H. V., Han, O.-K., Min, H.-K., et al. (2019). Effect of the sowing and harvesting dates on the agronomic characteristics and feed value of corn and sorghum×Sorghum hybrid in youngnam mountain area. *J. Korean Soc. Grassland Sci.* 39 (2), 53–60. doi: 10.5333/KGFS.2019.39.2.53

Liu, M., Lv, P., Xia, X. Y., Zhao, Y., and Shi, Z. G. (2019). Status and development trend of sorghum industry in Hebei province. *Outlook Agric.* 15, 64–75. doi: CNKI:10.3969/j.issn.1673-3908.2019.10.012

Martínez, D., and Andree, N. (2024). *Methane Cycling in Arid Soils: Methanotrophic Microbiomes and Associations With Plants* (San Diego: University of California).

Mundia, C. W., Secchi, S., Akamani, K., and Wang, G. (2019). A regional comparison of factors affecting global sorghum production: the case of North America, Asia and Africa's sahel. *Sustainability* 11, 2135. doi: 10.3390/su11072135

Okot, F., Laing, M., Shimelis, H., and de Milliano, W. A. J. (2022). Diagnostic appraisal of the sorghum farming system and breeding priorities in sierra lenone. *Sustainability* 12. doi: 10.3390/su14127025

Porcuna-Ferrer, A., Calvet-Mir, L., Faye, N. F., Klappoth, B., Reyes-García, V., and Laveyrie, V. (2024). Drought-tolerant indigenous crops decline in the face of climate change: A political agroecology account from south-eastern Senegal. *J. Rural Stud.* 105, 103163. doi: 10.1016/j.jrurstud.2023.103163

Rocha, L. D., Gadotti, G. I., and Bernardy, R. (2023). Data mining for ranking sorghum seed lots. *Rev. Cattinga* 36, 471–478. doi: 10.1590/1983-21252023v36n224rc

Sawatzky, S. (2024). *Effect of Nitrogen Rate and Timing on Forage Sorghum Production and Quality* Quality (PHD Thesis). Oklahoma State University, Stillwater, USA.

Shu, K., Kozak, M., Ben Fradj, N., Zylowski, T., and Rozakis, S. (2020). Simulation of sorghum introduction and its impacts on land use change—A case study on lubelski region of eastern Poland. *Global Change Biol. Bioenergy* 12, 252–274. doi: 10.1111/gcbb.12669

Singh, S., Ramani, K. V., and Panda, R. (2024). Millets for sustainable development in India: A social cost benefit analysis from a policy perspective. *Asia Europe J.* 22, 463–479. doi: 10.1007/s10308-024-00713-0

Yan, X., Jiang, D., Fu, J., and Hao, M. (2018). Assessment of sweet sorghum-based ethanol potential in China within the water-energy-food nexus framework. *Sustainability* 10 (4), 1046. doi: 10.3390/su10072564

Zou, J. Q. (2023). World sorghum industry analysis based on 1961–2020 FAO data. *J. Shanxi Agric. Univ. (Natural Sci. Edition)* 43, 1–10. doi: 10.13842/j.cnki.issn1671-8151.202301027