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Analysis on the Current Status and Future Prospect of Space Breeding

—Taking Space Tomatoes as an Example

Abstract: Agricultural breeding is a fundamental issue concerning the advancement and safety of modern agriculture, as well as a critical scientific and technological challenge. As a new approach to seed breeding that integrates space technology, biotechnology, and agricultural breeding technology, space breeding has already shown significant advantages and great potential in improving the quality, quantity, and availability of food. By selecting space tomatoes as a case to analyze the characteristics of space breeding in comparison with traditional seed breeding, this paper aims to promote space breeding on a larger scale, so as to better advance agricultural development and safeguard food security.
Key words: Space breeding, space tomatoes, agricultural development

"Food is the paramount necessity of the people." China has long been a major producer and consumer of agricultural products. As living standards improve, people have shifted from just having enough to eat to eating well, increasing the demand for better quality, security and diversity of food, which necessitates utilizing science and advanced technology to achieve this goal. Seed breeding is a key part of it.

Currently, with the continuous deepening of space exploration, scientists are no longer content with developing conventional seed breeding techniques. Rather, some turns their attention to studying space breeding technology. By conducting field investigations of important space breeding bases in China and distributing questionnaires on citizens' willingness to purchase space tomatoes, this paper analyzes the development status and future prospects of space breeding, expecting to help more organizations and individuals understand its importance of the agricultural industry and its role in promoting the sustainable development of crops and vegetables.

I. Overview of Space Breeding Research and Development

(1) Concept of Space Breeding

Space breeding, also known as space mutagenesis breeding, is a breeding method that utilizes comprehensive factors of extreme space environments (such as space radiation, microgravity, high vacuum, and high-energy particle radiation) to induce recombination and mutation of the genetic material DNA in plants. The beneficial mutations are then selected to cultivate new varieties of plants with high yield, high quality, and multiple resistances.

(2) Advantages of Space Breeding Compared to Traditional Breeding

Space breeding has many advantages. First, it can greatly increase the probability and degree of seed gene mutation. In the space environment, the beneficial gene mutation rate can reach 2-3%, 3 to 4 times higher than that of conventional methods. Moreover, each mutation involves a large number and a wide range of changes, compensating for the shortcomings of traditional mutagenesis. Second, space breeding can shorten the breeding cycle. In traditional seed breeding, stable variation requires 6 to 8 generations, while the variations induced by the space environment can be stabilized in the 3rd or 4th generation, shortening the breeding cycle by 3 to 4 years. Third, space breeding is highly safe. The variation produced by space environment mutagenesis occurs within the DNA, belonging to endogenous gene self-mutation improvement and hence ensuring high gene safety.

(3) Space Breeding Cultivation Process

The cultivation process of space breeding is mainly divided into four stages. In Stage 1, homozygous seeds with excellent traits are selected and sent into space with a recoverable spacecraft. In Stage 2, genetic mutations occur under the comprehensive effects of space such as high vacuum, strong cosmic rays, microgravity, and weak magnetic fields. In Stage 3, the seeds are returned to Earth, where those with beneficial traits are selected after being planted in labs. In Stage 4, the chosen seeds are sown, grown, and selected for 2 to 4 times using traditional breeding methods, allowing them to self-cross and reproduce to obtain stable genetic traits of high yield and quality. After successful trials, they are finally marketed.

(4) Current Status of Space Breeding Research and Development

The research on space breeding has a long history. Since the 1960s, countries such as the United States, the Soviet Union, Canada, Japan, Finland, Australia, and Brazil have carried out space biology research and space breeding practices. For example, the U.S. "Giant Cotton No. 1" is a high-yielding new variety of insect-resistant cotton obtained through space breeding.

China's space breeding began in the 1980s. In August 1987, China successfully sent the first batch of crop seeds and other biological materials into space through its ninth recoverable scientific experiment satellite. Since then, China has used recoverable satellites, Shenzhou spacecraft, Tiangong space laboratory, and other recoverable spacecrafts more than 40 times to carry plant seeds, cultivating over 700 high-quality, high-yield, and strong-resistant space varieties such as rice, wheat, corn, peppers, tomatoes, forage grass, alfalfa, flowers, and herbs. More than 20 provinces, municipalities, and autonomous regions in China have participated in space breeding selection, and regions such as Beijing, Gansu, and Hainan have established specialized space breeding bases. By 2023, over 300 new space breeding varieties have been approved and promoted for planting by national or provincial authorities, with an annual promotion area of over 2.668 million hectares and a total planting area of over 2.4 million hectares, generating economic benefits of over 200 billion yuan, and an increase in grain production of about 1.6 billion kilograms.

II. Application Value of Space Breeding—Taking Space Tomatoes as an Example

Tomatoes are annual herbaceous plants of the genus Solanum in the Solanaceae family, native to South America. Due to their wide adaptability, unique flavor, and high nutritional value, they are widely cultivated and have become the world's leading vegetable crop. Therefore, in 1987, when China conducted its first space experiment with crop seeds, tomatoes were sent into space as an important experimental material. Currently, several provinces in China have established space breeding bases, where new varieties of space tomatoes are being cultivated and will later be promoted in Beijing, Hebei, Inner Mongolia, Shaanxi, Shandong, Heilongjiang, and Hainan. Hence, this paper takes space tomatoes as a representative crop of space breeding, studying and analyzing the differences between space tomatoes and ordinary tomatoes in terms of botanical traits, fruit traits, resistance, and yield. Furthermore, we also investigate people's willingness to purchase space tomatoes to explore the advantages and promotion value of space breeding.

(1) Comparative Analysis of Space Tomatoes and Ordinary Tomatoes Traits

To further understand the cultivation of space tomatoes, we conducted research at Beijing Shenzhou Lvpeng Agricultural Science&Technology Co., Ltd. As a member of the China Aerospace Science and Technology Corporation, this company specializes in the research and development of space breeding technology, the selection of new varieties, and the promotion of space breeding products. According to the data, the germination rate of space tomatoes cultivated in the company’s greenhouses is generally above 95% (the national germination rate standard is above 85%), and the survival rate is about 90.25%. The greenhouse temperature is maintained at 25-30°C during the day and 18°C at night, with a light/dark cycle of 15/9 hours. The period from sowing to transplanting for space tomatoes is about 45 days, and from transplanting to fruiting is about 40 days. The time from fruit set to maturity is affected by the season, such as about 35 days in spring, and the commercial fruit harvesting period can last for 3 months.

1.Comparison of Botanical Traits and Yield of Different Tomato Varieties

Table 1 Comparison of Botanical Traits and Yield of Cherry Tomatoes

Category	Type	Ripening Phase	Growth Habit	Single Fruit Weight (g)	Yield per Plant (kg)	Hectare Yield (kg)
Space Tomato	Space Red Diamond	Mid-Early	Indeterminate	18.7	2.5	76156
	Space Green Diamond	Mid-Early	Indeterminate	22.5	2.8	86139
	Space Black Diamond	Mid-Early	Indeterminate	20.1	1.9	59970
	Hang Pink Cherry No.1	Medium	Indeterminate	26.3	3.3	89755
	Hang Red Cherry No.1	Mid-Early	Indeterminate	22.5	2.7	82247
	Hang Green Cherry No.2	Medium	Indeterminate	28.9	3.7	114028
	Hang Green Cherry No.3	Mid-late	Indeterminate	29.5	3.8	115756
Common Tomato	Feng Green	Mid-Early	Determinate	13.4	1.94	69715
	Huang Meiren	Mid-Early	Determinate	12.5	1.76	63418

Among the seven varieties of space cherry tomatoes, only the single fruit weight of "Space Red Diamond" is below 20 grams, while the other six varieties all exceed 20 grams, with "Hang Green Cherry No.3" being the heaviest. The single fruit weight of ordinary cherry tomatoes "Feng Green" and "Huang Meiren" are below 15 grams. "Hang Green Cherry No.3" has the highest per hectare yield at 115,756 kg. The yield of "Hang Green Cherry No.2" " Hang Pink Cherry No.1" and "Space Green Diamond" are also notable, all exceeding 85,000 kg, significantly higher than the two ordinary cherry tomatoes.

According to Table 1, ordinary cherry tomatoes "Feng Green" and "Huang Meiren" are determinate types, while all space cherry tomatoes are indeterminate, showing higher potential in growth.

2. Comparison of Fruit Traits of Different Tomato Varieties

Table 2 Comparison of Fruit Traits of Cherry Tomatoes

Category	Type	Shape	Color	Flavor	Firmness
Space Tomato	Space Red Diamond	Round	Bright red	Crisp & sweet	Medium
	Space Green Diamond	Round	Green	Crisp & sweet	Medium
	Space Black Diamond	Round	Purple-black	Sweet & sour	Medium
	Hang Pink Cherry No.1	Round	Pink	Sweet & sour	Good
	Hang Red Cherry No.1	Round	Bright red	Crisp & sweet	Good
	Hang Green Cherry No.2	Long oval with a tip	Green	Refreshing & sweet	Medium
	Hang Green Cherry No.3	Oval	Green	Honey flavor	Good
Common Tomato	Feng Green	Long oval	orange-yellow	Moderate sweetness	Medium
	Huang Meiren	Round	orange-yellow	Moderate sweetness	Medium

The cherry tomatoes in Table 2 have four fruit shapes: round, long oval with a tip, long oval, and oval. Regarding fruit color, there are five: bright red, green, purple-black, pink, and orange-yellow. In terms of flavor and taste, "Space Red Diamond" "Space Green Diamond" and "Hang Red Cherry No.1" have better taste, being sweet and crisp, making them more popular in the market. "Space Black Diamond" and " Hang Pink Cherry No.1" have a rich sweet and sour taste, while " Hang Green Cherry No.3" has a particularly unique taste. In contrast, "Feng Green" and "Huang Meiren" have only ordinary taste with no outstanding features.

3. Comparison of Resistance of Different Tomato Varieties

Table 3 Comparison of Resistance of Large Fruit Tomatoes

Category	Type	Disease Resistance
Space Tomato	Hang Pink No.3	Leaf mold, tobacco mosaic virus, wilt, verticillium
	Hang Pink No.4	TY, TMV, wilt, verticillium
	Hang Pink No.5	TY, TMV, grey leaf spot, wilt, verticillium
	Astronaut No. 3	Antiviral, late blight
	Astronaut No. 4	Antiviral, late blight
Common Tomato	Pink Fruit General	Wilt
	Red Star Fl	Antiviral

(Note: Resistance refers to the plant's ability to withstand adverse environments)

According to Table 3, "Hang Pink No. 3," "Hang Pink No. 4," and "Hang Pink No. 5" have more resistance types, mainly resistance to TY, TMV, wilt, and verticillium. "Astronaut No. 3" and "Astronaut No. 4" are resistant to viral diseases and late blight. The resistance levels of ordinary tomatoes "Pink Fruit General" and "Red Star F1" are relatively low.

4. Comparative Analysis of Planting Conditions of Space and Ordinary Tomatoes

(1) Comparison of Botanical Traits

From the data, space tomatoes have significantly improved in yield, regardless of single fruit weight, single plant yield, and per hectare yield, better meeting the increasing demand for tomatoes. Also, various kinds of space tomatoes mature at different times, filling the gap in the fruit market during the off-season and becoming an important alternative in fruit consumption.

(2) Comparison of Taste Quality

Space tomatoes have diverse fruit shapes, rich colors, and moderate fruit firmness. In terms of taste quality, space tomatoes are sweeter and crisper, with more juicy and flavorful characteristics. This means that when tasting space tomatoes, people can enjoy various different tastes and texture changes, increasing the satisfaction of consumption, which will attract more people in the future.

(3) Analysis of Resistance Performance

According to data analysis, space tomatoes exhibit excellent resistance. They can adapt to a wider range of environmental conditions and have stronger resistance to major diseases (such as late blight, viral diseases, TY, TMV), reducing the impact of pests and microbial diseases on space tomato plants, improving both yield and quality while also contributing to food safety.

In summary, compared to ordinary tomatoes, space tomatoes generally have higher yield, better quality, and stronger resistance, allowing them to better meet the demand for high-quality tomatoes. They have broad development prospects in the future market, thus having great promotional value and providing new ideas for agricultural production.

(II) Survey on the Willingness to Purchase Space Tomatoes

Research on space breeding aims to better serve agricultural development and practice. Therefore, to further understand the market application value of space tomatoes, this paper explores the public will to purchase space tomato products through a questionnaire survey. Using a random sampling method, the questionnaire targeted urban residents of Shijiazhuang City, Hebei Province, and was distributed via social media platforms. A total of 386 valid questionnaires were collected. The data obtained were analyzed to determine people's willingness to purchase space tomatoes and the reasons behind it. The results showed that 291 respondents, accounting for 75.39%, were willing to purchase space tomatoes, while 24.61% were not.

1.Multi-factor Analysis of Respondents Willing to Purchase Space Tomatoes

To further promote the marketing of space tomatoes, this paper assumes three influential factors: gender, age, and monthly income, and investigates which group would more be likely to purchase them.

Table 4 Intention of Groups to Buy Space Tomatoes

Factor	Gender		Age				Monthly Income (yuan)			
Group	Male	Female	≤24	25-35	36-55	≥55	2000-3000	3000-5000	5000-10000	≥10000
Proportion	75.4%	75.3%	71.4%	75.3%	78.5%	74.3%	73.2%	76%	71.8%	84.9%

The data analysis indicates that the proportion of each group willing to purchase space tomatoes is over 70%, regardless of gender, age, or monthly income. This shows that these are not factors influencing the marketing of space tomatoes, and purchasing intentions are high for each group, indicating a broad market potential for space tomatoes.

2. Multi-factor Analysis of Respondents Unwilling to Purchase Space Tomatoes

For respondents unwilling to purchase space tomatoes, two main reasons are provided: high price and concerns about food safety. Among them, 63.16% of respondents with no purchase intention are worried about food safety, while 80% believe the price is too high.

Table 5 Reasons for reluctance to buy space tomatoes

Factor	Gender		Age				Monthly Income (yuan)			
Group	Male	Female	≤24	25-35	36-55	≥55	2000-3000	3000-5000	5000-10000	≥10000
Price proportion	85.7%	75.5%	72.7%	76.9%	84%	100%	90.9%	77.8%	77.5%	87.5%
Safety proportion	64.3%	62.3%	63.6%	64.1%	56%	77.8%	27.3%	72.2%	57.5%	100%

As shown in Table 5, the proportion considering the price too high is generally higher than those concerned about food safety, especially in the group aged 55 and above. Only among those with a

monthly income above 10,000 yuan regards safety concerns as an issue of more importance.
Therefore, for most non-purchasing groups, the main reason for not purchasing space tomatoes is the high price, with secondary concerns about food safety.

3. Conclusion and Analysis

The questionnaire survey analysis found that more than three-quarters of the respondents are willing to purchase space tomatoes. This group, regardless of gender, age, or income level, shows a willingness to purchase, indicating a significant market demand and suggesting the potential for wider cultivation promotion.

At the same time, reducing the price of space tomatoes by methods such as lowering planting costs could make them acceptable to more consumers. Meanwhile, for respondents concerned about food safety and thus unwilling to purchase, increasing publicity about its safety could help alleviate public concerns.

III. Prospects and Future Development Considerations for Space Breeding

(1) Challenges Space Breeding Face

As an emerging breeding technology, space breeding has shown notable advantages in increasing the quantity, quality, and availability of food. However, it still faces several challenges. The limited carrying capacity of spacecraft and the uncertainties of the space environment restrict the scale and extent of space breeding experiments. Additionally, distinguishing different traits on a large scale is still a technological challenge, especially when it comes to identifying micro-traits. It is also hard to accurately orient how genetic mutations take place.

(2) Future Prospects of Space Breeding

The future of space breeding technology is bright and broad. With the continuous advancement of space technology and improvement on the carrying capacity of spacecrafts, the costs of space breeding are likely to lower. This will provide more possibilities for further experiments. At the same time, further development of biotechnologies, such as gene editing and synthetic biology, will assist in making space breeding more precise and accurate.

In the future, space breeding will focus more on innovation and efficiency. Instead of valuing mainly yield, traits like flavor, color, and texture would also be taken into account, suiting the needs of each individual and thus gaining more popularity in the market. Furthermore, space breeding technology can help us cultivate crop varieties with better adaptability and resistance, making them more adaptable to extreme climatic conditions, thereby ensuring the stability of global food supply.

(3) Considerations for the Future Development of Space Breeding

At present, there are still many problems yet to be solved, such as high technical difficulty, high research and development costs, insufficient promotion efforts, lack of brand effect, and a shortage of technical personnel. This paper suggests measures to be taken in the following aspects to address these issues:

1.In-depth analysis of the molecular mechanisms of space-induced mutagenesis. Making full use of space station technology and strengthening research on the mechanisms of space-induced genetic breeding will allow scientists to further understand the mutagenesis rules of different individual and combined factors. This will help improve efficiency and accuracy by achieving targeted mutagenesis

and enhancing the mutagenesis effect.
2.Increase promotion efforts. Given the current limited public understanding of space breeding, educational activities can be conducted in schools, starting from students and extending to parents, thereby deepening people's understanding of space breeding.
3.Build a space breeding brand. Enhance brand promotion and protection awareness, establish a platform for the promotion and protection of current brands, and create a highly reputable and market-recognized space breeding brand. This can help lower safety concerns and better meet the public's demand for high-quality varieties.
4.Establish inter-departmental cooperation. Establish and improve the industry-academia-research cooperation mechanism to promote close cooperation between research institutions, universities, and enterprises. Through joint research and achievement transformation, it can promote the industrial application of space breeding technology, as well as providing more technical support for agricultural production.
5.Train professional talents. Professional talents are the core force for the development of space breeding. Therefore, it is important to strengthen the construction of related disciplines, train qualified personnel, and cultivate a team of high-quality talents with knowledge in space science, biology, and agronomy. Additionally, we need to enhance worldwide cooperation while introducing excellent foreign talents and advanced technologies.

(4) Conclusion

After more than thirty years of development, the number and quality of varieties bred through space breeding in China have continuously improved, and the scope of promotion and application has expanded. Now, the industrial value is gradually being realized, with space breeding playing an important role in fields like agriculture, forestry, and microbial manufacturing.

With six key launches of the Chinese space station and the completion of the T-shaped structure of the Chinese space station, space breeding has entered the space station era. In this new stage of development, true space-induced mutagenesis breeding will be carried out with space radiation biology exposure equipment and technology. This will help to precisely design and deeply analyze the mechanisms of space-induced mutagenesis, discover more beneficial strains of significant value, and enrich the genetic diversity of seeds, providing more choices and possibilities for agricultural production and human food security.

In summary, space breeding is a burgeoning agricultural technology with broad prospects and immense potential. Although it currently faces some challenges, these issues will gradually be resolved with the continuous advancement of science and further exploration of space. In the future, the scientific research results of space breeding will gradually integrate into people's daily lives, becoming an important driving force for ensuring global food security and improving people's welfare, making an invaluable contribution to human society.

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