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Review paper

Achievements and challenges in hybrid rice breeding in Iran

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Abstract: To ensure food security for the growing population, raising the yield potential of rice remains a priority in Iran. Based on the per capita rice consumption of 35 kg and a stable rice cropping area of 650,000 hectares, the rice yield should be increased to approximately 8,000 kg per hectare. However, achieving high rice yields has become increasingly challenging. This article examines the achievements and challenges associated with hybrid rice breeding in Iran. Its aim is to analyze the current status, identify barriers and propose solutions for improving hybrid rice breeding processes. The key factors that constrain hybrid rice development are analyzed, and possible solutions to these challenges are proposed. Modern technologies in hybrid rice breeding, including gene editing (CRISPR/Cas9 technology), transgenic technology, and artificial intelligence, significantly enhance the ability to improve desirable traits such as disease resistance and grain quality. However, the effective implementation of these technologies in Iran faces multiple challenges, including the lack of a clear regulatory framework, public and social concerns, insufficient research infrastructure, and the need for investment. Ultimately, Iran's efforts in hybrid rice breeding are crucial for enhancing agricultural productivity and ensuring food security. There is a need for continuous investment in research, farmer education, and sustainable practices to strengthen the country's capacity to produce rice despite increasing challenges.

Keywords: Hybrid rice breeding, food security, cytoplasmic male sterility (CMS), *Oryza sativa*.

Introduction

Rice is one of the most important agricultural products in Iran, playing a vital role in ensuring food security and supporting farmers' livelihoods. Rice is primarily cultivated in the northern provinces, where the climate and soil conditions are favorable for rice growth. The provinces of Gilan and Mazandaran are the leading rice-producing regions (Gava et al., 2024), benefiting from abundant water resources and suitable growing environment (Zamanialaei et al., 2022). The production of rice in these areas not only supports local economies but also provides employment opportunities for thousands of farmers and agricultural workers. However, the rice sector faces several challenges, including water scarcity, climate change, and competition from imported rice. The huge surge of rice import in 2013 and 2023 (FAO, 2024) set the import records (Fig 1). Figure 1 provides crucial insights into the relationship between population growth and rice imports in Iran, highlighting the challenges faced by the country in achieving self-sufficiency in rice production and the urgent need for effective agricultural strategies to enhance domestic output. These factors pose significant risks to both production levels and the livelihoods of farmers (Zamanialaei et al., 2022). To address these challenges, efforts are being made to enhance rice breeding programs, improve water management practices, and promote sustainable agricultural techniques. By focusing on these areas, Iran aims to secure its rice production and ensure that this vital crop continues to support food security and the economy for years to come. Given the increasing demand for rice production due to population growth and the impacts of climate change (Ali et al., 2021a), improving and developing cultivation methods has become essential. In this context, hybrid rice breeding has emerged as an effective strategy for enhancing yield and improving the quality of rice (Chen et al., 2024b; Wang et al., 2024; Zheng et al., 2024).

In recent years, significant advancements have been made in hybrid rice breeding in Iran. These advancements include the identification of new hybrid varieties (Dorosti et al., 2006; Afkhami Ghadi, 2020); improvements in cultivation practices and management strategies (Modarresi, 2023), and increased awareness and training for farmers in the use of these varieties (Nematzadeh et al., 2003). However, several challenges remain that may affect the development and expansion of hybrid rice. These challenges include limitations in water resources, climate change impacts, and the need for greater investment in research and development (Afkhami Ghadi, 2020; Modarresi, 2023).

This study examine the achievements and challenges associated with hybrid rice breeding in Iran. The objective of this study is to analyze the current status, identify barriers and challenges, and propose solutions for enhancing hybrid rice breeding processes in the country. Given the importance of rice in feeding the population and promoting sustainable agricultural development, this topic requires careful consideration and thorough investigation to optimize production and productivity in this vital sector.

Iran's future demand for high yield and quality rice

To secure food for the expanding population, enhancing the yield potential of rice is a key priority in Iran (Keramat et al., 2021). Considering the per capita rice consumption of 35 kg and a consistent rice cultivation area of 650,000 hectares (Ministry of Jihad Agriculture (FAO, 2024), it is necessary to elevate rice yields to approximately 8,000 kg per hectare by 2030. However, increasing these yields has become progressively more difficult.

Iran's future demand for high-yield and high-quality rice is expected to rise significantly due to several factors:

Population growth

As the population of Iran continues to grow, the demand for staple foods (Elferink and Schierhorn, 2016), particularly rice, will increase. This requires higher production levels to ensure food security (Ponnuswamy et al., 2024).

Changing dietary preferences

With rising incomes and urbanization, there has been a shift towards higher consumption of rice and other staple foods. This trend further drives the need for improved rice varieties that meet quality expectations.

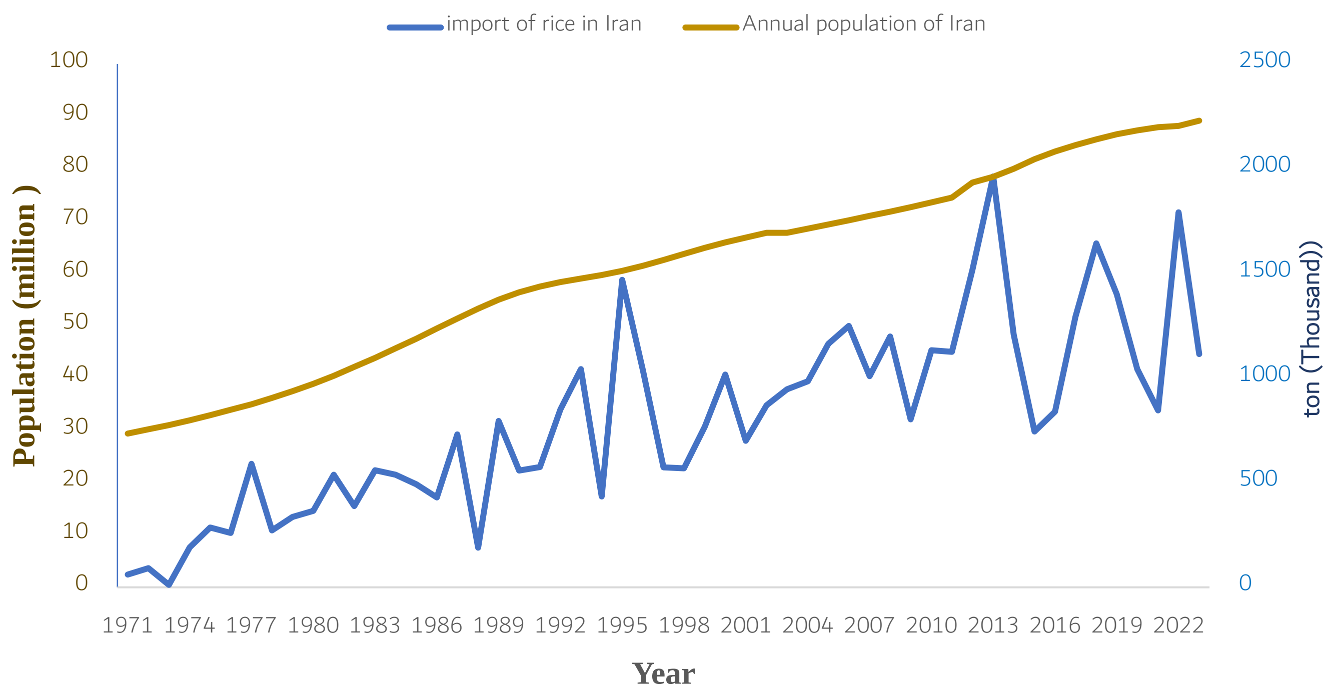

Figure 1. Variation in the population and import of rice in Iran (1971-2023).

Economic development

As the economy develops, the demand for quality food products likely increase. Consumers may seek rice varieties that offer better taste, nutritional value, and cooking qualities (Anang et al., 2011).

Climate change and environmental factors

Climate change poses challenges to traditional rice farming practices, making it essential to develop high-yield varieties that are resilient to changing environmental conditions, such as drought and temperature fluctuations (Javadi et al., 2024; Li et al., 2024).

Sustainability goals

There is a growing emphasis on sustainable agricultural practices. High-yield rice varieties can help meet food demand while minimizing the environmental impact of farming by reducing the land and water needed for cultivation (Sharma, 2024).

Government policies and investments

The Iranian government has been focusing on agricultural self-sufficiency and food security (Shayanmehr et al., 2024). Investments in research and development for high-yield rice varieties, as well as improvements in agricultural practices, will likely enhance production capabilities.

In summary, Iran's future demand for high-yield and quality rice is driven by demographic, economic, and environmental factors. Addressing this demand will require a concerted effort in agricultural innovation, investment and sustainable practices to ensure that the country can meet its food security needs effectively.

Progress in hybrid rice development in Iran

Development of CMS lines in hybrid rice breeding in Iran

Rice breeding in Iran has undergone three distinct periods, each characterized by unique strategies and methodologies aimed at enhancing rice production and quality. The first was Before 1979, only local rice varieties were used; the second was between from 1978 to 2000, when high-yielding semidwarf varieties were introduced; The third one began in 1991 with the introduction of certain cytoplasmic male sterile (CMS) lines from the International Rice Research Institute (IRRI)

(AghaAlikhani et al., 2013; Afkhami Ghadi, 2020). V20A and W32A, were the first CMS lines introduced from IRRI to Iran. The first attempts with hybrid rice in Iran were made at the Sari Science of Agriculture College and Amol Rice Research Center through the introduction of two CMS lines (V20A and W32A) from IRRI in 1987 and later in 1990 (Nematzadeh, 1977). Two other CMS lines, IR58025A and IR29298A, were introduced from IRRI and the study and breeding of new CMS lines from well-adapted and high-yielding improved varieties began in 1991. Dr. Jauhar Ali played a pivotal role in advancing rice breeding techniques through his coordination of hybrid and molecular rice breeding program as part of the International Rice Research Institute (IRRI)-Iran project from 2003 to 2009 (ICRISAT, 2014). This initiative enhanced rice production and improve the resilience of rice varieties to various environmental challenges. In this context, Dr. Ghorbanali Nematzadeh also played a vital role as the project leader for hybrid rice in Iran. His leadership and guidance of the research team significantly contributed to the development and implementation of effective strategies in hybrid rice breeding. Additionally, his efforts in foster international collaborations and facilitat the transfer of modern technologies to Iran greatly enhanced local capacities in this field. The first cytoplasmic male sterile lines were developed by Nematzadeh (1991) in Iran from indica sources of cytoplasm (IR58025A) in the genetic background of indica varieties Kazar, Nemat, Neda, Dasht, and Champa by backcrossing (Nematzadeh et al., 2003). Some appear well adapted to the tropics, possess acceptable grain quality, are good general combiners, and exhibit satisfactory outcrossing rate. Afkhami *et. al.* reported that NematA, Shastak mohammadiA, GerdeA, HasaniA and KhazarA are complete and stable sterile lines (Afkhami et al., 2013; Afkhami et al., 2015). Table 1 provides information on the cytoplasmic male sterile (CMS) lines that have been utilized for developing hybrid rice in Iran. This information reflects the diversity and efforts made to improve CMS lines and their adaptation to climatic conditions in Iran. This event marked the advent of hybrid rice technology in Iran, leading to the development of hybrid rice varieties (Nematzadeh et al., 2003).

Development of fertility restoration lines in hybrid rice breeding in Iran

The successful use of hybrids depends on effective fertility restoration mechanisms. Here, we present an overview of the process and key considerations involved in developing fertility restoration lines in hybrid rice breeding in Iran.

Restorer lines were selected from testcross nurseries based on the fertile reaction of the F_1 plants. The use of restorer lines such as IR24R, IR60969R, IR56R, and Amol 1R for Neda A, including a study of allogamy associated traits, for new improved CMS lines was carried out (Nematzadeh et al., 2003). Ahmadikhah et al. (2007) showed that lines IR28, Amol1 and Amol2 carry the *Rf4* gene linked with SSR marker RM171 on the long arm of chromosome 10, lines IR36 and IR60966 carry the *Rf3* gene linked with SSR marker RM1 on the short arm of chromosome 1, line IR62030 carries the *Rf5* gene on the short arm of chromosome 10, and finally line IR24 carries the *Rf4* gene on the long arm of chromosome 10 and an unknown *Rf* gene, respectively. Sattari et al. (2007) reported that because of their close linkage to *Rf* genes and distinct banding patterns, STS markers RG140/PvuII and S10019/BstUI are well suited for marker-aided selection, enhanced backcross procedures, and pyramiding of *Rf* genes in agronomically superior non-restorer lines. Ahmadikhah and Alavi (2009) in study of cold-inducible modifier QTL affecting fertility restoration of WA CMS in rice and reported that one major QTL (qRf-1-1) localized on the short arm of 1st chromosome near RFLP marker RG140 and the other one (qRf-1-2) localized on the same chromosome between RM7180 and RM6100d. Alavi et al. (2009) showed that *Rf3* was flanked by tow SSR markers RM1 and RM3873 at distances of 5.6 and 14 cM, respectively. Majidi et al. (2009) revealed that among candidate genes, only two genes, OsIFCD036677 and *Rf1*-B, showed differential expression among restorer and cytoplasmic male sterile lines, especially during the heading stage. As a result, these two genes were identified as the most likely candidates for fertility restoration at the *Rf4* locus within the WA CMS system.

A. Baluch-Zehi et al. (2013) investigated genetic distance among parental lines of hybrid rice using cluster analysis of morphological traits. Their findings indicated that the lines R9, R2, IR50, and Poya were potential restorer lines. A restorability test with known wild-abortive restorer lines (viz. IR36 and IR24) showed that combination of Yosen A × IR24 could produce highly fertile F_1 hybrid (Yazdanpanah, 2009; Ahmadikhah et al., 2015). reported that two STS makers of RG140 which are linked to the *Rf3* locus on chromosome 1, and S10019 which is linked to the *Rf4* locus on chromosome 10, were used to screen a restorer line. Kiani (2018) validated SSR markers linked to restoring fertility (*Rf*) genes and genotyping rice lines at *Rf* loci reported that RM258, RM171, and RM3148 markers could be used for screening of genotypes to identify restorers and non-restorer lines in hybrid rice breeding programs Afkhami Ghadi et al. (2019) identified male sterility maintainer and fertility restorer lines from Iranian landraces and improved rice cultivars and reported that IR50 and IR67924R lines with more than 96% and 80% fertility, respectively, were strong fertility restorer lines. Mirzababapour Amiri et al. (2021) reported that three genotypes (K7, K12 and K16) were found to desirable fertility restorer lines for NedaA due to their beneficial characteristics as well as representing more than 80% fertility percentage of pollen grains and seed setting in their panicles. Mahdikhani et al. (2023) showed that IR65622-151-1-2-2-2R for NedaA and IR68078-15-2-1-2-2-R and IR86403-5-5-2-1-1-1-1-1R were suitable fertility restorer lines for JelodarA.

Photoperiod-sensitive genic male sterility in rice breeding

Two well established male sterility systems in rice are cytoplasmic genetic male sterility (CMS), a three-line system, and environmentally sensitive genic male sterility (EGMS). EGMS has two types of mechanisms: PGMS and TGMS. Sattari (2001) confirmed the induction of photoperiod-sensitive genic male sterile (PGMS) mutants of rice, and identified them as genetic male sterile mutants of the Nemat variety.

Table 1. CMS lines introduced and developed in Iran by transferring WA cytosterility into the genetic background of elite breeding lines and varieties.

CMS line	Developed at	Pedigree	Breeder
IR58025A	IRRI	IR 22/Improved Sabarmati//V20A	IRRI
IR29298A	IRRI	-	IRRI
OM 6378A	IRRI	Type3/Jasmine 85//NedaA	IRRI
IR75596A	IRRI	-	IRRI
IR70416-53-2-2A	IRRI	IR 66295-71-2/IR 66696-97-4-3-1//NedaA	IRRI
NedaA	Iran	Hasansaraiy/Sangetarom/Amol 3//IR58025A	Nematzadeh et. al. (2003)
NematA	Iran	Hasansaraiy/Sangetarom/Amol 3//IR58025A	Nematzadeh et. al. (2003)
KazarA	Iran	IR2071-625-152 /TANU7456//IR58025A	Nematzadeh et. al. (2003)
DashtA	Iran	Amol1/IR24//IR58025A	Nematzadeh et. al. (2003)
ChampaA	Iran	Champa/NedaA	Nematzadeh et. al. (2003)
ShiroudiA	Iran	Deilamani/Khazar//NedaA	Afkhami (2020)
RoshanA	Iran	Mutant of Nemat//NedaA	Afkhami (2020)
JelodarA	Iran	Tarom deylamani/Sange tarom//NedaA	Afkhami (2020)
Shastak mohammadiA	Iran	Shastak mohammadi/NedaA	Afkhami (2020)
GerdeA	Iran	Gerde/NedaA	Afkhami (2020)
OndaA	Iran	Italy germplasm/NedaA	Afkhami (2020)

Table 2. Some of promising three-line hybrid rice combinations identified in Iran with quantity and quality characteristics.

Hybrid combination	Plant height (cm)	Duration (d)	Pollen sterility	Yield (kg m 2)	Kernel length (mm)		Aroma	Amylose content (%)
					Before cooking	After cooking		
DashtA/IR 68061-27-3-	118.00	131	27.67	863.03	6.66	11.40	Intermediate	23.56
JelodarA/IR 68061-27-	115.33	126	15	884.24	6.35	10.70	None	19.90
ShastakA/IR 57301-	165.00	128	10	938.95	5.86	10.43	Intermediate	20.75
DashtA/IR 73014-59-2-	120.00	125	15	900.94	6.71	10.60	None	22.00
IR75596A/MILYANG	117.33	123	23	1159.30	5.95	10.37	Strong	25.25
DashtA/SUWEON 294	125.67	129	18	1242.30	6.46	10.50	Intermediate	23.07
IR68899A/SUWEON	125.67	130	20	1286.12	6.00	10.13	None	19.02
NematA/IR 56	125	131	9	1074.10	6.75	11.60	Intermediate	25.64
IR68280A/ IR 56	117	122	23	1022.00	6.73	11.00	None	22.63
IR68899A/ IR 56	118	131	9	1045.70	6.78	10.63	None	25.99
IR102572A/ IR 9761-	120	125	11	998.34	6.28	10.90	None	23.56
IR78369A/IR46R	122	128	9	901.00	6.89	10.97	Intermediate	20.28
IR102572A/NSIC RC	120.67	124	6	969.95	6.56	10.97	None	28.65
IR102572A/IR 85593-	127.67	124	14	1196.50	5.90	10.13	Intermediate	19.02
IR 78369A/IR8 5593-	125	122	9	1322.30	6.16	11.00	Strong	19.30

Afkhami et al. (2015) evaluated the sterility stability of several rice cytoplasmic male sterile lines and reported that the IR68899A line, which demonstrated complete sterility, was fertile under high temperature (> 24°C) and low light (< 13.75 h) conditions in the greenhouse. Therefore, it could be used for two-line hybrid programs. Siahchehreh et al. (2023) tagging of temperature-sensitive genic male sterility (TGMS) gene in rice mutant Nemat cultivar reported that RM110 and RM29 primers had a high correlation with TGMS gene (5.74 and 11.63 c M, respectively).

Yielding ability and grain quality of hybrid rice in Iran

Hybrid combinations were evaluated using four kinds of experiments: advanced yield trials (AHRT), preliminary yield trials (PHRT), observational yield trials (OHRT), and combining ability experiments (CA) (Virmani, 1997). The best hybrid combinations in each experiment are promoted to the next yield trial in the following season. The first hybrid rice to be introduced to Iran was the hybrid Dilam (Bahar 1), which achieved an average yield of 7.5 tons per hectare (Dorosti et al., 2006).

This hybrid was developed by crossing of IR58025A and IR42686R. In comparison with the control variety Khazar, this variety exhibited a standard heterosis of 57.9%. Additionally, the two parent lines had a maturity difference of 5 days. Hashemi et al. (2009)used 16 rice genotypes, including three cytoplasmic male sterile (CMS) lines, five restorer lines, and eight hybrid combinations. Out of 16 SSR markers, 10 markers showed polymorphic bands. The first hybrid rice, IRH1, was distinguished from other hybrids using SSR markers. Afkhami Ghadi (2020) evaluated the morphological and molecular characteristics of cytoplasmic male sterile maintainer lines and fertility restorer lines from various genetic sources of rice by introducing 13 rice hybrids with a yield of over 1,000 grams per square meter. They reported the hybrids IR 75596 A/MILYANG 54 and IR 78369 A/IR85593-23-2-1-3-1-2-1-1-1 as among the most aromatic hybrids, comparable to the quality of the aromatic variety Hashemi. The priorities of rice grain quality characteristics vary from region to country. The main quality characteristics for the commercial evaluation of rice varieties include: 1) milling and head rice recovery, 2) shape and appearance of the grain, and 3) cooking and eating characteristics.

Iran has made significant strides in the development of hybrid rice varieties recently (Fig 2, Table 2). Table 2 examines various hybrid rice combinations and their quantitative and qualitative characteristics. These data demonstrate the advancements made in developing high-yield hybrids of suitable quality, assisting farmers and researchers in making better cultivation choices. Figure 2 depicts the historical development of hybrid rice in Iran from the beginning of efforts in 1987 to 2024. Key trends, including the introduction of CMS lines and advancements in hybrid production, are illustrated in this figure. This information can help researchers understand the trajectory of hybrid rice development in Iran and the associated challenges. This progress is crucial for enhancing rice production, improving food security, and meeting the growing demand for high-quality rice. Here are some key aspects of this progress:

Figure 2. A shematic history of hybrid rice in Iran of 1987-2024.

Innovating hybrid rice production in Iran

Research and development

Research and development in hybrid rice production in Iran are key to improving rice production and enhancing its quality (Peykani et al., 2008). Iranian agricultural research institutions are actively engaged in developing hybrid rice varieties that are better suited to the country's climatic conditions. Collaborations with international agricultural research organizations have also facilitated knowledge transfer and access to advanced breeding techniques (Virmani et al., 2006; FAO, 2014).

High-yield varieties

Hybrid rice varieties developed in Iran have shown substantial increases in yield compared to traditional varieties. These hybrids are designed to be more productive, with some varieties yielding up to 20-30% more than conventional rice (Afkhami Ghadi, 2020).

Resilience to environmental stress

Many new hybrid rice varieties are bred to be more resilient to environmental stresses, such as drought, salinity, and pests (Singh et al., 2024). This is particularly important given the challenges posed by climate change and water scarcity in Iran.

Government support and policies

The Iranian government recognizes the importance of hybrid rice in achieving food security and has implemented policies to support research, development (Virmani et al., 2006), and dissemination of hybrid seeds. Financial incentives and subsidies for farmers adopting hybrid rice cultivation have also been introduced.

Training and capacity building

Extension services and training programs for farmers have been established to promote the adoption of hybrid rice cultivation practices. This includes educating farmers on best practices for planting, fertilization, and pest management to maximize the benefits of hybrid varieties (Salam and Sarker, 2023; Gupta et al., 2024).

Market acceptance

As hybrid rice varieties have gained popularity, acceptance between consumers and farmers has increased. The improved yield and quality of hybrid rice help boost its market presence (Gupta et al., 2024)

Sustainability considerations

Efforts are being made to ensure sustainable hybrid rice cultivation. Research has focused on minimizing the use of chemical fertilizers and pesticides, promoting integrated pest management, and optimizing water usage.

Future prospects

The future of hybrid rice in Iran appears to promising, with ongoing research aimed at developing even more resilient and high-yield varieties. Continued investment in agricultural technology and infrastructure are essential for maintaining this progress. In conclusion, Iran's progress in hybrid rice development represent a critical step toward enhancing agricultural productivity (Peykani et al., 2008) and ensuring food security. By focusing on research, farmer education, and sustainable practices, Iran seeks to strengthen its rice production capabilities despite growing challenges.

Challenges in hybrid rice breeding

Grain quality of hybrid rice needs improvement

With the increasing living standards of rice consumers in Iran, it is necessary to improve the grain quality of rice (Butardo et al., 2019). In comparison with landrace rice, hybrid rice exhibits poorer grain quality in terms of head rice recovery and aromatic (Gong et al., 2023). The development of rice hybrids with both high yield and good grain quality remains a challenge for breeders (Zeng et al., 2019).

The sources of male sterility-inducing cytoplasm for developing better CMS lines are poor

Currently, 100% of the CMS lines used in trial production are WA types (Afkhami Ghadi, 2020). This dominant cytoplasm in the existing three line hybrid rice cultivars could lead to the development of destructive pests and diseases (Virmani et al., 2003; Faiz et al., 2007).

Screening for resistance to biotic stresses

The incorporation of resistance to the major biotic stresses of the region is necessary for the successful adoption of hybrids. Hence, promising hybrids are regularly screened for resistance to major pests and diseases (Horgan and Crisol, 2013).

Future perspectives

Develop hybrids with acceptable grain quality that meet the specific requirements of different regions. The magnitude of heterosis should be enhanced to 20% and above by developing two line and intersubspecific hybrids (Ali et al., 2021b). Enhance seed yields beyond 2.0 t ha^{-1} to bring down the seed cost. In addition to the above, efforts on technology transfer have been intensified through the conduct of a large number training programs to create awareness about the benefits of hybrid rice among rice farmers and consumers across the country. Policy interventions by the government for increased support, aggressive efforts to popularize hybrids, and the assured procurement of hybrid rice produce at a minimum support price are needed at this juncture.

Modern technologies in hybrid rice

Gene editing technology

CRISPR/Cas9- This technology allows precise editing of genes, enabling the enhancement of desirable traits such as disease resistance and improved grain quality in rice (Romero and Gatica-Arias, 2019; Zafar et al., 2020; Chen et al., 2024a).

Transgenic technology

Gene transfer from other species- Transgenic methods facilitate the introduction of genes associated with traits such as abiotic stress tolerance, pest resistance, and increased photosynthetic efficiency, thus improving yield potential and resilience in rice varieties (Sabar et al., 2024).

Bioinformatics technologies

Modeling and simulation- Advanced software and algorithms are used to predict genetic traits and performance in hybrid rice (Xu, 2007; VanRaden, 2008; Xu et al., 2014; Xu et al., 2021; Fritsche-Neto et al., 2024).

The use of artificial intelligence (AI) in hybrid rice technology

By utilizing artificial intelligence systems and algorithmic processing, it has become possible to analyze large volumes of data, including genotype, phenotype, generations, and grain quality of rice (Sabouri and Sajadi, 2022; Crossa et al., 2024). This capability allows for the rapid generation of millions of potential rice combinations for hybrid rice production (Xu et al., 2022; Ashraf et al., 2024). Furthermore, in the consumer market, the development of identification and detection methods for rice seeds through artificial intelligence can significantly reduce fraud and seed mixing, ultimately ensuring seed purity (Hruthik Chandra et al., 2022; Felizardo et al., 2024).

Limitations of using these technologies in Iran

Legal and policy considerations

Lack of clear regulatory framework- The absence of well-defined laws and regulations regarding transgenic and gene-editing technologies can hinder research and commercialization efforts (Mohajer et al., 2011).

Public and social concerns

Public resistance to transgenic products- There are concerns among consumers and farmers regarding the safety and ethics of transgenic and gene-edited crops, which may hinder acceptance (Akbari et al., 2023).

Lack of awareness and education- Insufficient information and education about the benefits and safety of these technologies can lead to resistance (Akbari et al., 2023).

Technical and Economic challenges

Insufficient research infrastructure- Many research institutions and universities in Iran lack the advanced equipment and technology needed for cutting-edge research in gene editing and transgenics.

Need for investment- Research and development in these areas require significant investment, which may be challenging under current economic conditions.

High costs- The costs associated with research, development, and commercialization of new technologies can be a barrier for farmers and private companies (Spielman et al., 2012; Spielman et al., 2021).

Competition with imported products- Imported products that may utilize more advanced technologies can pressure local markets and farmers.

Environmental, cultural and social challenges

Environmental impact concerns- The use of modern technologies may raise concerns about their environmental effects, such as impacts on biodiversity and ecosystems.

Climate change- Climate change can affect the performance of modern technologies and pose challenges for agriculture (Lu, 2024).

Resistance in local communities- Some communities may resist changes due to traditional agricultural practices and cultural beliefs.

Social impacts- Changes brought about by modern technologies may affect the social and economic structures of rural communities. While modern technologies in hybrid rice hold great potential for improving production and quality, their effective implementation in Iran faces various challenges. Addressing legal, public, technical, economic, environmental, and cultural issues is essential for maximizing the benefits of these technologies and enhancing food security in the country.

Conclusion

Rice is a crucial agricultural product in Iran. The rice sector significantly contributes to food security and farmers' livelihoods, but it faces challenges such as water scarcity, climate change, and competition from imported rice. The surge in rice imports in 2013 and 2023 highlighted the need for enhanced domestic production. To address these challenges, Iran is focusing on improving rice breeding programs, water management practices, and sustainable agricultural techniques. The future demand for high-yield and quality rice in Iran is driven by factors such as population growth, changing dietary preferences, economic development, climate change, and sustainability goals. To meet this demand, raising yield potential is essential, with projections indicating a need for an increase to 8.076 tons per hectare by 2030.

Hybrid rice breeding is a promising strategy to enhance yield and quality. Significant advancements have been made in this filed, including the introduction of new hybrid varieties and improved cultivation practices. However, challenges remain, such as limited water resources and the need for increased research and development investment. The study analyzes the current status of hybrid rice breeding in Iran, identify barriers, and propose solutions to optimize production. Iran's hybrid rice breeding has progressed through three distinct periods, beginning with local varieties, followed by the introduction of high-yielding semidwarf varieties, and a recent focus on cytoplasmic male sterile (CMS) lines. The development of fertility restoration lines and the use of environmentally sensitive genic male sterility (EGMS) are crucial for the successful implementation of hybrid rice. Despite progress, challenges such as improving grain quality, sourcing male sterility-inducing cytoplasm, and ensuring resistance to biotic stresses persist. Future efforts should focus on developing hybrids with acceptable grain quality, enhancing heterosis, and increasing seed yields.

In conclusion, Iran's progress in hybrid rice development are vital for enhancing agricultural productivity and ensuring food security. Continued investments in research, farmer education, and sustainable practices will strengthen rice production capabilities despite growing challenges. The government's support and policies play a critical role in promoting hybrid rice cultivation and ensuring its success in meeting the country's food security needs.

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Conflict of Interest Statement

The authors declare no conflict of interest.

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مقاله مروری

دستاوردها و چالش‌های اصلاح برنج هیبرید در ایران

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چکیده: افزایش پتانسیل عملکرد برنج، جهت تضمین امنیت غذایی برای جمعیت رو به رشد، همچنان یک اولویت در ایران است. بر اساس مصرف سرانه برنج به مقدار ۳۵ کیلوگرم و سطح زیرکشت برنج پایدار ۶۵۰ هزار هکتار، عملکرد دانه باید به حدود ۸۰۰۰ کیلوگرم در هکتار افزایش یابد. این مقاله به بررسی دستاوردها و چالش‌های مرتبط با اصلاح برنج هیبرید در ایران می‌پردازد. هدف آن بررسی وضعیت فعلی، شناسایی موانع و پیشنهاد راه‌حل‌هایی برای بهبود فرآیندهای اصلاح برنج هیبرید است. عوامل کلیدی که توسعه برنج هیبرید را محدود می‌کنند، تجزیه و تحلیل شده و راه‌حل‌های ممکن برای این چالش‌ها پیشنهاد می‌شوند. فناوری‌های مدرن در اصلاح برنج هیبرید، شامل ویرایش ژن (فناوری CRISPR/Cas9)، فناوری انتقال ژن و هوش مصنوعی، به طور قابل توجهی توانایی بهبود ویژگی‌های مطلوب مانند مقاومت به بیماری و کیفیت دانه را افزایش می‌دهند. با این حال، اجرای مؤثر این فناوری‌ها در ایران با چالش‌های متعددی از جمله نبود چارچوب قانونی مشخص، نگرانی‌های عمومی و اجتماعی، کمبود زیرساخت‌های تحقیقاتی و نیاز به سرمایه‌گذاری مواجه است. در نهایت، پیشرفت‌های ایران در توسعه برنج هیبرید برای افزایش بهره‌وری کشاورزی و تضمین امنیت غذایی بسیار ضروری است. نیاز به سرمایه‌گذاری مستمر در تحقیقات، آموزش کشاورزان و شیوه‌های پایدار برای تقویت قابلیت‌های تولید برنج کشور در مواجهه با چالش‌های فزاینده وجود دارد.

کلمات کلیدی: اصلاح برنج هیبرید، امنیت غذایی، لاین‌های نرعقیم سیتوپلاسمی (CMS)، *Oryza sativa*.

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