Current Status of Speed Breeding Technology in Rice (*Oryza sativa* L.)

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Abstract Rice (*Oryza sativa* L.) is a core crop for ensuring food security and seed industry independence. Although traditional breeding has made significant progress in dwarfing and hybrid systems, its limitations including long generation cycles and reliance on field phenotypic selection render it inadequate for addressing climate change and resource constraints. In recent years, the integration of controlled environment agriculture (such as plant factories) with technologies including genomics, high-throughput phenomics, and CRISPR-Cas has driven the development of both the concept and practice of speed breeding. This article systematically reviews the facility evolution from off-site generation advancement to on-site generation advancement and then to plant factories, and compares the limitations of traditional methods such as mutation breeding, transgenic breeding, and hybrid breeding. It critically highlights the breakthroughs in efficiency and precision achieved by molecular marker-assisted selection, gene editing, and molecular design breeding. Key components, including illumination, temperature, soilless cultivation with nutrient management, and mild stress induction, are analyzed. Through case studies such as the IRRI SpeedFlower system and China's plant factory-based generation advancement systems, the paper demonstrates the technical feasibility and application prospects of achieving 5 – 6 generations per year.

Key words Rice; Speed breeding; Plant factory; Environmental control; Molecular breeding; Generation acceleration

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Rice (*Oryza sativa* L.) is one of the world's most important food crops, and the stability of its production and supply directly impacts food security. Over 60% of the nation's population relies on rice as their staple food[1], highlighting the absolute central role of rice in the country's food supply system. Therefore, continuously improving the genetic gain efficiency of rice to ensure stable yields, high productivity, superior quality, and multi-resistance of its varieties is a strategic requirement to guarantee that "Chinese people's rice bowl" remains firmly in their own hands.

Over the past decades, traditional breeding methods represented by "dwarfing breeding" and "hybrid rice" have achieved globally recognized successes, significantly increasing rice yield per unit area. However, the traditional breeding model heavily relies on field phenotypic selection, with its core bottleneck being an excessively long generation cycle. The breeding of an excellent new rice variety typically involves multiple stages, including parental hybridization, multi-generation selection, trait stabilization, and regional trials, a process that may take 10 to 15 years to complete[2]. In the face of severe challenges such as intensifying global climate change, frequent extreme weather events, degradation of soil resources, and the continuous emergence of new races of pathogens and pests including rice blast and brown planthopper, this slow pace of varietal change is no longer sufficient to meet the urgent demand for rapid genetic improvement in modern agriculture.

With the rapid advancement of modern biotechnology and environmental engineering, powerful technological pathways have emerged to overcome the aforementioned bottlenecks. On one hand, Controlled Environment Agriculture (CEA) systems, represented by plant factories, enable year-round continuous cultivation of rice by breaking the constraints of natural seasons through precise control of key factors such as illumination, temperature, and nutrition. On the other hand, the deep integration of genomics, high-throughput phenomics, and gene-editing technologies such as the CRISPR-Cas system has enabled the precise design and targeted improvement of the breeding process.

The length of the rice breeding cycle not only restricts the speed of new variety development, but also directly impacts the efficiency of rapidly identifying, genetically characterizing, and pyramiding superior genes from a vast pool of precious germplasm resources. This has significant strategic implications for safeguarding national rice germplasm security and ensuring seed industry independence and controllability. Therefore, establishing an efficient, stable, and low-cost speed breeding system for rice has become a forefront hotspot in modern breeding research. This paper provides a systematic review of the latest advances in rice speed breeding, focusing on key perspectives including the evolution of breeding concepts, the development of modern facilities, regulatory strategies for key components of these facilities, and the integration and advancement of core speed breeding techniques. The goal is to present theoretical reference and technical insights for accelerating

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Evolution of the Speed Breeding Concept in Crops

Since modern times, the length of the breeding cycle has been an extremely critical aspect of agricultural production. How to stably and efficiently produce superior varieties has consistently been a central focus for breeders. The concept of rapid crop breeding emerged from in-depth exploration of plant growth laws and humanity's pursuit of enhanced agricultural efficiency. As early as the beginning of the 20th century, botanists observed that many plants exhibited significantly accelerated flowering under continuous light conditions, which laid the groundwork for subsequent research focused on accelerating crop growth cycles through artificial interventions and enabling speed breeding[3]. In 1939, Goulden first proposed that the " single-seed descent method" could significantly accelerate the breeding speed of crops such as rice, thereby shortening the breeding cycle. It marked a preliminary shift of speed breeding from theory to practice[4]. In 2003, researchers at the University of Queensland, Australia, inspired by a rapid wheat rotation method demonstrated on the NASA space station, first introduced the concept of "Speed Breeding"[5] and formulated protocols for dramatically shortening crop generation cycles. By extending photoperiods and optimizing light quality and temperature, this technology significantly accelerates crop flowering and seed-setting processes. It has reduced the generation cycles of crops such as wheat, barley, and chickpeas by more than half[6]. In recent years, with advancements in the understanding of plant growth and development mechanisms and related industrial technologies, the concept of "Speed Breeding", an approach for achieving rapid generation-adding breeding by shortening plant life cycles through artificial interventions, has gained widespread acceptance. It has led to the development of a series of classic varieties in turn. Currently, China faces dual pressures of food security challenges and arable land scarcity. Rice is a vital food crop for the nation. Accelerating the progress of rice breeding can significantly improve the efficiency of cultivating new varieties, thus enabling a faster response to food demand and ensuring food security in China.

Advances in Facilities for Rice Speed Breeding

One of the core driving forces behind speed breeding technology is the revolutionary advancement of breeding facilities. The evolution from off-site generation advancement utilizing natural light and temperature conditions, to on-site generation advancement with local environmental control[7], and further to plant factories that completely break free from natural constraints[8], represents a series of leaps. Each leap has dramatically " compressed" the growth cycle of rice, securing invaluable time for breeders.

Off-site generation advancement refers to the transfer of rice breeding materials to different geographic locations, utilizing local naturally-suitable light and temperature resources of warm or tropical regions to accelerate generational cycles. For instance, in 1945, Borlaug[9] adopted a shuttle breeding method in Mexico, which involved staggered cultivation between highland and lowland sites, which successfully achieved two rice breeding cycles per year, effectively halving the breeding cycle. This method was subsequently leveraged to facilitate the breeding of varieties with broad adaptability[10]. The most iconic practical application of off-site generation advancement in China is the "Southern Propagation" (Nanfan) in Hainan. This approach involves transporting seeds or seedlings to tropical regions such as Hainan for cultivation during the winter, thereby providing suitable growth and development conditions for rice and enabling two or even multiple cropping cycles per year. The application of Southern Propagation has accelerated the transformation process from breeding materials to new rice varieties by approximately 50%, significantly enhancing the speed of generational advancement[11].

On-site generation advancement refers to the practice of fully utilizing various local artificial facilities to create suitable conditions for rice growth and development through controlled environments, thereby achieving the goal of shortening the generational process and the overall breeding cycle. Its greatest advantage lies in eliminating the need to transfer breeding materials. Early-stage on-site generation advancement primarily relied on plastic greenhouses or solar greenhouses. The core function of these facilities is to utilize natural light for heat preservation during winter. Supplemented by basic heating equipment, they enables rice to grow during non-traditional planting seasons. Globally, Japan pioneered the use of greenhouses for generation advancement research as early as the 1930s, successfully breeding several renowned varieties such as "Toyonishiki" and "Yukihikari". In China, following research conducted from 1986 to 1994, a comprehensive supporting system for greenhouse generation advancement was established, successfully achieving 2 – 3 generations of rice per year[12]. However, on-site generation advancement often requires expensive greenhouse structures and corresponding auxiliary facilities, making it difficult to conduct large-scale breeding and generation advancement work. With the progress and development of the times, breeders have explored a set of "Non-Greenhouse On-Site Generation Advancement Technology". This method does not rely on costly heated greenhouses. Instead, it achieves two breeding cycles per year with simple facilities and key technical controls, at an investment cost significantly lower than that of greenhouse-based or off-site generation advancement[13].

In recent years, with the advancement of technology, plant factory technology has gradually become widespread. A plant factory is a highly efficient agricultural system that achieves year-round, continuous, and industrialized production of plants within an enclosed and controlled environment, using artificial lighting and nutrient solution cultivation techniques. Plant factories first appeared in some developed countries in Europe and America in the 1950s. China started relatively late in this field, but the development has been rapid. China has now become one of the largest plant production countries in the world. Unlike off-site and on-site generation advancement, the core advantage of plant factories lies in their ability to eliminate dependence on arable land for plant growth. They utilize multi-layer cultivation racks and apply nutrient solution-based methods such as hydroponics, aeroponics, or substrate culture for relevant crops. This approach dramatically increases land use efficiency while ensuring precise supply of nutrients, achieving simultaneous and optimized delivery of water and fertilizers. By leveraging computer programming technology, customized combinations of optimal light quality, intensity, and photoperiod can be designed and implemented for different growth stages. It enables "unmanned" or "less manned" management in rice breeding.

Technological Progress in Speed Breeding of Rice

In recent years, propelled by the rapid development of modern molecular biology, genomics, and related biotechnology fields, the breeding field is undergoing a profound transformation from traditional methods toward efficient and precise modern breeding approaches.

Traditional breeding

Mutation breeding Mutation breeding involves the use of physical or chemical agents to artificially induce mutations in the genetic material of an organism, followed by the selection of varieties that meet desired criteria. The core value of this method lies in its ability to break tight linkages between traits and to create novel alleles that are rare or non-existent in nature, making it an important technical pathway in traditional breeding. Mutagenesis methods are primarily divided into two major categories: radiation mutagenesis and chemical mutagenesis. The former utilizes physical radiation to efficiently induce genetic variation and is suitable for rapidly constructing large-scale mutant libraries, whereas the latter involves treating biological materials with chemical mutagens to induce mutations.

In rice breeding practice, ethyl methanesulfonate (EMS) is widely recognized as one of the most efficient and extensively used chemical mutagens[14]. As a potent alkylating agent, EMS primarily induces base mismatches through alkylation reactions with DNA bases[15], thereby generating a high frequency of point mutations across the genome. Through systematic screening of EMS-mutagenized progeny populations (*e.g.*, the M_2 generation), researchers can isolate and identify a large number of novel alleles that influence key agronomic traits in rice, such as plant type, growth period, disease resistance, yield, and quality. These mutants not only serve as invaluable genetic materials for functional genomics research in rice, but also play a pivotal role in breeding improvements. They have made significant contributions, particularly in enhancing rice resistance to abiotic stresses (such as drought, salinity, and low temperature) and biotic stresses (such as rice blast and bacterial blight), providing strong support for the development of new varieties with high yield, stable performance, and broad adaptability.

However, mutation breeding technology also possesses inherent limitations. Its primary constraint lies in the randomness and non-directionality of the induced mutations. This characteristic makes it difficult to precisely control the sites and types of mutations, resulting in significant uncertainty in obtaining desired beneficial traits. Furthermore, while mutagenic treatments generate beneficial mutations, they inevitably and simultaneously produce a large number of neutral or deleterious mutations, often leading to the linkage and accumulation of unfavorable agronomic traits[16]. Therefore, to effectively eliminate detrimental variations, pyramid desirable traits, and ensure their stable inheritance, breeders must commit substantial resources to conduct large-scale, multi-generational phenotypic evaluation and genetic screening within the mutagenized progeny. This process not only significantly increases the workload, but is also a major factor contributing to the extension of the overall breeding cycle.

Transgenic breeding Transgenic breeding, a modern genetic engineering approach based on molecular biology principles, centers on the stable integration and functional expression of an exogenous target gene cloned *in vitro* or artificially modified into the genome of a recipient organism. This process is achieved using a specific vector system, enabling the targeted improvement of specific traits in the host organism[17].

In the practice of rice genetic transformation, the most widely adopted mainstream methods are *Agrobacterium*-mediated and gene gun-mediated transformation. Additionally, some studies have explored alternative pathways, such as the pollen-tube pathway method, electroporation, and polyethylene glycol (PEG)-mediated protoplast transformation[18].

Utilizing these technologies, a variety of rice materials with significant breeding value have been developed. For example, insect-resistant rice varieties carrying *Bacillus thuringiensis* genes, such as "Huahui 1"[19], can effectively combat infestation by lepidopteran pests. Another example is "Golden Rice" enriched with β-carotene, which aims to address vitamin A deficiency in target populations[20].

Despite the substantial theoretical and practical potential demonstrated by transgenic technology, widespread public concern regarding the perceived risks of genetically modified organisms (GMOs) and their derived foods has resulted in transgenic rice facing significant challenges and societal resistance in China, hindering its commercial promotion and practical application in production.

Hybrid breeding Hybrid breeding is a classic breeding method. It involves the crossing of parental lines with different genotypes, leading to genetic recombination. This process aggregates desirable traits from the parents into the hybrid offspring. New rice varieties are then formed through selection and evaluation over several generations.

China's research in the field of hybrid rice occupies a leading position globally. In 1964, Yuan Longping initiated China's hybrid rice breeding efforts, laying the cornerstone for the country's hybrid rice research[21]. By the 1970s, China had pioneered the successful development and large-scale promotion of the "three-line" hybrid rice system, achieving a historic breakthrough in rice yield. In 1973, the discovery by Shi Mingsong of the photoperiod-sensitive genic male-sterile (PGMS) rice material "Nongken 58S" provided the crucial germplasm foundation for establishing the "two-line" hybrid rice system[22]. Seizing this opportunity, China's research system achieved a significant technological leap from the three-line to the two-line method. The two-line system streamlined the breeding procedures, significantly enhancing the flexibility and efficiency of breeding. In the 21st century, it has become the mainstream core technology for hybrid rice breeding in China[23].

By integrating breeding strategies that combine ideal plant type improvement with the utilization of strong heterosis, Chinese scientists have successively developed multiple super hybrid rice varieties, such as "Liangyoupeijiu", "9308", and "Shennong 265"[21], consistently promoting the breakthrough of rice yield potential.

However, hybrid breeding of rice also faces significant challenges and bottlenecks. Firstly, the effectiveness of genetic improvement is highly constrained by the genetic backgrounds of the parental lines, making it difficult to break through the limitations of genetic diversity within existing germplasm resources. Secondly, the breeding cycle is relatively long, and the efficiency of selection largely depends on the accuracy of phenotypic evaluation, which is susceptible to interference from environmental factors. This severely restricts both the efficiency and precision of the breeding process.

In summary, while traditional breeding methods, exemplified by hybrid breeding, have been widely applied and achieved remarkable success in rice improvement, their inherent limitations such as long breeding cycles and constrained selection efficiency cannot be overlooked. This situation underscores an urgent demand for the innovation and application of modern breeding technologies.

Molecular breeding

Molecular Marker-Assisted Selection (MAS) breeding The screening and identification of superior individuals constitute the core of crop genetic improvement. Traditional breeding primarily relies on the indirect selection of phenotypic traits. However, phenotypes are susceptible to interference from environmental factors, which limits the accuracy and efficiency of selection. Modern breeding systems have introduced direct selection based on genotype, namely Molecular Marker-Assisted Selection (MAS)[24].

Molecular markers represent the fourth generation of genetic markers, following morphological, cytological, and biochemical markers. Their primary types encompass Restriction Fragment Length Polymorphism (RFLP), Random Amplified Polymorphic DNA (RAPD), Simple Sequence Repeats (SSR), and Single Nucleotide Polymorphisms (SNP). MAS is an efficient breeding strategy that enables the rapid and precise identification of individuals carrying desirable genotypes as early as the early breeding generations. This is achieved by utilizing molecular markers that are tightly linked to target genes[25]. Theoretically grounded in quantitative trait locus (QTL) mapping and the construction of high-density genetic linkage maps, when integrated with conventional breeding techniques, this approach can significantly enhance the efficiency and predictability of selection. In rice breeding practice, MAS has been extensively applied to the genetic improvement of complex traits such as yield, quality, disease resistance, and stress resistance, achieving remarkable success. For example, by using markers tightly linked to rice bacterial blight resistance genes, breeders can rapidly introduce these resistance genes into high-yielding but susceptible background parents. Furthermore, employing specific markers for assisted selection of major genes controlling eating quality and *GS3* gene controlling grain length has become a standard procedure in high-quality rice breeding.

MAS technology offers multiple advantages over traditional phenotypic screening. Firstly, it enables early-stage identification of target traits during the seedling phase, thereby eliminating the need to plant and manage a large number of plants with undesirable genotypes in the field. That is to say, it can effectively shorten the breeding cycle and substantially reduce resource investments in land, labor, and time, lowering the overall maintenance cost of breeding programs. Secondly, molecular marker detection can be conducted at any developmental stage of crop growth, without being restricted to specific phenological phases. This significantly enhances the flexibility of the breeding process and the efficiency of multi-generational selection.

With the rapid advancement of high-throughput sequencing technologies and automated analysis platforms, the development throughput and cost-effectiveness of molecular markers are continually being optimized. This technological progress provides robust support for the large-scale commercial application of MAS, making its position increasingly prominent within modern crop breeding systems.

Gene-editing breeding Gene editing is a targeted molecular technology that enables precise modifications to specific DNA sequences within the genome of an organism. The core mechanism of this technology involves the use of engineered nucleases to induce DNA double-strand breaks at predetermined genomic target sites. The generation of double-strand breaks (DSBs) activates the cell's endogenous DNA repair pathways, primarily Non-Homologous End Joining (NHEJ) and Homology-Directed Repair (HDR). By guiding and harnessing these repair pathways, targeted gene knockout, insertion, or replacement can be achieved, enabling precise editing of the genomic sequence[26].

Among various current gene-editing platforms, the CRISPR/Cas system has emerged as the most rapidly developed and widely adopted platform, owing to its advantages in simple target design, high editing efficiency, remarkable cost-effectiveness, and powerful versatility (such as multi-gene editing and transcriptional regulation).

The revolutionary genome-editing tool CRISPR/Cas9 has brought unprecedented technological breakthroughs to both functional genomics research and genetic improvement in rice. This technology enables precise targeting and highly efficient modification of specific genomic sequences, playing a central role in directed optimization of key agronomic traits in rice. For instance, researchers have successfully used CRISPR/Cas9 technology to knock out the *BADH2* gene, thereby blocking the degradation of 2-acetyl-1-pyrroline (2AP) and creating novel fine rice germplasm with a stable fragrance[27]. Additionally, through precise editing of the Waxy gene, the synthesis content of amylose has been regulated to directionally improve the cooking and eating quality of rice[28].

Breeding scientists can apply gene-editing technology to rapidly create novel germplasm carrying specific superior alleles and achieve targeted pyramiding of multiple beneficial genes. This approach aims to simultaneously enhance rice yield potential, grain quality, and resistance to both abiotic and biotic stresses.

Compared with traditional transgenic technology, which relies on the random integration of exogenous genes, gene-editing technology enables precise modification of the endogenous genome without introducing foreign functional DNA sequences. Through segregation in progeny, it is relatively easy to obtain non-transgenic, stably inherited improved varieties. This not only significantly enhances the precision and efficiency of breeding, but also provides a highly efficient, precise, and potentially less regulated new pathway for broadening and innovating rice germplasm resources.

Molecular design breeding With the rapid advancement of crop genomics, the reference genome sequencing and functional annotation of major crops such as rice have become increasingly comprehensive. A large number of genes and quantitative trait loci (QTL) controlling key agronomic traits have been precisely identified and localized. Against this backdrop, a new paradigm of molecular design breeding has emerged, characterized by the deep integration of genomics, molecular biology, bioinformatics, and genome-editing technologies.

The core concept of this breeding paradigm lies in, firstly, systematically identifying the key genes governing target traits and their superior allelic variations based on well-defined breeding objectives. Secondly, with the aid of bioinformatics and computational models, it involves simulating and predicting the genotypes and phenotypes of offspring from different parental combinations, in order to design and screen for the optimal breeding strategy and parental mating scheme. Finally, by combining gene-editing technology for targeted genetic modification or directed improvement of key genes, and guided by Molecular Marker-Assisted Selection (MAS), the efficient pyramiding of multiple genes and early screening of superior individual plants are achieved, ultimately leading to the cultivation of new ideal varieties that conform to a pre-designed genetic structure[29].

For example, by "designing" and "assembling" superior allelic variants of ideal plant type, panicle grain number and grain weight genes in rice, novel germplasm resources with significantly enhanced yield potential have been successfully created. This model transforms the traditional breeding paradigm heavily relying on empirical knowledge and phenotypic selection into a predictable and designable precision breeding approach based on genetic information. This shift has greatly enhanced breeding efficiency and success rates. By integrating genomic selection strategies, Molecular Design Breeding (MDB) can not only directly create novel germplasm carrying specific alleles, but will also significantly accelerate the breeding process and reduce research and development costs, propelling crop breeding into a new era of intelligentization and high efficiency. In summary, traditional breeding technologies, such as hybrid breeding, typically rely on multiple generations of crossing, backcrossing, selfing, and rigorous phenotypic selection to achieve the stable inheritance of desirable traits. For example, a conventional hybrid breeding program often requires continuous screening of the F_1, F_2, and subsequent multiple generations before a target line can be obtained. This entire process typically spans over ten generations, resulting in an extremely lengthy breeding cycle. As for mutation breeding, due to the randomness and low frequency of induced mutations, breeders must handle and screen massive mutant populations, which presents significant screening challenges and often leads to an even more protracted breeding cycle.

In contrast, the advantages of modern molecular breeding technologies in enhancing breeding efficiency and shortening breeding cycles are evident. While transgenic breeding can shorten the improvement process, its commercial application still faces complex regulatory and social acceptance challenges in many countries.

Comparatively speaking, other molecular technologies offer more significant cycle improvements. MAS allows breeders to directly screen for individuals carrying target genes through genotypic detection at the seedling stage, without waiting for trait expression. This avoids long-term field observation and ineffective resource input. Gene-editing technology, on the other hand, enables precise improvement of one or multiple target genes within the genetic background of an excellent popularizedvariety, achieving " targeted upgrading" of rice germplasm resources. Furthermore, MDB, through the systematic integration of the aforementioned modern biological tools, makes the ideal of precisely and efficiently breeding new rice varieties a tangible reality. Therefore, the establishment and refinement of molecular breeding systems provide the core technological foundation for realizing the concept of rice speed breeding.

Key Components of Speed Breeding Facilities

Illumination

In non-natural agricultural systems such as growth chambers and plant factories, precise regulation of light is a key strategy for shortening the rice growth cycle. As a typical short-day plant, the transition of rice from vegetative growth to reproductive growth is primarily induced by photoperiod signals. This process is tightly regulated by a complex photoperiod regulatory network.

To maximize the acceleration of the rice growth process, most breeders adopt a phased photoperiod switching control mode. During the early vegetative growth stage of rice, plants are maintained under long-day conditions for a long time. This strategy aims to increase the cumulative photosynthetically active radiation, thereby promoting rapid biomass accumulation and the formation of effective tillers, laying the material foundation for subsequent reproductive growth.

When the plants reach a preset leaf age or a specific developmental threshold, the light conditions are rapidly switched to a short-day environment. This artificially created short-day environment serves as the essential signal for activating the endogenous heading genes in rice. Specifically, two pathways determine floral induction in rice. One is the OsGI-Hd1-Hd3a pathway, which is homologous to the GI-CO-FT pathway in *Arabidopsis*[30]. Hd1 has a dual function. Under short days, it promotes flowering, whereas under long days, it represses flowering[31-32]. The other is a pathway unique to rice, the Ghd7-Ehd1-Hd3a/RFT1 pathway[33]. Under long-day conditions, Ghd7 inhibits the expression of downstream genes, thereby delaying heading[34]. Through precise manipulation of the photoperiod transition, the dependence of rice on natural seasons and latitudes under field conditions can be artificially overcome. This significantly shortens the time from sowing to heading, thereby achieving optimization and acceleration of the rice breeding cycle.

Furthermore, light quality and intensity are also indispensable. Light quality serves not only as the energy source for photosynthesis, but also as a critical signal regulating photomorphogenesis in rice. The growth and development of rice are co-regulated by red, blue, and far-red light. The ratio of blue to red light, as well as the ratio of red to far-red light, is particularly crucial for rice growth and development. Red and blue light correspond to the primary absorption peaks for photosynthesis. Blue light, mediated by cryptochromes and phototropins, promotes short and strong plants, well-developed root systems, and enhanced root activity in rice[35]. Therefore, an appropriate amount of blue light contributes to shaping the ideal compact and sturdy plant type, which is suitable for high-density cultivation. Red light, primarily acting through phytochromes, efficiently drives photosynthesis, promotes stem elongation growth, increases dry matter accumulation, and facilitates root morphological development. Therefore, in rapid breeding, optimizing the red-to-blue light ratio has a positive impact on rice growth, proving superior to treatment with a single light spectrum[36]. However, an excessively high proportion of red light may lead to excessive growth and delayed heading in rice. Far-red light, on the other hand, serves as a key signal regulating the flowering process in rice. In speed breeding practice, supplementing with additional far-red light can significantly promote rice flowering and greatly compress the generation cycle[37]. Regarding light intensity, it directly determines the rate of photosynthesis and the speed of biomass accumulation. Research indicates that both excessively low and high photosynthetic photon flux densities can cause varying degrees of damage to rice[38]. Therefore, it is generally maintained at $500-600\ \mu mol/(m^2\cdot s)$ to meet the high metabolic demands of plants during rapid growth. Rational design of light intensity and quality ensures compact internodes and moderate plant height, thereby enhancing cultivation efficiency.

Temperature

Temperature is a core environmental factor regulating rice metabolic rate and driving phenological progression. The growth cycle of rice is closely linked to the accumulation of its required effective accumulated temperature[39]. Therefore, the primary environmental strategy in rice speed breeding facilities is to provide constant and optimal temperature conditions, which enables rice to complete its developmental requirement for total accumulated temperature in the shortest possible time, thereby maximally compressing the generation cycle.

To achieve the "rapid" objective, these systems generally employ a constant high-temperature strategy during the vegetative growth phase. Compared with the diurnal and seasonal temperature fluctuations in traditional field environments, facilities can maintain a constant temperature at the upper limit of the optimum range for rice growth. Under these conditions, the rapid increase in leaf age and the occurrence of tillering are significantly promoted, maximizing the "accumulation efficiency of daily accumulated temperature".

However, during the reproductive growth phase, particularly from meiosis to flowering and pollination, rice is extremely sensitive to high-temperature stress[40]. If the high-temperature strategy from the vegetative growth phase is continued during this stage, it is highly likely to trigger pollen abortion, abnormal spikelet opening, and reduced stigma receptivity, resulting in a precipitous drop in seed setting rate and meaningless breeding.

Therefore, efficient temperature regulation for speed breeding must adopt a "phased management" mode. It involves using constant high temperatures during the vegetative growth phase to "accelerate" developmental processes, followed by a prompt reduction of temperature to a safe threshold upon transitioning into the reproductive growth phase. This precise temperature control strategy is the key technological pathway for achieving the maximum compression of the generation cycle while ensuring effective reproduction.

Cultivation methods and nutrition management

Speed breeding in rice plant factories commonly adopts soilless cultivation systems. This mode offers advantages such as reduced pest and disease incidence, water and fertilizer saving, and high controllability[41].

Solid substrates for soilless cultivation primarily include rockwool, vermiculite, perlite, sand, gravel, sawdust, coconut fibre, peat moss, bark, and mushroom residue. These can be used individually or blended in specific ratios according to requirements.

Currently, the common practice is to mix two or three of these substrates to create a composite growing medium for use. Solid substrates provide essential nutrients for rice growth, prevent water deficiency while maintaining good aeration. They offer sufficient physical support for plant development. This supportive role helps stabilize the plant's root system and reduces the risk of root damage or fatigue breakage.

In speed breeding systems, rice relies entirely on nutrient solution supply throughout its entire life cycle. Nutrient solution management serves not only to provide essential nutrients but also as a dynamic tool for regulating rice physiological processes. Internationally recognized nutrient solution formulations for rice serve as the foundational basis for research. However, within the closed-loop and high metabolic rate conditions of plant factories, these formulas require modification. For instance, the Yoshida formulation was originally designed for studies on rice mineral nutrition. Its relatively high iron (Fe) concentration may need adjustment in recirculating systems to prevent precipitation.

Furthermore, accurately monitoring key parameters of the nutrient solution is a crucial aspect of perfecting soilless cultivation. Electrical Conductivity (EC) indicates the total salt concentration in the nutrient solution. An excessively high EC can damage the root system, while an overly low EC fails to meet the growth and developmental needs of rice. Therefore, the EC is generally adjusted throughout the rice growth cycle as needed. The pH level is another critical parameter in the nutrient solution that significantly influences rice growth and development. The demand for pH varies among different rice varieties, but most of them thrive within a range of 5.5 to 7.5. Prolonged exposure to excessively high or low pH levels can cause damage to both the root system and the aboveground part of the rice plant, leading to symptoms such as wilting and yellowing.

Abiotic stress

The core of rice speed breeding technology lies in optimizing the environment to shorten the generation cycle. However, precisely controlled "abiotic stress induction" can also serve as an auxiliary strategy. By applying mild stress, this approach can accelerate the transition of rice from vegetative growth to reproductive growth.

Water stress is a precisely utilized method within this strategy. Research indicates that, following the accumulation of sufficient biomass at the end of the vegetative growth stage, implementing precise water control (such as a moderate water deficit) can effectively suppress ineffective tillering, promote physiological transition, and thereby induce earlier flowering.

Similarly, nutrient stress, particularly nitrogen limitation, is also applied to regulate the developmental process. Given that excessive nitrogen application in field conditions commonly delays flowering, speed breeding facilities can exploit this mechanism in reverse. By precisely controlling nitrogen supply in the nutrient solution to create a state of "mild nutrient hunger", this mild nutrient limitation compels the plant to suppress vegetative growth and prioritize resource allocation towards reproductive growth, thereby shortening the generation cycle. However, similar to water stress, nutrient limitation must be moderate. Excessive deficiency will severely impair the plant's growth foundation and pollen viability, ultimately affecting seed production.

In addition, other methods include manipulating light intensity, ultraviolet radiation, temperature, plant crowding, root pruning, and mechanical stimulation to induce accelerated growth in rice[42].

In summary, whether applying water or nutrient stress as an induction strategy for accelerating breeding, the core principle lies in "precision" and "moderation". It require implementation within a highly controlled environment to achieve the compression of developmental time without sacrificing critical reproductive capacity.

Application Cases and Practical Outcomes

In recent years, numerous breakthrough achievements have been made both at home and abroad in the application of rice speed breeding. Regarding facility-based breeding, the early Biotron system (BBS) in Japan successfully achieved a single generation of Nipponbare rice within 60 d. Subsequently, Tanaka[43] simplified the BBS to make it more suitable for large-scale adoption in breeding programs, thus creating the simplified Biotron breeding system (sBSS). In 2020, researchers in Germany, employing an LED lighting scheme supplemented with far-red light, achieved flowering in rice within 60 d following short-day treatment. The far-red light supplementation resulted in flowering approximately 20 d earlier[37]. The "SpeedFlower" system, recently developed by the International Rice Research Institute (IRRI), induced flowering in rice within 52 – 60 d by combining an initial phase of 24-h illumination with subsequent short-day regulation. Validation results show that 198 varieties with diverse genetic backgrounds completed one generation cycle in 58 – 71 d, corresponding to an annual propagation rate of 5.1 – 6.3 generations[44]. Progress is also ongoing in China regarding plant factory-based generation advancement. Breeders in Hainan have achieved rapid generation advancement of four cycles per year for rice through methods such as dense planting, dry direct seeding, controlled water, and controlled fertilizer application[45]. Fully controlled plant factories in Wuhan and other areas, utilizing measures such as high temperature, short photoperiod, and customized LED light spectra, have achieved cycles of 3 – 4 generations per year[46]. Some facilities in Jiangsu Province complete one generation in 75 – 77 d[47]. Furthermore, the SpeedyPaddy protocol developed by an Indian research team, utilizing high light intensity and dense planting techniques, requires only 68 – 75 d per generation, enabling 4 – 5 generations per year[48]. Desert-based speed breeding experiments in Xinjiang can also complete one generation in approximately 63 d through multi-layer vertical soilless cultivation.

Main Challenges

Despite demonstrating immense transformative potential, in the process of moving from laboratory models to industrialization and universal application, the speed breeding technology of rice still faces significant challenges from many dimensions, such as economy, technology and biology.

High economic cost

Establishing a rapid breeding system requires constructing facilities capable of precise environmental control (such as large-scale growth chambers or plant factories) and equipping them with specialized LED lighting systems, both of which entail substantial initial capital investment. The operational costs are also prohibitively high, particularly the electricity consumption for high-intensity lighting and constant temperature/humidity control, which far exceeds that of conventional greenhouse models. Consequently, speed breeding technology is currently primarily concentrated within well-funded research institutions, creating a significant barrier to its broader adoption by small and medium-sized units.

Bottlenecks in large-scale application

The issue of "protocol universality" requires attention. Many current successful speed breeding protocols have been optimized for specific or improved varieties. Traditional varieties highly sensitive to photoperiod or materials with complex genetic backgrounds may not be directly applicable, often necessitating iterative exploration for adaptation schemes. In the promotion process, it is also necessary to prevent potential biological risks, such as whether extreme growth conditions will cause unexpected genetic or epigenetic effects, and whether long-term cultivation will affect seed quality and adaptability. These issues still lack systematic research.

Conclusions and Future Perspectives

Rice speed breeding, as a core acceleration mechanism within modern crop genetic improvement systems, is gradually transitioning from theoretical exploration to practical application and industrial-scale implementation. Through the precise engineering control of environmental factors and the deep integration of modern biotechnologies, this technology has significantly shortened the rice generation cycle and substantially increased breeding efficiency. It provides an innovative pathway for addressing global food security challenges, overcoming limitations in germplasm resources, and accelerating the pyramiding of superior genes. Currently, significant landmark progress has been achieved both at home and abroad in areas such as facility construction, light and temperature control strategies, integration of molecular tools, and multi-generation advancement practices. These advancements have preliminarily confirmed the technical feasibility of achieving 5 – 6 generations of rice per year, indicating that rice breeding is entering an era of high-efficiency development.

However, achieving the widespread adoption and sustainable development of speed breeding technology still faces multiple challenges. On one hand, the high costs associated with facility construction and operation constrain its broader application within small-to-medium-sized breeding institutions and public research platforms. On the other hand, current protocols are often optimized for specific genetic backgrounds. Their generalizability to photoperiod- and temperature-sensitive local varieties or complex hybrid materials still requires enhancement. Furthermore, long-term, multi-generational cultivation under artificial and extreme conditions may lead to issues such as unintended genetic variation, epigenetic changes, or reduced seed vigor, necessitating systematic evaluation and long-term monitoring.

Looking ahead, the development of rice speed breeding will present three main trends. The first is intelligence enhancement. Technologies such as the Internet of Things (IoT), artificial intelligence (AI), and automated control will be integrated to build intelligent plant factories with capabilities for self-perception, self-decision-making, and self-regulation, shifting from fixed-parameter control to dynamic optimization. The second is low-cost and green transformation. It is necessary to develop high-efficiency LED light sources, optimize energy management strategies, and incorporate renewable energy sources such as solar power. These measures will reduce energy consumption and carbon footprint per generation, thereby enhancing the technology's economic viability. The third is systematic integration. We will promote the deep integration of speed breeding with cutting-edge technologies such as genome design, gene editing, and phenomics. This will establish an integrated, high-efficiency breeding pipeline encompassing " design, editing, accelerating, and testing". Relying on regional public service platforms, this approach aims to foster an open, collaborative, and shared breeding innovation ecosystem.

It can be anticipated that with the gradual overcoming of technical bottlenecks and the continuous expansion of application fields, rice speed breeding will not only become a core driving force for accelerating the development of new varieties, but will also reshape the paradigm of modern seed industry research and development. It will provide robust technical support for safeguarding national food security and contributing to global food supply.

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