Innovative Molecular Breeding Technologies Supporting China's Seed Industry Development (Postprint)

Authors: Xue Yongbiao, Zhong Kang, Han Bin, Gui Jianfang, Haichun Jing

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Abstract

The transformation of China's principal social contradictions in the new era and food security issues have imposed higher demands on the modern agricultural industry system. "Agriculture begins with seeds," yet for many years, China's seed industry has suffered from insufficient independent innovation capabilities, backward breeding concepts and methods, and continues to exhibit prominent issues such as blind decision-making and excessive reliance on experience. This article provides an overview of the molecular module design breeding technology system innovatively proposed by Chinese scientists, introduces its explorations and practices in theoretical development, technological research, and variety design, and points out that molecular design breeding will become an important means to enhance independent innovation capabilities in the seed industry and address the "bottleneck" technological challenges in its development.

Full Text

Designer Breeding by Molecular Modules: Innovation and Achievements in China

Abstract

With over 1.3 billion people, food security remains the foremost priority on China's governmental agenda. Sustainable food production requires continuous innovation in crop breeding. This paper outlines the research efforts and outputs over the past five years of the Chinese Academy of Sciences' Strategic Priority Project "Innovation System of Designer Breeding by Molecular Modules," providing examples of how cutting-edge life science theories and technologies can be integrated to design rice varieties and other species. The achievements demonstrate that this project has made substantial progress in designer breeding using molecular modules.

Keywords: molecular modules, designer breeding, innovation system

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Food Security Challenges in the New Era

China's transition to a new era of social development and its evolving food security concerns have placed unprecedented demands on the modern agricultural industry system. "Agriculture begins with seeds," yet for years, China's seed industry has suffered from insufficient independent innovation capacity, outdated breeding concepts and methods, and persistent problems of blind, experience-dependent practices. This article summarizes the innovative molecular module design breeding technology system proposed by Chinese scientists, introducing its theoretical development, technological innovation, and practical applications in variety design, while highlighting how molecular design breeding will become a crucial tool for enhancing independent innovation capacity and resolving critical technological bottlenecks in China's seed industry development.

China has nearly 1.4 billion people, making agricultural and food security perpetually one of the top priorities for Party and government governance. Over 40 years of reform and opening up, China's rapid economic development and social progress have created a "Chinese miracle." In agricultural production, crop yields have increased for 13 consecutive years, with abundant supplies of agricultural and livestock products. However, Chinese agriculture still faces enormous challenges.

In 2017, China's total grain output reached 610 million tons, while grain imports totaled approximately 130 million tons (including 95.53 million tons of soybeans and 34.46 million tons of cereals), accounting for one-fifth of domestic production. China's grain self-sufficiency rate has dropped to only 82.4%, significantly breaching the 95% safety threshold, with over 200 million people dependent on imported grain. In fact, China has long been a major agricultural importer. In 2017, agricultural imports reached $125.86 billion, a year-on-year increase of 12.7% [1]. The world food production situation remains concerning, with 700 million people still living in extreme poverty and nearly 800 million suffering from chronic malnutrition, including 159 million stunted children under age five [2]. Therefore, China must rely on itself for food security, as President Xi Jinping has repeatedly emphasized: "The Chinese people's rice bowl must be firmly held in our own hands at all times, and our bowl should mainly contain Chinese grain."

In the new era, "Chinese grain" in President Xi Jinping's vision encompasses not only traditional staple foods but also meat, eggs, and milk. While importing large quantities of grain and oil, China also imports livestock products and forage. In 2017, China imported 5.41 million tons of meat and dairy products and 1.86 million tons of forage grass, with most imported soybeans used for animal feed. Thus, food security has largely become feed grain security. At current domestic meat demand growth rates, China's meat supply gap is projected to reach 28 million tons by 2030. If dairy consumption reaches the Asian average level, the supply gap will be 72 million tons.

Agriculture was one of the earliest fields of economic cooperation between China and the United States. Since 2001, bilateral agricultural trade has grown at an average annual rate of 15%, with U.S. exports to China increasing 17% annually, maintaining a long-term trade surplus. In 2017, the United States was China's largest source of agricultural imports. During the recent China-U.S. trade war, agricultural products became a focal point. If the U.S. were to embargo grain rather than chips, where would China's national security stand? These challenges extend beyond grain and oil crops to include forage crops and livestock.

Current Status and Bottlenecks of China's Seed Industry

"Seeds are the 'chips' of agriculture." According to the latest report from the International Service for the Acquisition of Agri-biotech Applications (ISAAA), the global seed market exceeded $56 billion in 2017, with most commercial seed markets concentrated in 20 countries. The United States ranks first globally, accounting for about 40% of the world market [2]. For years, China has been the world's second-largest seed market, reaching ¥78 billion in 2015, with domestic seed output of 1.865 million tons. By 2020, China's commercial seed market is projected to exceed ¥100 billion, with seed demand reaching 2 million tons. Among sales categories, rice seeds account for approximately 29.9%, corn seeds 40.4%, and vegetable, cotton, rapeseed, and melon seeds 29.7%.

Overall, China has about 4,500 seed companies—far more than the few dominant companies in Europe and the United States—but this reflects low industry concentration and the absence of oligopolistic players. Additionally, low R&D investment by seed enterprises, urgent need for improved innovation capacity, and rising seed production costs are all challenges facing China's seed industry. China's seed industry struggles to adapt to the impacts of rapid globalization and increasing monopolization in the global seed market. International seed giants, with their substantial capital, advanced technology, and integrated business models, control the international seed market. The world's top ten seed companies, including Monsanto and Pioneer, occupy 70% of the global market, showing high concentration. Although China possesses the world's second-largest seed market and will be a primary engine for global seed market growth, only by cultivating a group of "breeding-extension-marketing integrated" seed industry groups can China defend its seed industry security 底线.

Under 积极引导 from national policies, we have seen ChemChina successfully acquire Syngenta, while Longping High-Tech is accelerating its development and mergers. Consequently, Chinese companies now occupy two positions among the world's top ten seed companies in 2017. However, fundamentally changing this unfavorable situation and strengthening the seed industry requires top-level design and source-level technological innovation. The collapse of China's soybean industry, the monopoly of foreign companies in vegetable seeds, and the dominance of "Xianyu 335" in corn varieties all demonstrate the scarcity of technological supply capacity in China's seed industry. A comparison of grain production capacity between China and the United States shows that one American farmer's productivity equals that of 236 Chinese farmers, with one fundamental reason being the gap in agricultural production technology supply capacity.

For years, China's seed industry has lacked independent innovation capacity, with many technological innovation capabilities needing urgent strengthening. Original and integrated innovation capabilities are insufficient, with redundant research content, inadequate research depth, fragmented industry sectors, and dispersed research layouts, leading to outdated breeding concepts and methods, narrow genetic diversity, long breeding cycles (generally over 10 years), and blind, experience-dependent breeding practices. The new era calls for a breakthrough breeding innovation system.

Molecular Module Design Breeding Technology System

Molecular modules are heritable functional units comprising functional genes and their regulatory networks [5]. Since complex traits result from gene-gene and gene-environment interactions, and most agronomic (economic) traits are regulated by multiple genes with "modular" characteristics, it is necessary to comprehensively apply the latest advances in molecular biology, genomics, and systems biology to study the functions of molecular modules controlling complex traits. Using computational and synthetic biology approaches, these modules can be organically coupled to conduct theoretical simulations and functional predictions, systematically exploring the comprehensive regulatory potential of molecular module interactions on complex traits. This enables the organic coordination and unification of module coupling with genetic background and regional environments, maximizing the non-linear 叠加 effects of molecular module groups on complex traits and effectively achieving directional improvement of complex traits (Figure 1 [Figure 1: see original paper]) [6]. Thus, molecular module breeding is a forward-looking, strategic research field that organically combines frontier life science questions with breeding practice, representing a new direction for future biotechnology development.

Transgenic breeding technology has achieved remarkable results over the past 22 years, with cumulative planting in 67 countries and regions reaching 2.3 billion hectares—an 112-fold increase—generating $17.2 billion in output value in 2017. However, transgenic technology primarily targets trait improvement controlled by a few single genes, making it difficult to breed breakthrough new varieties for complex trait improvement. Genomic selection [3], an extension of marker-assisted selection across the entire genome, has long been considered the optimal method for predicting phenotypes in unknown populations and achieving more comprehensive, reliable selection for complex traits. However, this method does not emphasize mechanistic studies of gene function and interaction, making breeding selection more of a theoretical model prediction "game," with no reports of integrated breeding for complex traits to date. Monsanto's use of molecular markers to pyramid multiple drought resistance loci into a highly drought-resistant corn variety (gene stacking) represents a successful case of complex trait improvement through molecular markers. Additionally, the recent emergence of technology systems using controlled environments to accelerate crop growth provides new ideas for shortening breeding cycles [4]. However, these advances have not systematically integrated molecular- and cellular-level gene function and interaction research with genome-level selection from a design perspective to develop new breeding theories and technology systems for complex traits. Therefore, developing a new generation of breeding theory and technology systems is an urgent need for modern seed industry development.

Strategic Priority Project Implementation

In November 2013, the Chinese Academy of Sciences launched the Strategic Priority Project (Category A) "Innovation System of Designer Breeding by Molecular Modules." The project integrated strengths in agricultural biology and breeding research, comprising 4 projects, 12 topics, 64 sub-topics, and 144 task-specific projects, with a total team of over 2,100 personnel. Focusing primarily on rice breeding, with wheat and carp as secondary targets, the project utilized wild varieties, landraces, elite cultivars, and superior germplasm resources to parse molecular modules controlling important agronomic (economic) traits such as high yield, stable production, quality, and efficiency; reveal the systematic parsing and coupling rules of molecular modules; optimize strategies for multi-module assembly variety design; establish a modern biotechnology breeding innovation system from "molecular modules" to "variety design"; and cultivate new super agricultural biological varieties to promote the healthy, rapid development of China's biological breeding technology and meet major demands of agricultural development in China and worldwide.

Over five years of implementation, the project has preliminarily established a modern biotechnology breeding innovation system from "molecular modules" to "variety design," representing a bold practice and successful exploration that disrupts traditional breeding technologies.

Theoretical and Technological Innovations in Module Breeding. Deep analysis of the rice cold tolerance molecular module COLD1 elucidated the molecular mechanism of crop low-temperature perception, with results published as a cover paper in *Cell* [7]. Research on the genetic mechanism of rice heterosis promises to shorten each generation of hybrid breeding from 8 years to 3-5 years, published in *Nature* [8]. Deep analysis of the rice broad-spectrum and durable blast resistance module Pigm, published in *Science*, revealed a novel epigenetic regulatory mechanism balancing broad-spectrum disease resistance and yield, which has been widely applied in disease resistance molecular breeding and large-scale promotion [9].

Practical Applications of Module Breeding. The project has parsed 67 molecular modules and 43 molecular module systems with important application value; approved 15 new rice, soybean, wheat, and high-yield silver carp varieties (including 5 nationally approved varieties); obtained 16 new lines in production trials, 65 in regional trials, and 118 in preliminary trials. In the middle and lower Yangtze River and Huang-Huai rice regions, module-based new varieties such as "Jiayouzhongke" 1, 2, 3, "Zhongheyou 1," and "Zhongkeyan 1" have achieved perfect integration of super-high yield, quality improvement, and enhanced resistance (Figure 2 [Figure 2: see original paper]). In Northeast China, the nationally approved variety "Zhongke 804" shows significant promotion potential in the first accumulated temperature zone of Northeast China and Northwest regions (Figure 3 [Figure 3: see original paper]). The multi-module coupling new rice variety "Zhongke 902," bred with "Kongyu 131" as the chassis, combines blast resistance, cold tolerance, early maturity, and fragrance characteristics, promising to solve current bottlenecks of degraded disease resistance and declining grain quality in 35 million mu of rice in Heilongjiang's Jiansanjiang region. The nationally approved variety "Allogynogenetic Silver Carp Zhongke 5" offers advantages including 18.20% faster growth, 13% higher survival rate during disease outbreaks, and fewer fish bones (9% reduction in total intermuscular bones), with potential for variety renewal within three years.

Based on these major achievements, under the guidance of Chief Scientist Yongbiao Xue, the project management office organized an 8-paper special issue in the *Bulletin of Chinese Academy of Sciences*, summarizing project outcomes in rice, wheat, soybean, corn, and fish breeding, and introducing domestically developed molecular breeding equipment such as crop phenotyping detection and seed slicing, demonstrating China's world-leading theoretical research, technology applications approaching world advanced levels, and the major strategic significance of "designer breeding by molecular modules" for guiding future crop genetic improvement.

Future Perspectives

Seeds are the lifeblood of agriculture, and breeding theory and engineering technology are the "bottleneck" technological issues constraining seed industry development. Industrial competition is essentially competition in technological reserves and supply capacity. "Molecular modules" is a theory proposed by Chinese scientists. Through the strategic layout of this priority project, the Chinese Academy of Sciences has conducted excellent forward-looking, targeted, and reserve strategic research on the molecular module design breeding technology system, achieving remarkable results. However, we must 清醒地 recognize that "key core technologies cannot be begged for, bought, or obtained through charity," and we must "dare to take paths that predecessors have not taken, striving to achieve independent control of key core technologies and firmly grasp the initiative in innovation and development."

Looking ahead, to meet future agricultural product development demands on breeding technology, the molecular module design breeding technology system should emphasize integration with the latest research achievements in several fields:

1. **Synthetic Biology.** The rapid development of molecular biology, omics, and systems biology has greatly enhanced our understanding of speciation mechanisms. In the next round of molecular module design breeding innovation, integrating disruptive common technologies such as computational biology, synthetic biology, and genome editing with engineering technology systems will enable species synthesis and reconstruction based on chassis varieties. Future breeding may integrate molecular module systems for multiple complex traits based on target regional needs to create synthetic functional species through specific design.
2. **Designer Breeding Big Data.** Emphasis should be placed on integrating imaging, omics, species diversity, crop individual development, and environmental adaptation data to construct big data knowledge graphs based on complex systems and indicator systems for regional natural resource endowments at different scales. Integrating deep learning technologies, statistical models such as time-series-based scoring matrices and probabilistic matrix factorization should be established to enable prediction of molecular module-designed varieties.
3. **Intelligent Management of Designer Breeding.** Based on big data intelligent analysis of correlation, time series, classification, and clustering, optimal allocation and control models for light, temperature, water, heat, fertilizer, and pesticides should be constructed. Intelligent variety design through module system coupling should be implemented for yield quality, disease and pest control, and resource-efficient utilization. Planting, weeding, and fertilizing robots should be developed, along with visualization, automation, natural language processing, and deep learning supercomputing platforms to serve intelligent management of designer breeding.

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Author Information

XUE Yongbiao
Director, Beijing Institute of Genomics; Principal Investigator, Institute of Genetics and Developmental Biology, Chinese Academy of Sciences; Chief Scientist, CAS Strategic Priority Project "Innovation System of Designer Breeding by Molecular Modules." His research focuses on plant molecular genetics, including the molecular mechanisms of self-incompatibility in flowering plants, cloning of important functional genes, and genome sequencing. He has published over 100 SCI-indexed papers and holds more than 10 authorized patents. He has supervised 43 PhD students and 10 postdoctoral fellows. E-mail: ybxue@genetics.ac.cn

CHONG Kang
Institute of Botany, Chinese Academy of Sciences, Beijing 100093, China

HAN Bin
Institute of Plant Physiology and Ecology, Shanghai Institutes for Biological Sciences, Chinese Academy of Sciences, Shanghai 200032, China

GUI Jianfang
Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan 430072, China
*Corresponding author

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