

REVIEW

China-CIMMYT collaboration enhances wheat improvement in China

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Abstract China and CIMMYT have collaborated on wheat improvement for over 40 years and significant progress has been achieved in five aspects in China. A standardized protocol for testing Chinese noodle quality has been established with three selection criteria, i.e., gluten quality, starch viscosity and flour color are identified as being responsible for noodle quality. Genomic approaches have been used to develop and validate gene-specific markers, leading to the establishment of a KASP platform, and seven cultivars have been released through application of molecular marker technology. Methodology for breeding adult-plant resistance to yellow rust, leaf rust and powdery mildew, based on the pleiotropic effect of minor genes has been established, resulting in release of six cultivars. More than 330 cultivars derived from CIMMYT germplasm have been released and are now grown over 9% of the Chinese wheat production area. Additionally, physiological approaches have been used to characterize yield potential and develop high-efficiency phenotyping platforms. CIMMYT has also provided valuable training for Chinese scientists. Development of climate-resilient cultivars with application of new technology will be the priority for future collaboration.

Keywords adult-plant resistance, bread wheat, breeding, gene-specific marker, germplasm exchange, processing quality

1 Introduction

International Maize and Wheat Improvement Center (CIMMYT) is the global leader in publicly-funded maize and wheat research and related farming systems. The international wheat breeding program at CIMMYT, initiated by Norman E. Borlaug in the late 1940s and supported by multidisciplinary research teams, has been unique in several aspects, such as operation of shuttle breeding in two contrasting environments, utilization of newly developed technologies, international testing network and free distribution of elite germplasm, and close collaboration with national programs and advanced institutes. CIMMYT germplasm is broadly used in both developing and developed countries, largely due to its high yield potential, broad adaptation, and disease resistance and has achieved great impact globally^[1].

China is the largest wheat producer and consumer in the world, with annual production area of about 24 Mha, and a production of 130 Mt in 2017. In comparison with 1978, average yield and production have increased approximately 2.9- and 2.4-fold, respectively, while the production area has decreased by about 22%. This is largely due to the development of improved cultivars and crop management technologies including utilization of introduced germplasm from other countries, increased inputs, such as, fertilizer, irrigation and machinery, and favorable agricultural policy^[2]. China's economic reform in the late 1970s provided a unique opportunity for developing China-CIMMYT collaboration in wheat improvement. The history of this partnership can be divided into three phases, i.e., 1970–1985, purchase of commercial seeds from Mexico and introduction of new germplasm; 1986–1996, initiation of shuttle breeding and training program; 1997–

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2018, establishment of a CIMMYT office in China and operation of joint research programs supported by CIMMYT programs in Mexico and other locations. China-CIMMYT collaboration has contributed significantly to improving Chinese wheat production, research capacity and training. It has been continuously supported by the Ministry of Agriculture and Rural Affairs, Ministry of Science and Technology, National Natural Science Foundation of China, State Administration of Foreign Experts Affairs and China Scholarship Council. CIMMYT's contributions to wheat improvement in China have been highly recognized, four CIMMYT scientists have received the Friendship Award from Chinese government, and CIMMYT was selected to be the recipient of the International Collaboration Award from State Council in 2016. This collaboration is considered to be an excellent example of win-win partnership in China as well as globally. The objective of this paper is to review the progress of China-CIMMYT collaborations in several aspects: understanding wheat quality, development of gene-specific markers and KASP assays, developing germplasm with adult-plant resistance based on minor genes, germplasm introduction and utilization, and collaborative platform and training.

2 Understanding wheat quality in China

2.1 Evaluating noodle quality

Very little information on wheat quality in China was available before the 1990s because improvements of yield potential and disease resistance had always been the major breeding objectives. Therefore, recent efforts have focused on development of standardized protocol for traditional products such as noodles and steamed bread which represent about 85% of wheat consumption in China, characterization of leading cultivars and advanced lines from major wheat regions, and development and application of gene-specific markers since the establishment of CIMMYT China Office in 1997.

Work on noodle quality in China has been reviewed^[3], so only major progress is summarized here. A standardized laboratory method for assessing noodle quality is crucial in wheat breeding programs targeted on development of cultivars for improved noodle quality. The recommended preparation formula for Chinese white noodles is 60% flour extraction, 35% water addition, 1% salt concentration, and follows the establishment of a standardized laboratory noodle preparation protocol^[4]. The score values given to each noodle trait, i.e., color, appearance, firmness, viscoelasticity, smoothness, and taste and flavor, were 15, 10, 20, 30, 15 and 10, respectively. To improve consistency among panel members, a new scoring method was developed, and each attribute was classified into seven classes, i.e., excellent, very good, good, fair, poor, very

poor and unacceptable, and a score was assigned to each class based on comparison with a reference sample at each panel session^[5]. Major traits responsible for noodle quality have been identified, i.e., gluten strength and extensibility, starch viscosity and flour color, and selection criteria for each trait have been recommended^[5–7]. At present, the above noodle preparation, testing, scoring system, and selection criteria are widely used in China and several noodle cultivars such as Zhongmai 175 have been released and widely adopted by farmers.

2.2 Understanding wheat quality

A quality classification system for wheat is not well established in China. Wheat is characterized by a combination of grain hardness, acceptable protein content, medium-weak dough and poor extensibility, and substantial variation is presented for all quality traits. In general, the quality is acceptable for many traditional Chinese products, however, quality for mechanized products, such as pan bread and noodles, is poor. For wheat, grain hardness is not matched with protein content and protein quality, i.e., usual type such as hard kernel with high protein content and weak dough quality is commonly presented. Therefore, improvement in dough quality, starch viscosity and color are important breeding objectives, both for traditional products and for European-style pan bread. The presence of the 1B/1R translocation is high in major wheat regions such as Yellow and Huai River Valleys, thus poor dough quality is expected. Cultivars with outstanding pan bread quality have been developed within the past 20 years, including Zhongyou 9507, Zhongmai 578, Gaocheng 8901, Shiluan 02-1, Jinan 17, Jimai 20, Jimai 44, Yumai 34, Yumai 47, Xinmai 26, and Zhengmai 366. Cultivars with outstanding noodle quality include Jing 411, Jing 9428, Zhongmai 175, Jimai 19, Jimai 20, Yumai 34, Yumai 49, and Zhengmai 366. It has also been possible to develop quality cultivars for both pan bread and noodles, e.g., Yumai 34 and Zhengmai 366.

3 Development of gene-specific markers and KASP assays

A shortage of gene-specific markers and high-efficiency genotyping platforms are two major factors limiting the utilization of molecular markers in wheat breeding. Thus, a genomic approach has been employed to clone genes associated with wheat quality, and then develop and validate gene-specific markers. Significant progress in this area has been achieved, as reviewed in 2012^[8], and about 50 gene-specific markers have been developed and extensively used in 20 countries.

Two aspects of molecular marker development need to be highlighted. The genes associated with noodle color are shown in Table 1, with the gene cloning and development

Table 1 Genes and gene-specific markers associated with noodle color

Gene	Chromosome	Marker	Allele	Phenotype
Phytoene synthase (<i>Psy</i>)	7A	YP7A	<i>Psy-A1a/Psy-A1c</i>	High
			<i>Psy-A1b</i>	Low
	7B	YP7B	<i>Psy-B1a</i>	Medium
			<i>Psy-B1b</i>	Low
Phytoene desaturase (<i>Pds</i>)	4B	YP4B-1	<i>TaPds-B1b</i>	High
		YP4B-2	<i>TaPds-B1a</i>	Low
1BL.1RS	1B	H20F/R	<i>Y</i>	High
			<i>N</i>	Low
Polyphenol oxidase (<i>Ppo</i>)	2A	PPO18	<i>Ppo-A1a</i>	High
			<i>Ppo-A1b</i>	Low
	2B	F-8	<i>Ppo-B1a</i>	Low
			<i>Ppo-B1b</i>	High
	2D	PPO16	<i>Ppo-D1a</i>	Low
		PPO29	<i>Ppo-D1b</i>	High
Lipoxygenase (<i>Lox</i>)	4B	LOX16	<i>Lox-B1a</i>	High
		LOX18	<i>Lox-B1b</i>	Low
Peroxidase (<i>Pod</i>)	3A	Pod-3A1	<i>Pod-3Aa</i>	Low
		Pod-3A2	<i>Pod-3Ab</i>	High

of gene-specific marker for polyphenol oxidase given as an example^[9]. Low-molecular-weight gluten subunits associated with dough quality, and gene-specific markers for Glu-A3 and Glu-B3 have been developed and widely utilized in various quality testing programs^[10]. Due to the complexity and relatively minor contribution to processing quality, no molecular markers are available for genes at Glu-D3.

Recently, kompetitive allele-specific PCR (KASP) assays have been developed and validated for genes that underpin economically important traits in bread wheat including adaptability, grain yield, quality, and biotic and abiotic stress resistances^[11]. At present, 1500 cultivars can be genotyped with 150 available gene-specific markers, including those for quality attributes, within 2–3 days. In total, over 5000 cultivars and advanced lines from 20 Chinese wheat breeding programs and other major countries have been genotyped at the CAAS-CIMMYT laboratory.

More importantly, molecular markers have been routinely used to characterize crossing parents and advanced lines, and seven cultivars, such as Zhongmai 1062 and Jimai 23, with improved qualities developed by molecular programs have been released and adopted by farmers.

4 Developing germplasm with adult-plant resistance based on minor genes

Yellow rust, leaf rust and powdery mildew are the three major diseases in China, thus development of multi-

disease resistance germplasm is a national priority in most wheat regions. Wheat production in China has been affected by the loss of cultivar resistance for yellow rust and powdery mildew on several occasions since the early 1950s, due to the emergence of new races. The CIMMYT wheat breeding program in Mexico has successfully used adult-plant resistance genes in controlling leaf rust for 50 years, starting in the early 1970s. In the late 1990s, the Chinese Academy of Agricultural Science (CAAS) and Sichuan Academy of Agricultural Science started to collaborate with CIMMYT in breeding for adult-plant resistance targeting powdery mildew and yellow rust, respectively, as a novel approach to breed for disease resistance following frequent failures in protection using race-specific resistance genes. More than 400 genotypes including local and introduced cultivars have been screened for adult-plant resistance, and eight QTL conferring multi-resistance to yellow rust, leaf rust and powdery mildew have been identified^[12–14]. QTL mapping for historical cultivars conferring adult-plant resistance to yellow rust, leaf rust and powdery mildew indicated that the same locus was responsible for the rust and powdery mildew resistance^[15–20], with detailed information presented in two reviews^[21,22]. Additionally, more than 100 lines with resistance to the three pathogens were developed by integration of molecular marker-assisted selection and conventional breeding. These multi-disease resistance lines were confirmed by field testing and molecular markers, and they are considered to have durable resistance^[23,24]. Several representative cultivars and advanced lines are presented in Table 2. Chuanmai 82,

Table 2 Cultivars developed from molecular marker program

Cultivar	Cross	Traits	Release region and year
Zhongmai 996	Yumai 34/3* Lunxuan 987	IDQ, medium maturity	Tianjin, 2014
Zhongmai 998	Yumai 34/3* Lunxuan 987	IDQ, medium maturity	Tianjin, 2015
Zhongmai 1062	Yumai 34/3* Lunxuan 987	IDQ, medium maturity	MOA, 2016
Jimai 23	Yumai 34/3* Jimai 22	IDQ, early maturity	Shandong, 2016
Zhongmai 578	Zhongmai 255/Jimai 22	EBMQ, disease resistance	Henan, 2018
Zhongmai 29	Jimai 22/Shilian 02-1	EBMQ	Hebei, 2018
CA16015	Yumai 34/5* Zhongmai 175	EBMQ	Advanced line

Note: IDQ, improved dough quality; EBMQ, excellent bread making quality; MOA, Ministry of Agriculture of China.

with high yielding potential and adult-plant resistance, was released in Sichuan Province in 2017. Zhongmai 578, with excellent bread-making quality, adult-plant resistance, broad adaptation and 2–3 days earlier maturity than the check cultivar, was released in Henan Province in 2018. These cultivars represent excellent examples of utilization of durable resistance based on minor genes through combination of molecular markers and crossbreeding (Table 3).

5 CIMMYT germplasm introduction and utilization in China

Each year, about 2000 CIMMYT advanced lines are introduced to China through international nursery and breeder selection. Currently, about 20000 accessions of CIMMYT germplasm are stored in a gene bank located at CAAS. Multilocational testing in Mexico and key sites in China was conducted to understand the adaptation of CIMMYT germplasm in China. CIMMYT wheat germplasm can be directly used in Yunnan, Xinjiang and Gansu regions, but has served as crossing parents in other regions^[25]. In total, over 330 cultivars derived from CIMMYT germplasm have been released in China^[26], and cultivars such as Han 6172, Chuanmai 42 and Ningchun 4 (Table 4) have been widely adopted by farmers in various regions.

Contributions of CIMMYT germplasm to wheat improvement in China include three key traits. (1)

Improvement of yield potential in spring wheat regions, with annual genetic gains of 1.43%, 0.64%, 0.31% and 0.73% achieved in Xinjiang, Gansu, Yunnan and Sichuan regions, respectively, has been largely due to the utilization of CIMMYT germplasm with high yield potential and broad adaptation^[27]. Synthetic wheat developed by CIMMYT has made a significant contribution to cultivar development, and 10 cultivars including Chuanmai 42 have been released in Sichuan and Heilongjiang Provinces^[28]. (2) CIMMYT wheat has been a major source of genes for improving rust resistance, particularly in Sichuan and Yunnan Provinces. For example, five, seven, and nine cultivars conferring resistance to yellow rust have been released from synthetic wheat, cv. Milan and cv. Alondra, respectively. (3) CIMMYT germplasm has been used as a major quality donor for wheat. For example, Zhongzuo 8131-1 and Linfen 5064, derived from CIMMYT germplasm, have served as core parents for improving processing quality.

Based on a comprehensive analysis from 17 major wheat-growing regions, the use of CIMMYT germplasm has led to an increase in total factor productivity of wheat of from 5% to 14% (annual growth of between 0.17% and 0.45%), depending on the measurement used^[29]. This represents from 3.8 to 10.7 Mt of extra grain, worth 1.2 billion to 3.4 billion USD based on 2011 prices. The use of CIMMYT germplasm in China has increased, and CIMMYT contributions are present in more than 26% of all major wheat cultivars in China since 2000. They have significantly enhanced cultivar performance for important

Table 3 Germplasm with adult-plant resistance

Cultivar	Cross	Disease resistance	Release region and year
Chuanmai 82	Singh 6/3* 1231	YR, LR, PM	Sichuan, 2017
Chuanmai 86	R411/1572	YR, LR, PM	Sichuan, 2018
Zhongmai 578	Zhongmai 255/Jimai 22	YR, LR, PM	Henan, 2018
Zhongmai 255	Yumai 49/Sunstate	YR, LR, PM	Henan, 2018
BFB 10	Lumai 21/Bainong 64	YR, LR, PM	Advanced line
CA17114	Strampellia/5* Lunxuan 987	YR, LR, PM	Advanced line

Note: YR, yellow rust; LR, leaf rust; PM, powdery mildew.

Table 4 Important cultivars in China derived from CIMMYT germplasm

Cultivar	Cross	Release region and year
Han 6172	Han 4032/ Zhongyin 1	Northern Yellow and Huai River floodplains, 2001
Jinan 17	Linfen 5064 /Lumai 13	Shandong, 1999
Jinmai 19	Linfen 5064 /Lumai 13	Northern Yellow and Huai River floodplains, 2003
Emai 18	SKUA/ 865146 /Emai 11	Hubei, 2002
Miannong 4	75-21-4/76-19// Miannong 1	Sichuan, 1993
Chuanmai 42	Syn-CD769 /SW89-3243//Chuan 6415	South-western winter wheat region, 2003
Kefeng 3	Ke71F4-370-7/ Nadores 63	Heilongjiang, 1982
Ningchun 4	Sonora 64 /Hongtou	North-western spring wheat region, 1981
Xinchun 2	Siete Cerros /Qichun 4	Xinjiang, 1984
Xinchuan 3	Siete Cerros /Qichun 4	Xinjiang, 1986
Xinchun 6	Zhong 7906 /Xinchun 2 “S”	Xinjiang, 1993

Note: CIMMYT germplasm sources are indicated in bold.

traits including yield potential, processing quality, disease resistance and early maturity^[29], which is consistent with a previous assessment^[27].

6 Collaborative platform and training

Various types of training courses and visiting scientist programs, ranging from a few weeks to 12 months, have been conducted by CIMMYT since 1966, including breeding, molecular marker application, quality testing, physiology, pathology and crop management.

CIMMYT has established a strong wheat management and physiology program. Bed planting has been introduced and tested in Shandong, Henan, Sichuan and Gansu Provinces through a 3-month visiting scientist program in Mexico and follow-up visits of CIMMYT scientists to China. This system could reduce inputs by about 30%, and is currently being widely adopted in Gansu Province.

Physiology approaches can provide valuable solutions for improving yield potential as well as broadening adaptation, such as improving water use efficiency and heat tolerance^[30,31]. Unmanned aerial vehicle imagery has been employed to study physiological traits including wheat senescence rate^[32].

Establishment of the CIMMYT office in China in 1997 has greatly promoted training of Chinese scientists both in Mexico and in China. Over 100 postgraduate students and visiting scientists have been trained by joint CAAS-CIMMYT wheat program stationed at the Institute of Crop Sciences, CAAS. Currently, the China Scholarship Council offers ten training positions per year, for 12–24 months joint doctoral and collaborative research of visiting scientists. CIMMYT trained scientists have contributed greatly to Chinese wheat research programs.

A complete survey of the impact of CIMMYT wheat training in China was documented by Huang et al.^[33]. The

empirical findings of this survey on the impact of training are largely supported by the results of a trainee opinion survey. The majority of trainees highly appreciated the influence of CIMMYT training on their careers. Most of them claimed that the training helped them obtain new scientific knowledge and technology, improve their research and work experiences, access more germplasm resources and develop a better research network. Also, most of the respondents considered that the training programs have substantially contributed to wheat technological changes in China. They also suggested that CIMMYT could make an even more important contribution if training programs and collaborative work in China are expanded in the future^[33].

7 Future perspectives

Although significant progress has been achieved over the past 40 years, wheat production in China still faces huge challenges, particularly in the following three important areas. (1) The impact of climate change has been significant over the past 20 years. For example, rainfall in October in 2017 delayed sowing by about 2 weeks in the Yellow and Huai River floodplains. Then unusual fluctuation in temperatures, including extremely low temperature in winter and before anthesis, and high temperature during the grain-filling stage, significantly reduced the wheat yield by about 20% in 2018. Also, wheat irrigation frequency in Hebei Province had to be reduced from three or four times per year to twice per year due to the severe shortage of underground water. (2) Considerably more disease occurs now in major wheat regions in comparison to 20 years ago. Fusarium head blight (caused by *Fusarium graminearum*), which has been a major problem along the Yangtze for over 70 years, is currently at epidemic proportions in the Yellow and Huai River Valleys. Other plant health

problems, such as leaf rust, yellow rust, powdery mildew, crown rot, cereal cyst nematode, and sharp eyespot (caused by *Rhizoctonia cerealis*), have become much more serious than before. (3) Consumers are also now demanding much better quality wheat. Although significant progress has been achieved in genomics, greater effort is needed to integrate new technologies into breeding programs.

To meet demand for wheat from domestic production, China cannot deal with all these challenges alone, so it will benefit from working together with international partners such as CIMMYT. Climate-resilient cultivars along with smart agricultural technology are urgently needed to suit the objectives of green development. The future role of CIMMYT in wheat development in China it likely to include continuing provision of elite germplasm and applied technology, improved breeding technologies based on genomics and other new technologies, technology to reduce production inputs, training of Chinese scientists, and opportunities for increased presence of China in international wheat development in less developed countries.

Thus, we recommend that Chinese institutes work closely with CIMMYT to achieve a win-win partnership with research that impacts both scientific innovation and field practice. Joint research programs can be established to meet China's priorities, such as improving Fusarium head blight resistance through genomic approaches. However, such research activities will need full support of the Chinese government as international organizations are no longer financially supporting these activities in China. Crop management needs to be improved to reduce input costs so wheat can compete with other crops. Wheat production technology in China can also be transferred to less agriculturally developed countries through collaboration with CIMMYT.

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