Article

Accelerated Wheat Breeding and Production in the Face of Climate Change: The Case of Morocco

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ABSTRACT

Wheat is the most important food crop which originated in the Fertile Crescent, the cradle of human civilization. Currently, it grows an average of 220 million hectares globally with an annual production level of 810 million tons. In Morocco, wheat is grown on 3.2 million hectares, with production levels ranging from 3 to 7 million tons/year, depending on the amount and distribution of rainfall. Like many other countries in the CWANA region, wheat production in Morocco is affected by climate change, drought, heat, diseases (rusts, septoria, fusarium), and insect pests such as Hessian fly. Wheat breeding in Morocco started in the late 1920s, and since 1980, the National Institute of Agronomic Research (INRA) has released more than 52 varieties of bread wheat. This paper reviews and summarizes the wheat production and challenges, including the seed system, the wheat breeding history and methodologies, achievements, and prospects of accelerated wheat breeding, including modified shuttle breeding, doubled haploids, speed breeding, genomic selection, and hybrid wheat, which shorten breeding cycles and enhance the precision of trait selection. Rapid development and deployment of climate-smart wheat varieties, along with improved crop management technologies, are important to increase wheat production and ensure food security in the face of climate change.

KEYWORDS: accelerated breeding; climate change; drought; wheat

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INTRODUCTION

Wheat has played a fundamental role in human civilization and contributed to improving food security at global and regional levels since its origin in the Fertile Crescent about 10,000 years ago. It provides about

19% of the calories and 21% of the protein needs of daily human requirements at the global level [1]. Wheat production has increased from 220 million tons in 1961 to 810 million tons in 2023, while the production area remained almost the same at 220 million ha through the years. Common wheat (*Triticum aestivum*, 2n = 6x = 42, AABBDD) and *Triticum durum* (2n = 4x = 28, AABB) are the two dominant wheat species accounting for 95 and 5%, respectively, of global wheat production. Wheat cultivation in Morocco using improved wheat varieties dates to 1912. By the late 1940s, 1 million hectares of durum wheat and about 400,000 ha of bread wheat were cultivated. Currently, Morocco grows wheat on average of 3.2 million hectares per year, with 2.3 million hectares of bread wheat and 1 million hectares of durum wheat [2], indicating that the production area of bread wheat has tripled while the durum production area remains almost unchanged.

Wheat production and population in Morocco have increased from 0.72 million tons and 12.1 million people in 1961 to 7.5 million tons and 37 million people in 2021 (Figure 1). Similarly, wheat consumption has been increasing steadily, especially during the past 20 years, because of a growing population, changing food preferences and growing urbanization. Morocco imports more than 60% of its wheat needs on an annual basis. On average, Morocco imports 3 million tons per year to satisfy the demand for national food security. In 2022, however, Morocco imported more than 6 million tons of wheat due to the very low national wheat production associated with extreme drought during the season [3].

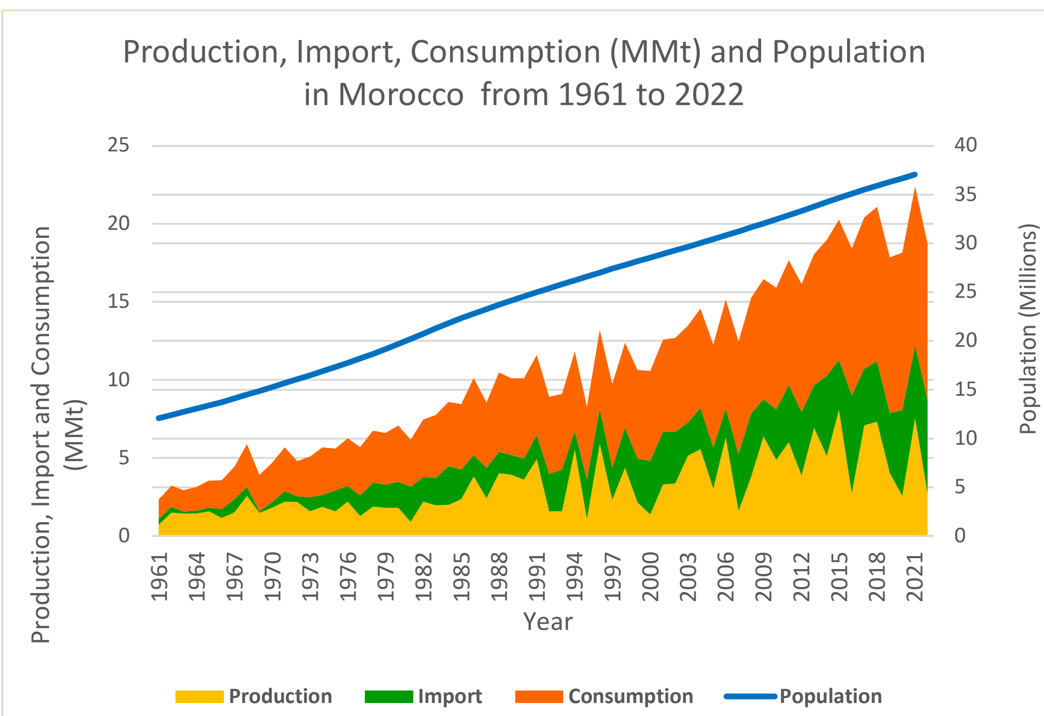

Figure 1. Wheat production, import, consumption, and population in Morocco from 1961 to 2022.

WHEAT PRODUCTION SYSTEMS AND AGRO-ECOLOGIES

Production systems and agro-ecologies could be classified considering different factors such as rain fall and water source and availability, temperature, vegetation cover, altitude, soil type and other factors. In Morocco, based on the source of water for crop production, the wheat production system could be classified into rainfed and irrigated wheat production systems. The rainfed production system accounts about 92% of the wheat production area and 85% of the total wheat production which makes it the most dominant system in Morocco [3]. Based on rainfall distribution, temperature gradient and altitude, the agro-ecological regions in Morocco could be grouped into:

(1) Arid and semi-arid agro-ecology: It is majorly characterized by low annual rain fall (less than 350 mm). This agro-ecology is located in the southern part of the country, and it accounts about 44% of the wheat production area and contributes 34% of the total wheat production. The major wheat production areas/regions in this category includes Casablanca, Settat, and Agadir.

(2) Humid and sub-humid agro-ecology: It is distributed in the centre and northern parts of Morocco with annual average rainfall levels of above 350 mm. This region represents about 47% of the total wheat production area and contributes 57% of the total wheat production. The major wheat producing regions under this category include Rabat-Salle, Makness, Fes and Tangier.

(3) Mountainous area: This covers areas with high altitudes surrounding the Atlas Mountain with rain fall levels ranging from 350–800 mm. It accounts about 9 percent of the total wheat production area and contributes 9% of the total wheat production (Figure 2) [4].

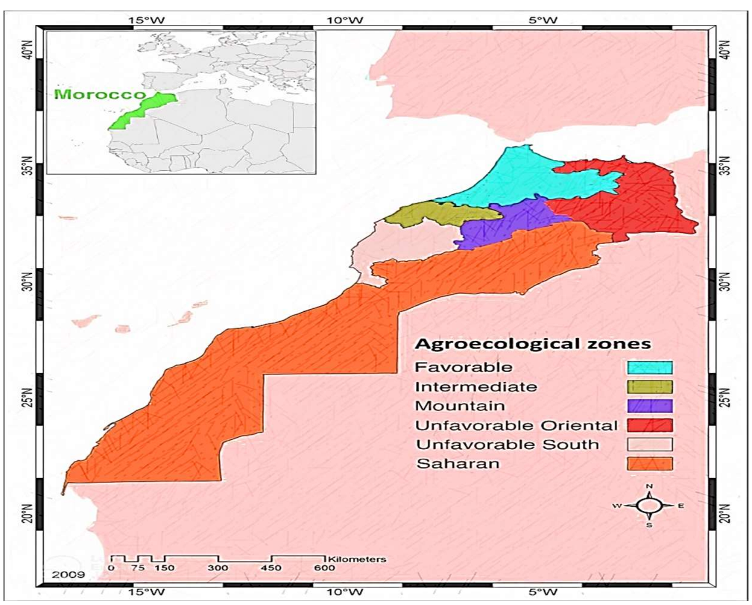

Figure 2. Major agro-ecological zones and representative research stations (Marchouch, Sidi Al-Aidi and Tassaout) in Morocco.

CHALLENGES AND CONSTRAINTS TO WHEAT PRODUCTION

Wheat production faces numerous challenges and constraints, including abiotic and biotic stresses, climate change, inadequate and inefficient seed system, and issues related to yield gap and stagnation [5].

Abiotic Stresses

Drought is by far the most important abiotic stress which limits wheat production in Morocco. Associated with climate change, the effect of drought has increased in intensity and frequency through the years affecting the distribution and amount of rainfall, which in turn affects the vegetation cover, crop production, water level in the dams and the way of life. Figure 3 shows the existence of a remarkable change in vegetation cover and amount of water at the Massira dam and Oum Arabia river in Morocco between 2018 and 2024 due to the prevalence of drought associated with climate. This provides clear evidence for those who deny the effect of climate change. Similar effects of climate change have been witnessed in other countries in the CWANA and SSA regions.

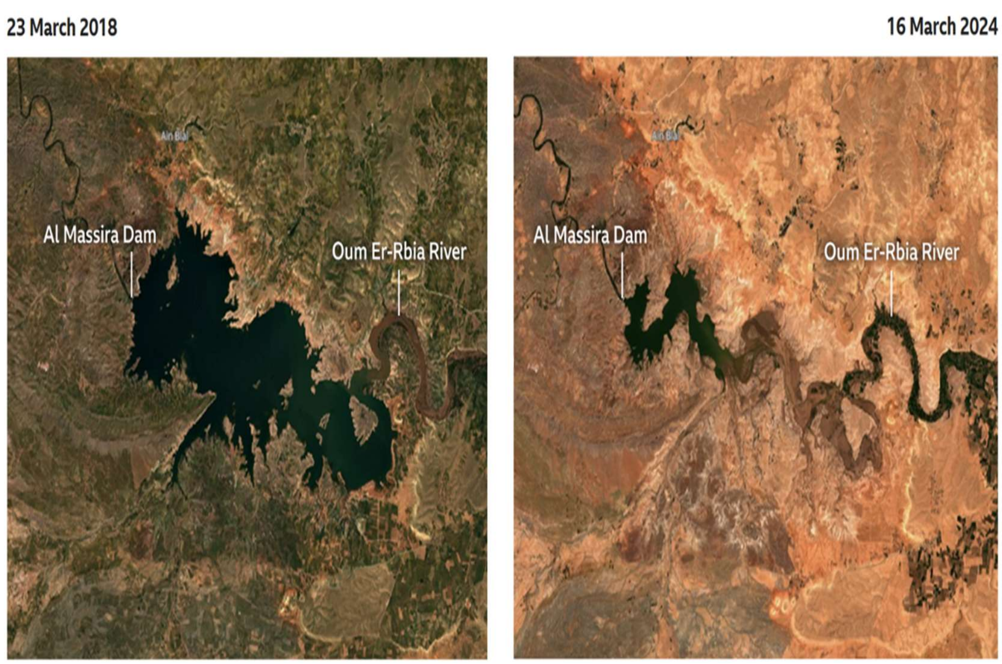

Figure 3. The effect of climate change at Al Massira Dam and its surroundings in Morocco [6].

The rainfall distribution has been erratic, and the total amount has reduced across the years, even in the humid and sub-humid regions of Morocco (Figure 4). On the contrary, temperature has increased through the years, which, in combination with drought/moisture stress, has affected wheat production. Heat, soil acidity, erosion, poor soil fertility, and pre-harvest sprouting are also important abiotic stresses which affect wheat production in Morocco [7]. Morocco has been grappling with drought stress over the past decade, which has significantly impacted its wheat production. Morocco's wheat output remains constrained, fluctuating between 3 to 7 million tons. The yield varies from 1 to 2.6 tons per hectare depending on the distribution and amount of rainfall [8].

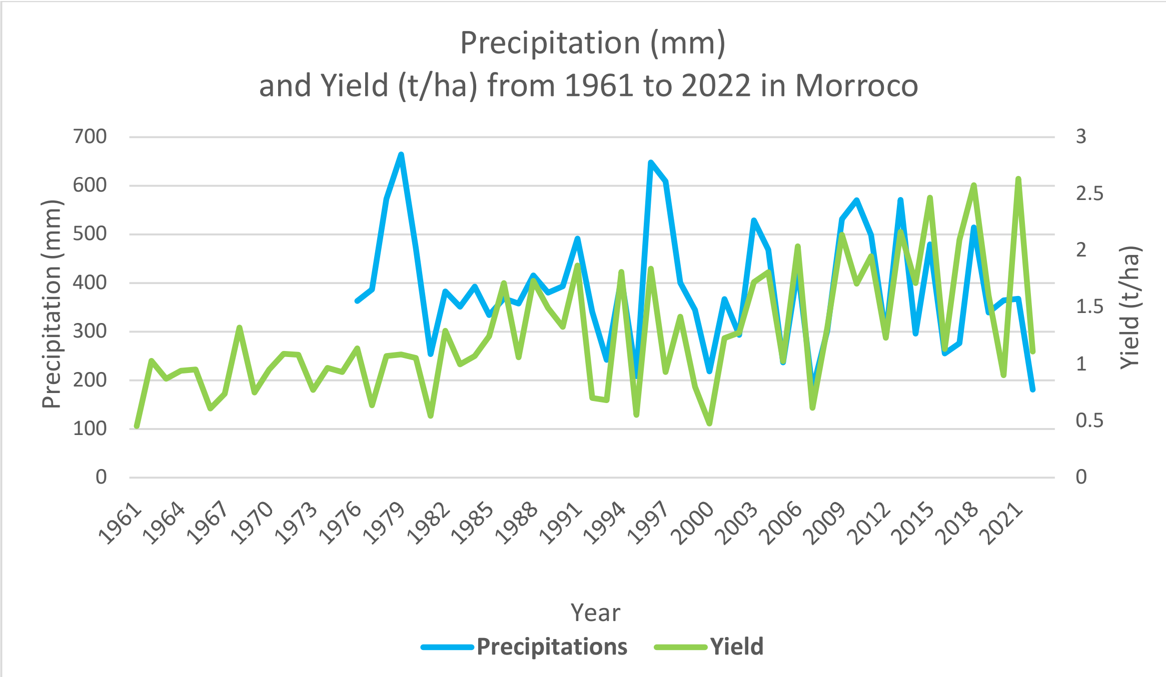

Figure 4. Precipitation and wheat yield in Morocco from 1961 to 2022 [2].

Biotic Stresses

The three main biotic factors affecting wheat productivity in Morocco are diseases, insects, and weeds. Important wheat diseases that are frequent in Morocco include rusts (*Puccinia* spp.), Helminthosporium, septoria (*Septoria tritici*), tan spot (*Pyrenophora tritici repentis*), fusarium (*Fusarium* spp.), smuts, take-all, and root rots [9]. In Morocco and the CWANA area, yellow rust caused by *Puccinia striiformis* f. sp. *tritici* is the most common and deadly wheat disease which has caused major production losses reaching up to 100% in the wheat belts of Morocco due to the failure of the *Yr27* gene present in the dominant wheat cultivar, Achtar, in 2010 [10].

Hessian fly (*Mayetiola destructor*) is the most important insect pest in which could cause up to 36% of wheat production losses in Morocco [11,12]. If HF infection occurs at the young stage of the crop, the whole crop may fail. The best method to combat the threat of HF damage is to utilize resistant varieties in conjunction with early planting dates. However, in Morocco's rainfed regions, planting times are mostly determined by the start of the rainy season in November and December [12].

Lack of Strong Seed System

The release and registration of high yielding varieties with resistance to the major biotic and abiotic stresses will not bring the desired impact unless these varieties are effectively multiplied and distributed to farmers. Like many other developing countries, Morocco faces significant challenges in early generation seed (EGS) production. SONACOS, the largest seed company in Morocco, has a royalty agreement with INRA to purchase newly released varieties. INRA is responsible for supplying 1 ton of breeder seed per variety, while SONACOS handles the multiplication of foundation and certified seeds and their distribution to farmers. However, due to INRA's limited capacity for EGS multiplication, the promised breeder seed was not provided, and no INRA-origin varieties have reached farmers in the last 15 years. This has clearly blocked utilization of genetic gain in the newly released climate resilient wheat varieties and thereby impedes the effort to increase production and ensure national food security. To address this, it is crucial to strengthen EGS multiplication at INRA to ensure the supply of 1-ton high-quality breeder seed to seed companies as per the agreement. Additionally, seed policies including royalties should be revised and updated to strengthen the seed system.

Yield Gaps

The yield gap in wheat refers to the difference between the potential yield (the maximum yield achievable under optimal conditions) and the actual yield (what farmers typically achieve under normal practices). Understanding the causes of the yield gap and designing strategies to lower yield gaps are critical for increasing wheat production and ensuring food security, especially in the context of a growing population and climate challenges. There is a significant gap between potential and realized yield, especially in rainfed environments [5]. This gap is mainly due to agronomic management and environmental factors. Agronomic management practices, such as plowing, crop rotation, planting date, seeding rate, and application of inputs like improved seed, fertilizers, irrigation, pesticides, and machinery, significantly impact wheat productivity. Farmers who implemented improved packages as per the recommendation achieved high wheat yield ranging from 4–7 t/ha in good seasons and 2–4 t/ha in dry seasons. On average, this range represents more than 50% yield gap. This is in line with previous reports [13]. According to [14], yield gap in wheat at global level ranges from 26% to 69%. The yield gap remains huge in developing nations because of high prices of inputs such as fertilizers, improved seeds, pesticides, machinery etc., limited extension and communication services; access to market and credits, and inadequate infrastructure. The presence of such big yield gaps indicates the availability of considerable room for improvement in agricultural practices and thereby lowering yield gaps and increasing wheat production.

Infrastructure and Policies

Agricultural policies that address on land use and tenure, technology development and deployment, subsidies, marketing and distribution of inputs, taxation, infrastructure, human capital development, and public-private partnerships are crucial for enhancing agricultural productivity and fostering socio-economic development [15]. These policies must remain flexible to accommodate timely adjustments in response to domestic, regional, and international changes.

Challenges such as limited public and private investment, ineffective extension services, and weak market and infrastructure connections significantly impede the growth of wheat production in Morocco [16]. Additionally, inadequate rural road networks and transportation options hinder farmers' access to agricultural inputs like seeds and agrochemicals, and complicate the collection, storage, and transportation of wheat to markets. The lack of energy infrastructure further restricts the development of agro-processing industries, irrigation systems, and technological advancements.

Addressing these issues requires tackling key policy and regulatory barriers that limit technology development and access, contract farming, innovative financing mechanisms, public-private partnerships, and the integration of wheat production, marketing, and agro-processing. Overcoming these challenges is essential for the prosperity of Morocco's wheat sector and its broader agricultural economy [15].

WHEAT BREEDING IN MOROCCO

Bread wheat production in Morocco began with the introduction of new varieties by the first settlers around 1912. Following World War I (1914–1918), the area dedicated to bread wheat production increased steadily, demonstrating significant potential. This growth prompted the establishment of a public agricultural research program in the 1920s which was later reorganized as INRA in 1981. Since the 1990s, both public and private sectors have been actively involved in crop breeding and registration in Morocco. Collaboration with international centers such as CIMMYT and ICARDA, as well as other foreign companies and institutions have played a crucial role in providing access to improved germplasm. These partnerships have facilitated the INRA's release and registration of new varieties following adaptation and registration trials.

Accelerated Breeding Methods

Following the crisis in Syria, ICARDA's wheat breeding program is based in Morocco since 2012 hosted by INRA. There has been regular revision and updates of breeding methods both at ICARDA and INRA based on the availability of new tools, facilities and production challenges to increase genetic gain and productivity. Accelerated breeding methods such as modified shuttle breeding, doubled haploids, speed breeding, and genomic selection have been deployed and explained below.

Modified shuttle breeding

This method involves rigorous screening and assembling parents into crossing blocks, generation of simple and top crosses using two cycles in the plastic/greenhouse, two cycles of generation advancement in the field at Merchouch station involving the main winter season (November–June) under rainfed conditions and summer season (July–October) using drip irrigation (Figure 5). Under this scheme, pedigree selection is employed at F2, F3 and F4 generations. The selected F4 head rows are promoted to preliminary yield trials (PYTs) to be tested across locations using augmented designs for a period of 1 year. The selected genotypes from stage 1 trials (PYT) are tested further across locations under the Advanced yield trial (AYT) for 1 year using alpha lattice design in two replications. A copy of the stage 2 trials (AYT) is also multiplied in non-replicated large plots of 6 m^2 at the same time for clean seed production. Rouging of seemingly segregant/off type plants and cleaning of seeds after harvesting will be carried out intensively. It takes only 4 years from crossing to the distribution of elite germplasm to national programs using this scheme [17].

Using the strong partnership of INRA and ICARDA, it should be possible to carry out stage 1 (National preliminary yield trial, NPYT) and stage 2 (National variety trial, NVT) trials across INRA stations representing the different agro-ecologies. Candidates identified based on the NPYT and NVT data of INRA trials are submitted for 2 years of registration trials, which effectively takes a total of 6 years from crossing to variety release. This method is the most feasible, rapid and efficient method to shorten the breeding cycle and increase genetic gain.

This scheme reduces the time required for variety development and registration by 50% compared to the conventional system, which involves one generation per year and includes additional stages such as quarantine, seed increase, observation nurseries, and preliminary yield trial at the national level following the acquisition of international nurseries from CIMMYT and ICARDA. In contrast, germplasm from INRA's crossing conventional program typically requires at least eight years for variety release. This strategy is implemented with selected key national programs in the CWANA region.

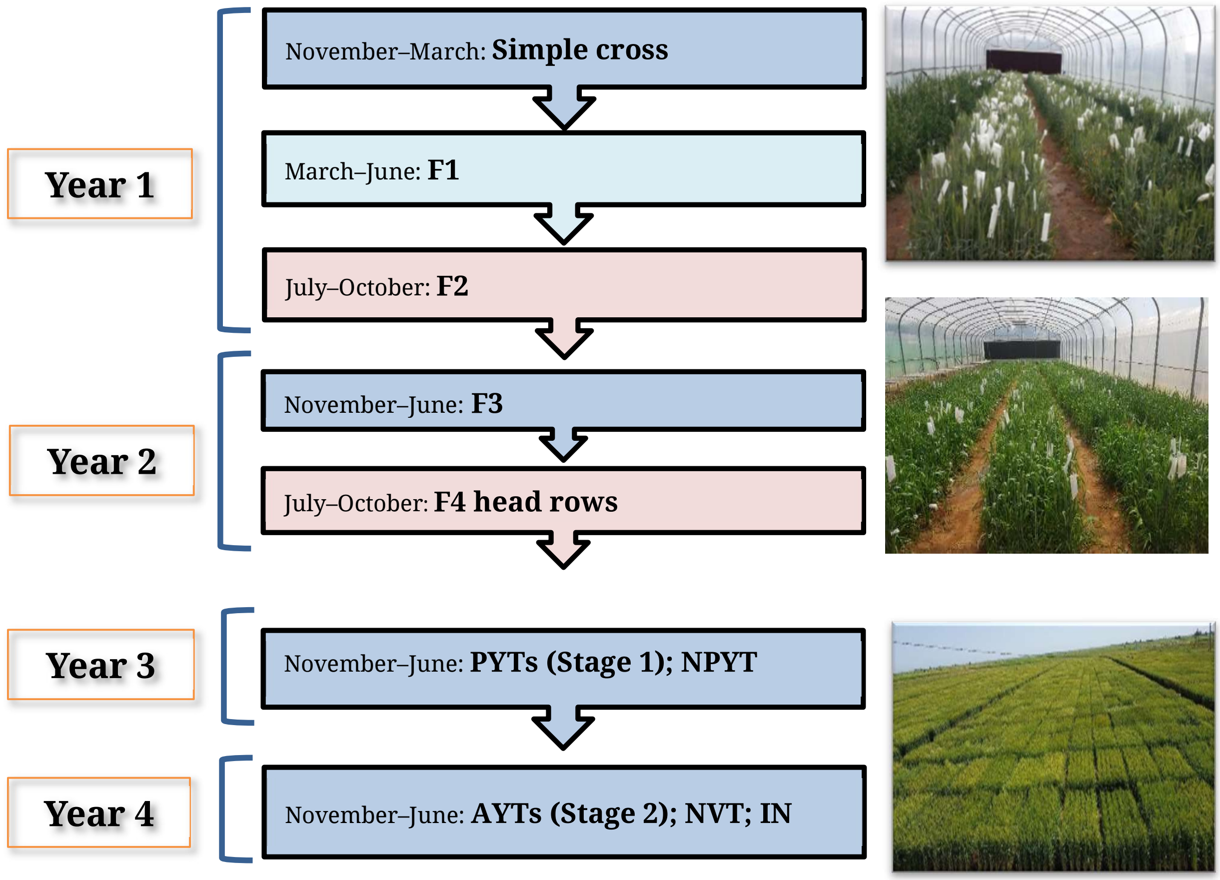

Figure 5. The modified shuttle breeding scheme at ICARDA. PYT: preliminary yield trial, NPYT: national preliminary yield trial, AYT: advanced yield trial, NVT: national variety trial, IN: international nursery.

The speed breeding scheme

Under this scheme, plants are grown in specialized growth chambers or greenhouses that provide precise control over temperature, humidity, light, and photoperiod (day length). These controlled conditions are designed to optimize plant growth and development. One of the critical aspects of speed breeding is providing plants with extended light exposure each day, often using artificial lighting to have an extended photoperiod, which triggers plants to grow faster and reproduce more quickly, resulting in shortened generation times. The scheme typically involves the single seed descent method and enables the production of up to 4 generations per year under the speed breeding chambers/greenhouses. Using this scheme, it may take on average, 4 to 5 years from crossing to the distribution of elite germplasm to the national programs. The speed breeding system is efficient in shortening the breeding cycle and for maintenance breeding activities. For example, if an adapted wheat variety is becoming susceptible to rust, it may be possible to undertake limited backcrosses with another rust-resistant variety which has relatively good adaptation and yield potential so that the segregating generation will be advanced and selected using artificial inoculation of virulent rust isolates under the speed breeding scheme. This will take 1 or 2 years to maintain and multiply the fixed variety which is ideal and cost effective. On the other hand, the speed breeding scheme might be limited and challenging to accommodate the desired number of crosses with an effective population size (1000–2000 plants per cross) at the F2 stage when the maximum level of segregation happens. This is the case for international breeding programs where there are on average 1000 crosses each cycle targeting the different product profiles and market segments/agro-ecologies. It is also difficult to expose the segregating generations for biotic and abiotic stresses under the speed breeding facilities/growth chambers. However, for national breeding programs or private breeding companies who are breeding for specific agro-ecologies and do not have shuttle breeding sites, speed breeding could be an important option so long as the population size using the single descent scheme remains large enough (more than 500 seeds planted and advanced individually) from F2 through F4 generations followed by head rows and stage 1 and stage 2 trials in the field. Genomic selection could use stage 1 materials to predict the performance of stage 2 trials across different locations.

Doubled haploid (DH) method

DH refers to a breeding technique which enables the production of completely homozygous lines in a single generation. This method accelerates the process of developing new wheat varieties by using techniques such as (a) anther culture, (b) microspore culture, and (c) wide hybridization (Wheat × maize or wheat × Hordeum bulbosum). These methods involve culturing of anthers, microspores and haploid wheat embryos after eliminating the maize or bulbusome component in special culture media, which results in the production of haploid plants followed by chromosome doubling using colchicine to produce fertile, homozygous doubled haploid plants. The anther and microspore cultures are less efficient and genotype dependent as compared to the wide hybridization method [18]. Using the DH method, some bread wheat varieties such as Kharouba, Malika and Khadija were developed and released by INRA, Morocco.

Genomic selection

Genomic selection (GS) in wheat breeding is a modern technique that uses genomic data to predict the breeding value of individual lines, accelerating the process of selecting wheat lines with desirable traits. Unlike traditional methods, which rely on phenotypic evaluation, genomic selection leverages information from the entire genome to predict a line's performance, even for complex traits controlled by many genes, such as yield, disease resistance, and drought tolerance. The process involves (1) phenotyping and genotyping of the training set, (2) model training, (3) prediction of genome estimated breeding value (GEBV), (4) selection of best lines based on their GEBVs for parentage or yield trial purposes [19].

GS helps to shorten the time between generations by using genomic data to make selection decisions without waiting for field evaluations; Improves the prediction of complex traits controlled by many genes; enables selection of plants even before they are fully grown, saving time and resources; reduces the need for extensive multi-environment field trials by relying more on genomic predictions and helps to undertake better trait control particularly effective for selecting traits like disease resistance, grain quality, yield, and stress tolerance, which are difficult to evaluate phenotypically in early generations [20]. However, GS also faces challenges, such as the high cost of genotyping and model accuracy, which depends on the quality of the training set data and the ability to predict complex traits. Genomic selection provides prediction which will not be an absolute match to actual phenotypic performance. The stage at which genomic selection needs to be carried out depends on the traits and objectives of the breeding program [21]. The wheat breeding program at ICARDA applies genomic selection at the stage 1 (preliminary yield trial) level to identify the best parents for parental recycling and to promote lines to stage 2 (advanced yield trials) by including those lines with the highest GEBVs across representative locations [13]. The wheat breeding program at ICARDA also applies functional markers for gene pyramiding purposes, such as stacking several disease-resistance genes to make a wheat variety more robust against multiple pathogens (stem rust, leaf rust, septoria, fusarium, etc).

Gene edition using CRISPR-Cas9 is one of the molecular tools which allows breeders to quickly introduce and stack/pyramid or knock out specific genes related to key traits, such as drought tolerance, disease resistance, and yield improvement, without the need for lengthy traditional breeding cycles. When coupled with speed breeding techniques, where environmental conditions are optimized to accelerate plant growth, gene editing could enable the production of multiple generations of wheat within a year, further accelerating breeding timelines. However, the gene edition is still under development and has not yet been deployed as a functional breeding method.

Hybrid wheat breeding

Hybrid wheat production is believed to increase wheat production as hybrid wheat provides higher grain yield, higher thousand grain weight, more tillers, higher biomass, deeper roots and better resistance to both biotic and abiotic stresses as compared to their parents. Reports indicated that there are more than 500,000 hectares of hybrid wheat production in Europe using the chemical hybridization agent (CHA). In China and India, the cytoplasmic male sterility (CMS) method has been used to produce hybrid wheat. However, the limited heterosis (10%–15%) coupled with the high cost of hybrid seed production have been the limiting factor for the expansion of hybrid wheat production [22]. Currently, ICARDA is working with Sydney University to deploy hybrid wheat variety development using the nuclear/genetic male sterility system based on the Blue-aleurone (BLA) system developed by the University of Sydney. The BLA line is an addition line with 43 chromosomes and blue seed colour and when it is planted, it segregates into white and blue seed which are fertile and sterile with 43 and 42 chromosomes, respectively. The blue seed is the maintainer while the white seed is sterile and will be used as female parent with a potential adapted male cultivar for the production of F1 hybrid seed. This system is highly effective for rapid variety development and deployment and increase genetic gain and productivity in the face of climate change with increasing challenges of biotic and abiotic stresses.

Variety Release and Deployment

Following the national variety trials, breeders identify candidates for registration trials. The variety release and registration system started with regulations for creating a national variety catalog in 1977. After 1980, the DPVCTF (Service de Contrôle des Semences et des Plants) became an independent body within the Ministry of Agriculture (MoA) responsible for variety release. Since 2010, ONSSA (Office national de Securite Sanitaire des produits Alimentares) has taken over this role. Variety release involves registration trials for distinctness, uniformity, and stability (DUS), as well as performance testing for value for cultivation and use (VCU). Both public and private breeding/seed companies can submit candidate varieties for DUS and VCU testing, adhering to national requirements, including a registration fee of 4000 Dhs, submission of agronomic and pedigree documents, 200 spikes, and 20 kg of seed per candidate variety. Successful candidates who pass both tests are added to the national variety catalogue. For varieties from public breeding programs (INRA), seed companies can acquire patent and ownership rights through a royalty system. In this system, the breeder must provide one ton of breeder seed to the seed company which is responsible for basic and certified seed production through contracts with farmers as well as for the commercialization of certified seed to growers. The seed companies must pay INRA a royalty of 2.5% of the total sales of certified seeds.

To date, 92 bread wheat varieties have been registered in the Moroccan national catalogue. Of these, 52 varieties originated from INRA, while 40 varieties originated from private breeding/seed companies. About 30 varieties of bread wheat from INRA were sold to private seed companies, while the rest are owned by INRA. The registered varieties can be categorized as (1) obsolete/old, (2) varieties more than 20 years old but still dominant (e.g., Achtar), (3) under seed multiplication, or (4) never multiplied or introduced to the market. Key traits for adoption include adaptation, stability, high yield, disease resistance, and good nutritional quality. INRA holds the breeder rights for 27 bread wheat varieties, while Florimond Desprez (France) and Lantmannen SW Seed AB/Svalof Weibul AB (Sweden) hold second and third place with 14 and 8 varieties, respectively.

Among INRA origin varieties, MARCHOUCH (KAL/CIANO/8156/3/BT908) released in 1984, SIRARA (KAI/CIANO/8156/3/RT908) and KANZ (PAVON'S'/4/PAT0(R)/CAL/3/SIETE CERROS/BB/CNO) released in 1987, ACHTAR (HORK/YMH//KAL/BB) released in 1988, KHAIR (MAYA//LR64/LR64/3/IZZP//Y54/23584), also released in 1988, MASSIRA (L2266/1406, 101//BUC'S'/3/VPM/MOS 83,11, 4,8 8//NAC) released in 1992, RAJAE (MOR'S'/MON'S') released in 1993, and AGUILAL (SAIS*2/KS-85-14-2 = TA1642/Witchita2), released in 1997 have been widely grown. Unfortunately, many of the varieties released by INRA during the last 15 years are not yet available in the market due to early-generation seed multiplication issues. Consequently, more than 55% of farmers are still cultivating cultivars that are over 20 years old. In recent years, varieties from private companies, such as Fayza, Radia, and Remax, are gaining traction in Morocco's favorable wheat production zones since private seed companies have better facilities and capacities for early-generation seed multiplication and certified seed production.

To address the impacts of climate change and the increasing demand for wheat in Morocco, it is crucial to implement an efficient mechanism for rapid variety development, fast-track seed multiplication, and accelerated wheat technologies scaling. Under the current ICARDA/INRA partnership, it is feasible to release new wheat varieties with a higher rate of genetic gain within just four years. The process begins with the identification of elite genotypes through joint germplasm evaluations conducted by INRA and ICARDA breeders at INRA experimental stations. These genotypes are then promoted by INRA to multi-location national variety trials for two years. After the first year's national variety trial, promising candidates are selected and purified through head-row nurseries. Based on the average performance of 1st and 2nd-year multi-location testing, the selected candidates are submitted for registration trials. At the registration trials, candidates will be evaluated for DUS (Distinctness, Uniformity, and Stability) for a period of one year and VCU (Value for Cultivation and Use) for a period of another 1 year.

To ensure the timely availability of seeds for commercialization, candidate varieties are multiplied using the fast-track seed multiplication scheme. By the time, the varieties are officially released following the DUS and VCU test, at least 1 ton of breeder seed is available for each variety. This is then provided to seed companies to initiate the basic and certified seed production.

The current variety release system is based on wide adaptation and stringent DUS tests. Given that wheat is a self-pollinated crop, traits such as glume colour, tiller synchronization or cytosine pigmentation might opt from the DUS test as these traits can be influenced by the seeding depth, environment and other agronomic management practices. Instead, varieties should be assessed based on overall phenotypic uniformity and their potential for agronomic performance for specific and/wide adaptation. Furthermore, strengthening the seed unit at INRA is very important to accelerate early generation seed multiplication which intern plays a significant role for rapid deployment and scaling of climate resilient wheat varieties.

Genetic Gains and Breeding Progress

Different methods have been used to assess the breeding progress and determine the rate of genetic gains in breeding programs. The rate of genetic gain in wheat breeding refers to the improvement in key traits such as yield, disease resistance, or stress tolerance per unit of time, typically measured annually.

The rate of genetic gain (ΔG) can be estimated using the equation:

$$\Delta G = \frac{i \times h^2 \times \sigma_g}{T} \quad (1)$$

Where: i = Selection intensity (the proportion of individuals selected from the breeding population; h^2 = Heritability of the trait (the genetic contribution to trait variability); σ_g = Additive genetic variance; T = Length of the breeding cycle.

These factors are important to determine the rate of progress in a breeding program. Selecting the top-performing genotypes, ensuring the presence of high heritability and additive genetic variance in the breeding population, and implementing the breeding cycle in a shorter period of time increases the rate of genetic gain. The availability of facilities and tools to shorten the breeding cycle, such as genomic selection, speed breeding, doubled haploids, shuttle breeding stations, precision phenotyping, key locations, machineries, marker-assisted selection, statistical packages, trained breeders, etc., are all important to increase the selection intensity and heritability while reducing the time required for completing the breeding cycle [23].

Breeders have used different data sets and analytical packages to determine the rate of breeding progress for their respective breeding programs. Regression analysis using the top 5 high-yielding varieties with the trial mean has been used to determine the rate of breeding progress [18]. Breeders also used relative performance calculated as percent of the best checks to show the genetic gain/breeding progress in a year or across years. As indicated in Figure 6, the performance of elite spring bread wheat genotypes from ICARDA’s bread wheat breeding program was determined in percent of the best checks, Qafedu and Atlas during 2023 and 2024 seasons at Merchouch station, Morocco. The two consecutive years (2023 & 2024) were dry seasons with a 200 mm average amount of rainfall during each growing season, and the two best checks, Qafedu and Atlas, gave average yield levels of 3 and 2.5 t/ha, respectively (Figure 6). Under this very low moisture level (200 mm), there were more than 200 lines which performed above 100% of the checks with actual yield levels of up to 4.5 t/ha, showing the presence of high-yielding and drought tolerant wheat genotypes with clear genetic gain/breeding progress as compared to the best check varieties in the program.

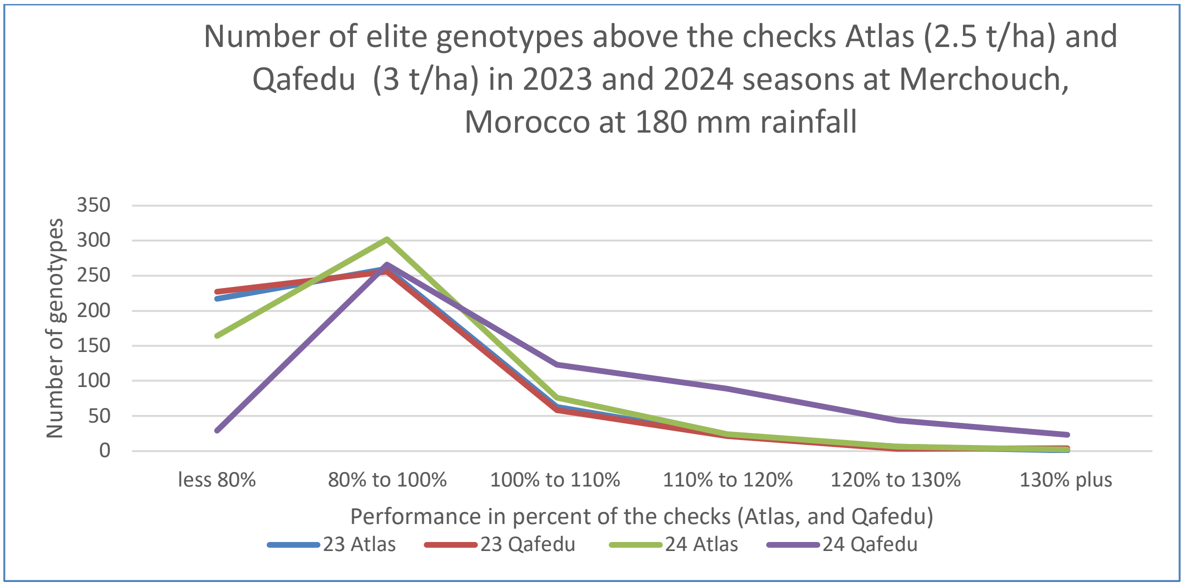

Figure 6. Yield gains above check varieties in elite genotypes in 2023 and 2024 at Merchouch, Morocco.

Previously, genetic gain analysis for bread wheat varieties released from 1980 to 2017 was determined by growing them at Merchouch station in Morocco for two seasons and regressing the yield of the varieties by their corresponding year of release, as indicated in Figure 7. The result showed that the relative genetic gain (RGG) has increased by 2.2% while the absolute genetic gain (AGG) has increased by 96 kg/year.

Breeding progress has also been evaluated for disease resistance and nutritional quality-related traits. Significant progress has been made in identifying and pyramiding stem rust and yellow rust-resistant genes within adapted wheat backgrounds at ICARDA. These efforts have led to the release of resistant wheat varieties in many national programs across the CWANA and SSA regions. In Morocco, INRA has identified and released high-yielding wheat varieties that are resistant to drought, yellow rust, and Hessian fly. Varieties such as Snina and Rachida are noted for their excellent nutritional qualities, with protein levels ranging from 12% to 14%. They also possess 5 + 10 (Glu-D1), 7 + 8 (Glu-B1) and 2* (Glu-A1) alleles. The 5 + 10 Glu-D1 allele, in particular, is highly correlated with protein quality and gluten strength, which is important for the preparation of high-quality French and Arabic bread [24].

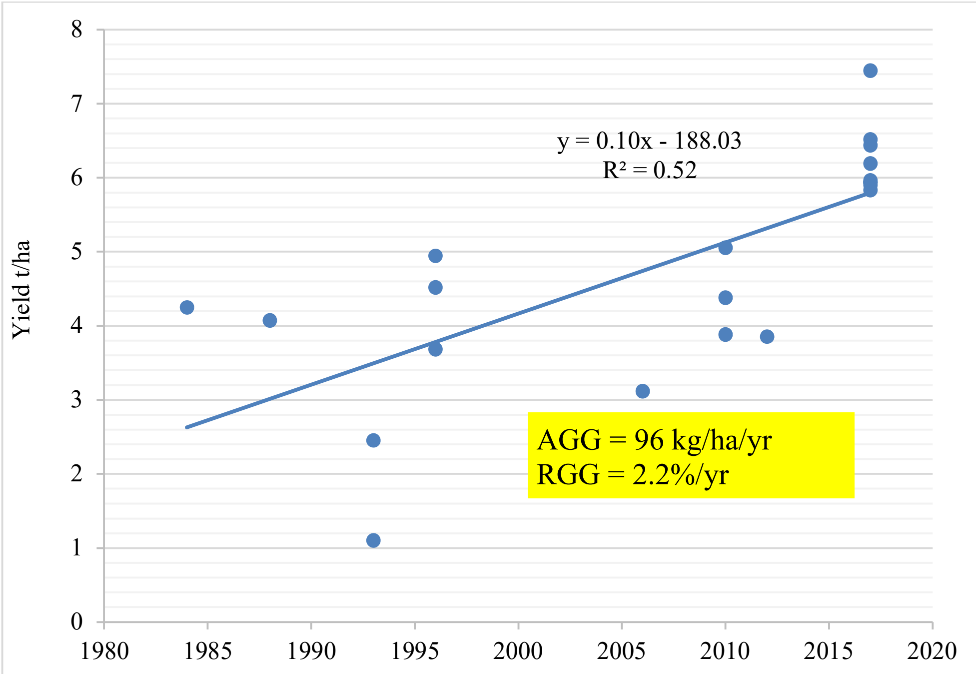

Figure 7. Progress in yield of released bread wheat varieties in Morocco: 1982–2017. AGG: absolute genetic gain, RGG: relative genetic gain.

FUTURE DIRECTIONS AND PROSPECTS

By the year 2050, the global human population will reach 9 billion, and the demand for wheat will increase to 900 million tons. Similarly, the demand for wheat in Morocco is set to increase with the increasing population, the effect of climate change, drought, water shortage, soil degradation, reduced supply and increasing cost of fertilizers, increasing demand for biofuel, and the emergence of new virulent diseases and pests which critically challenges wheat production and conservation of wheat genetic resources. To offset these challenges and increase wheat production while conserving the natural resource base, it is important to consider the following recommendations [25].

Rapid Variety Development and Deployment

A more robust and rapid variety development strategy involving shuttle breeding, gene mining and marker-assisted pyramiding, speed breeding, genomic selection, gene edition, precision phenotyping, and key location testing are important to develop varieties rapidly and efficiently. With such an integrated approach, it is possible to reduce the development of varieties from 10 to 5 years and increase the rate of genetic gain significantly [26]. For rapid variety deployment or scaling, cluster farming is very effective in accessing and using similar technologies such as inputs (improved seeds, chemicals, irrigation), machinery, warehouses, processing, packaging and marketing. Such an approach also facilitates the mechanization of farming activities through rental services.

Establish A More Efficient Seed System

The seed system includes policies and regulations associated with variety testing, registration, licensing, seed production (breeder seed, pre-basic, basic and certified seed) and marketing.

- In the existing system, the DUS test is stringent and needs to be a bit relaxed especially for those traits such as pigmentation and tillering which are affected by the soil type and depth of planting.
- Releasing varieties based on wide adaptation may be important for seed companies, but it limits genetic potential. Hence, variety testing and release should target the main target production environments (TPEs) so that the most adapted and high yielding varieties will be released for each TPEs which ultimately will increase genetic gain and variety adoption.
- The variety licensing agreement should include enforcement mechanisms so that seed companies will be obligated to multiply certified seed and sell to growers in a timely and efficient manner to effectively utilize the genetic potential of the newly released varieties. The current system does not have an enforcement mechanism.
- Lack of efficient mechanism for Early Generation Seed (EGS) production is the key limiting factor in the seed system of many countries including Morocco. Establishing a strong seed unit at INRA will help to produce breeder and foundation seed effectively and efficiently fulfilling the demand of the seed companies for the production of pre-basic, basic and certified seed.
- Strengthening/establishing innovation and scaling platforms are also important to build capacity, identify progressive farmers for contractual seed production and creation of small to medium scale seed growers.
- In addition to strengthening the formal seed sector indicated above, it is also important to encourage the informal seed sector. In most developing countries, farm-saved seed sources account for the largest seed sources for self-pollinated crops.
- Demonstration and diffusion of newly released varieties through a revolving seed system could play an important role in scaling climate-resilient wheat varieties using the informal seed system. In this approach, progressive farmers are selected and provided 10–25 kg seeds of newly released wheat varieties to be planted using improved agronomic packages. Demonstrations are given to other farmers, policymakers and stakeholders. The beneficiary farmers are required to sell seeds at a negotiated premium price for neighboring farmers who are willing to grow the new variety following the demonstration. Social media platforms such as WhatsApp are important for bringing participating farmers together in order to exchange information about crop management operations, monitoring and evaluation, harvesting, processing and marketing operations.

Application and Utilization of Integrated Crop Management (ICM) Practices

In the face of climate change, it is difficult to rely on a single best management practice as the challenges affecting wheat production are complicated and changing rapidly. Hence, integrated crop management practices include improved varieties, improved agronomic practices such as seed rate, planting time and density, conservation agriculture, irrigation methods, and integrated pests and disease control methods. For controlling wheat diseases effectively and sustainably, it is important to have zonal distribution and production of resistant varieties to reduce the chance of losing an entire crop and prevent the rise and fall of disease and pest populations over large areas. Adopting Integrated Pest Management (IPM) strategies, which integrate resistant varieties with chemical, cultural, physical, and biological control methods, presents a holistic and sustainable approach to pest management. Pre-emptive application of general fungicides such as Propiconazole at a rate of 0.5 L/ha is recommended to increase wheat yield, protect wheat from diseases, mitigate the accumulation of pathogens, and decelerate the mutation rate of wheat pathogens [27].

Invest in New Technologies such as Hybrid Wheat

Hybrid wheats have been developed using different systems such as the chemical hybridizing agent (CHA), cytoplasmic male sterility (CMS) and the genetic system using the blue aleurone addition line (BLA) systems. There have been 10%–15% heterosis levels reported in wheat hybrids developed using different systems. Continuous efforts and investments are required in the development and deployment of hybrid wheat to harness its potential. Similarly, investments in new technologies such as gene edition and genetically modified wheat (GMO) are important to develop climate-resilient wheat varieties and increase wheat productivity.

DATA AVAILABILITY

The study dataset is available from the authors upon reasonable request.

AUTHOR CONTRIBUTIONS

Conceptualization, WT; Methodology, WT; Software, ZE, KL and FER; Validation, GD, AA and MJ; Formal Analysis, KS; Resources, WT; Data Curation, KL and KS; Writing—original draft preparation, WT; Writing—review & editing, ZEG, ZK, GD, AA and MJ; Supervision, WT.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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