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Translating genetic gains into food security by bridging wheat breeding and seed systems in Africa

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Wheat is cultivated on approximately 12 million ha across Africa and produces about 30 million tons at an average yield of 2.5 t ha^{-1}. Algeria, Ethiopia, Egypt, Kenya, Mali, Morocco, Nigeria, South Africa, Sudan, Tanzania, Tunisia, and Zimbabwe are the most important wheat producing countries in Africa. Though wheat production is increasing both vertically and horizontally, Africa imports more than 50 million tons of wheat annually at a price of 20 billion dollars to fulfil its demand. The level of wheat consumption and demand continues to rise because of rapid population growth, urbanization and changing dietary preferences. Since the early 1960s, Africa's population has increased more than fivefold, whereas wheat production has increased only about three- to four-fold, widening the gap between domestic production and consumption and increasing vulnerability to international price and supply shocks. The central challenge is a translation gap where genetic gains and global breeding innovations are not yet converted into timely varietal turnover, affordable quality seed, resilient agronomy and food-security impact across the heterogeneous wheat environments of the continent. This review reframes wheat improvement in Africa as an innovation system linking target production environments, accelerated breeding, seed multiplication, regulatory pathways, farmer demand, market incentives and climate-smart crop management. We synthesize the main rainfed and irrigated wheat systems, the interacting stresses that define them and progress made through shuttle and speed breeding, doubled haploids, marker-assisted selection and genomic selection, and emerging tools such as gene editing and hybrid wheat. We argue that the decisive opportunity lies in integrating these tools with early-generation seed planning, rapid release and deployment pathways, regional harmonization, irrigation modernization, extension, mechanization and digital decision support. A practical agenda is proposed around environment specific product profiles, breeding to seed accountability, stress surveillance, decentralized but quality assured seed models and scaling platforms that connect varieties with agronomy, finance and markets. Such integration can convert genetic gain into grain, reduce import vulnerability and make wheat a stronger pillar of climate-resilient food security in Africa.

KEYWORDS
Africa, climate resilience, food security, genetic gain, seed systems, wheat

1 Introduction

Wheat is one of the most important staple crops in the world, supplying approximately 20% of global calories and protein and underpinning food security at a global scale (Silva et al., 2023). In Africa, its strategic importance has intensified because population growth, urbanization and changing diets have increased demand faster than domestic productivity. Population of the continent increased from about 283 million in 1960 to more than 1.5 billion in 2024 (UN DESA, 2024), whereas continent-wide wheat production rose from roughly 7–8 Mt in 1961 to 30 Mt in 2023 (FAOSTAT, 2025; Tadesse et al., 2022a, Figure 1). This three- to four-fold increase in production has been insufficient because per-capita wheat consumption has also increased, particularly in urban and peri-urban food systems. Africa therefore remains structurally dependent on wheat imports and exposed to international price volatility, geopolitical disruption and external supply shocks (Negassa et al., 2013; Tadesse et al., 2019a; Silva et al., 2023).

Over the past decades, many African countries have implemented policies and investment programs to increase wheat production and reduce dependence on imports, with varying levels of success (Tadesse et al., 2019a; Silva et al., 2023). Early efforts focused on expanding irrigation, promoting agricultural inputs and strengthening public breeding and seed systems (Minot et al., 2007; Bishaw and van Gastel, 2009; Jayne et al., 2018). More recent strategies have increasingly emphasized climate-resilient wheat production, improved seed-system performance, accelerated varietal replacement and stronger public-private partnerships in seed multiplication and technology dissemination (Silva et al., 2023; Tadesse et al., 2024a). Regional initiatives under COMESA, ECOWAS and SADC have also promoted seed regulatory harmonization to facilitate cross-border movement of improved varieties, although implementation remains uneven (Kuhlmann & Zhou, 2016; Lewis and Masinjila, 2018; Akinbo et al., 2021). Nevertheless, fragmented regulatory frameworks, slow variety release procedures and weak coordination among breeding, seed systems and extension services continue to constrain productivity gains and limit progress toward wheat self-sufficiency across the continent (Bishaw and van Gastel, 2009; Silva et al., 2023; Tadesse et al., 2024a).Despite these policy and investment efforts, the central challenge for wheat productivity in Africa remains a translation gap where genetic gains, disease-resistance discoveries and global breeding innovations are generated faster than they are converted into varieties, seed, agronomy and marketable grain in farmers' fields. This gap is most visible where improved germplasm exists but varietal turnover is slow, early-generation seed is scarce, variety release procedures are lengthy, irrigation and input systems are unreliable and farmers receive incomplete agronomic and market support.

Wheat production in Africa is spatially concentrated but agronomically diverse. In 2023, the continent produced approximately 30 Mt of wheat from 12 Mha (FAOSTAT, 2025; Tadesse et al., 2022a). North Africa accounts for nearly half of the wheat area, with Egypt, Morocco, Algeria and Tunisia as major producers, while in Sub-Saharan Africa, Ethiopia South Africa, Zimbabwe, Sudan, Tanzania, Keny, Nigeria and Mali are important wheat growers (Tadesse et al., 2019a; Senbeta and Worku, 2023). Ethiopia becomes the largest wheat producer in Africa because of the rapid expansion of irrigated wheat in Ethiopia into lowland environments with cultivated area now exceeding 3 Mha, illustrating the scale of impact possible when heat-tolerant varieties, irrigation, mechanization and coordinated deployment are aligned (Tadesse et al., 2022a). However, long-term trends since 1961 show that production growth has relied heavily on area expansion rather than sustained productivity gains (FAOSTAT, 2025; Figure 1).

Across the continent, yield outcomes differ sharply by target production environment. Well-managed irrigated systems,

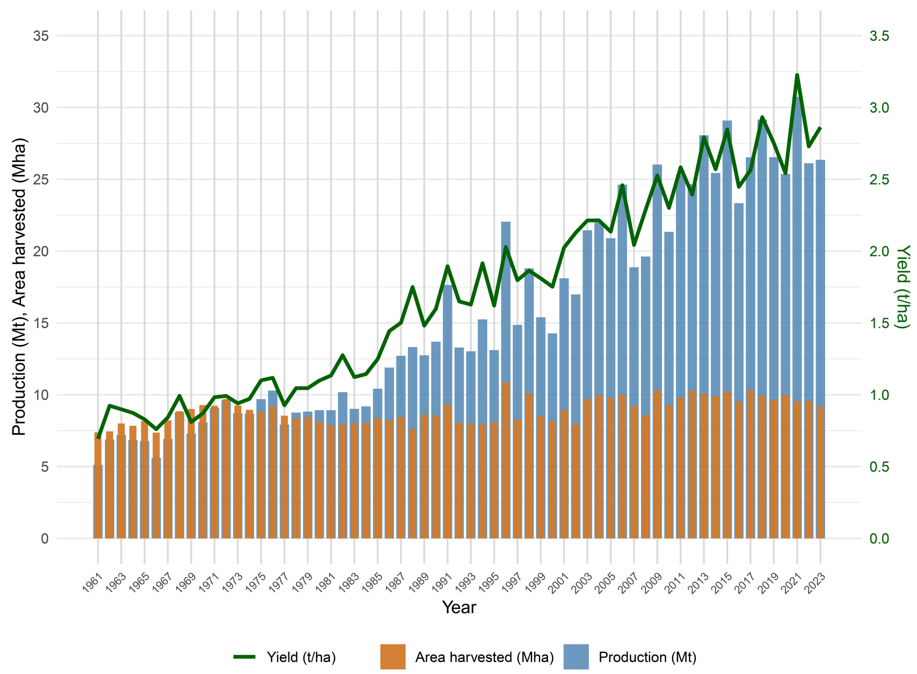

FIGURE 1
Wheat production (Mt), area harvested (Mha) and yield (t/ha) in Africa (1961–2023).

especially in Egypt, can reach approximately 7–8 t ha^{-1}, while many rainfed smallholder systems in North Africa and the East African highlands remain near 1–3 t ha^{-1} and are highly sensitive to rainfall, disease pressure and input access (Silva et al., 2021; Abdalla et al., 2023; Silva et al., 2023). These country- and environment-specific differences are more informative than a single continental average because they identify where breeding should prioritize heat tolerance, drought adaptation, rust and Septoria resistance, salinity tolerance, water-use efficiency or input responsiveness.

Yield gaps are further exacerbated by interacting abiotic and biotic stresses. Drought, heat stress, and salinity are widespread across African wheat-growing regions and are projected to intensify under climate change. Simultaneously, diseases such as stripe rust, stem rust, *Septoria tritici* blotch, and *Fusarium* head blight continue to cause recurrent and sometimes severe yield losses (Tadesse et al., 2019a; Wamalwa et al., 2022; Dehbi et al., 2024). Weak seed systems, slow varietal turnover, limited access to quality seed and inputs, and constrained extension and infrastructure further limit the uptake of improved technologies.

Recent advances in wheat breeding, including shuttle breeding, speed breeding, doubled haploids, marker-assisted selection and genomic selection, are already improving breeding efficiency in CGIAR and national pipelines serving parts of North, East and Southern Africa (Tadesse et al., 2019b; Alemu et al., 2021; Tadesse et al., 2024a). Other innovations, including hybrid wheat and genome editing, are promising but remain at different stages of validation, regulation and deployment and should not be treated as continent-wide solutions already available at scale. Their value will depend on whether they are embedded in realistic seed, agronomy and policy pathways.

This review therefore goes beyond a technical overview of breeding tools. It identifies the critical constraints that prevent genetic gains from becoming food-security impact, explicitly links advances in breeding with seed-system and deployment reforms, and proposes an integrated genetic-gain-to-grain framework for African wheat transformation. The central argument is that Africa's wheat future depends on synchronizing target production environments, product profiles, accelerated breeding, seed multiplication, release and regulatory systems, crop management, market incentives and regional policy coordination.

Our organizing thesis is that wheat innovation in Africa must be designed as a delivery pipeline rather than a sequence of disconnected projects. In such a pipeline, the success metric is not only the number of varieties released or the sophistication of the breeding method, but the speed and equity with which climate-resilient varieties reach farmers as quality seed, are grown with appropriate agronomy and irrigation, and generate grain that strengthens national and regional food security.

2 Target production environments: moisture regimes, yield gaps and deployment priorities

Moisture availability is the first factor for wheat adaptation in Africa. However, other factors including temperature during flowering and grain filling, disease pressure, soil constraints, irrigation reliability, and input access all determine whether an improved variety becomes a productive crop. For breeding and deployment, the continent can be organized into five broad target production environments (TPEs) (Figure 2): (i) Mediterranean rainfed systems of Morocco, Algeria and Tunisia, where terminal drought, heat and yield instability dominate; (ii) highly managed irrigated systems of Egypt, Ethiopian low lands and parts of Sudan, where yield potential is high but heat, salinity and water competition are increasing; (iii) East African highlands of Ethiopia, Kenya and Tanzania, where rusts, Septoria, waterlogging and soil fertility constraints interact with smallholder seed and input limitations; (iv) mixed rainfed-irrigated temperate systems of South Africa and neighboring countries, where drought, input costs and mechanization shape profitability; and (v) emerging dry-season irrigated and rainfed niches in West Africa, including Nigeria and Mali, where heat tolerance, irrigation scheduling and market linkages are decisive.

The recent expansion of irrigated wheat into the Ethiopian lowlands demonstrates that coordinated investments in irrigation, mechanization, heat-tolerant varieties and efficient seed delivery can successfully extend wheat production into new environments, while also creating new challenges related to heat stress, emerging pests and water management (Tadesse et al., 2023b). This example illustrates that successful wheat improvement depends not only on matching varieties to the biophysical conditions of each TPE but also on addressing the associated seed-system and adoption constraints. Consequently, target product profiles should be tailored to the specific requirements of each TPE, and multi-environment testing should represent the environmental and management conditions where varieties are ultimately intended to be deployed (Silva et al., 2021; Abdalla et al., 2023; Silva et al., 2023).

Rainfed wheat systems dominate large parts of Africa, particularly the Maghreb, Western Cape of South Africa and the East African highlands at approximately 1,900 – 2,700 meter above sea level. In North Africa, rainfed wheat accounts for an estimated 80 – 90% of total wheat area, with irrigation contributing the remaining 10 – 20% (Boussakouran et al., 2024; Tita et al., 2025). These environments are thermally suitable but highly variable, because rainfall is erratic, terminal drought is frequent and high temperatures increasingly coincide with grain filling (Simane et al., 1999; Belete et al., 2022; Negeri et al., 2025). Breeding priorities for these systems include drought escape and tolerance, stable grain set under heat, disease resistance, water-use efficiency and farmer-preferred grain quality.

Irrigated wheat production predominates in the arid and hyper-arid zones of Africa, especially the Nile Valley and delta in Egypt and large irrigation schemes in Sudan such as Gezira. These systems generally rely on canal, basin, surface or flood irrigation, supplemented in newer expansion zones by groundwater pumping, river diversion and small- to medium-scale pump systems. Controlled water supply enables higher and more stable yields than rainfed systems. However, many schemes are constrained by aging transportation infrastructure, poor drainage, uneven field leveling, inefficient scheduling, energy costs, salinization and weak maintenance. These gaps make irrigation modernization - including better

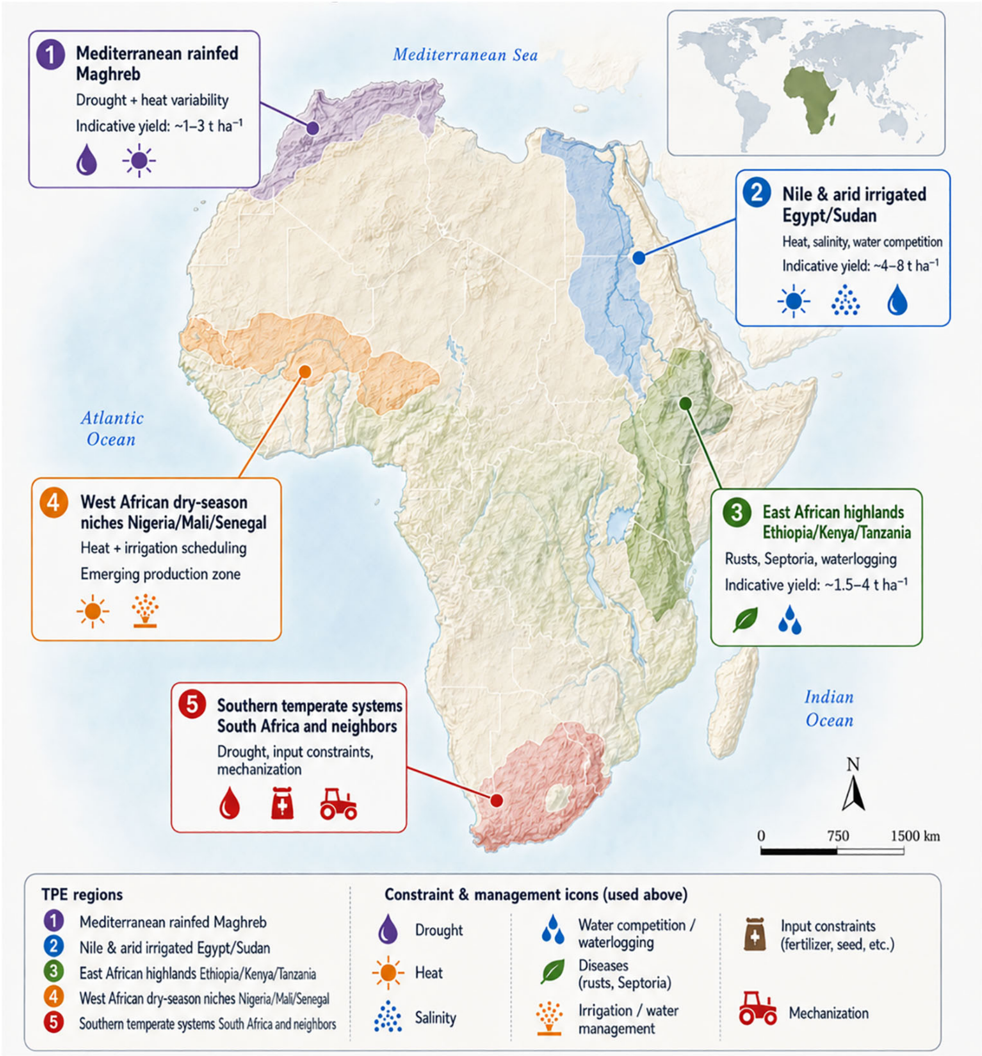

FIGURE 2
Africa wheat target production environments (TPEs), dominant stresses and indicative yield ranges across major wheat growing regions. The schematic summarizes rainfed Mediterranean systems, Nile and arid irrigated systems, East African highlands, Southern temperate systems and emerging West African dry-season wheat niches.

scheduling, drainage, land leveling, water accounting and locally appropriate sprinkler or drip systems - as important as genetic heat and salinity tolerance (Al Zayed et al., 2015; Multsch et al., 2017; Ahmed et al., 2025).

Over the past five years, irrigated wheat production has expanded rapidly beyond its traditional Nile corridor strongholds, particularly into the lowland and mid-altitude areas of Ethiopia and parts of West Africa, including Nigeria. This expansion has been supported by groundwater extraction and river diversion, often relying on surface or flood irrigation systems (Tadesse et al., 2022a; Ahmed et al., 2025). While these developments have contributed to increased domestic wheat production, they have also introduced new breeding challenges, including adaptation to high temperature stress, water use efficiency under nontraditional irrigation regimes, and tolerance to emerging pests and diseases in warmer environments.

In Southern region of the continent, wheat production occurs in mixed temperate systems that combine both rainfed and irrigated cultivation, particularly in South Africa. Yield stability in these systems is constrained by high rainfall variability, periodic drought, and generally low input use in rainfed areas. Consequently, breeding efforts must prioritize stress tolerance, yield stability, and input-use efficiency to ensure cultivar performance under variable and often resource-limited production conditions (Shew et al., 2020; Ajilogba and Walker, 2023). Similarly, in West Africa, especially in Nigeria and Mali, wheat production is expanding under both irrigated dry-season systems and emerging rainfed niches, driven by rapidly growing demand and policy efforts to reduce import dependence.

Taken together, the wheat environments of Africa require targeted breeding and deployment. Region-specific trait prioritization, representative multi-environment testing, stress surveillance and adaptive seed deployment are essential to convert genetic gain into yield gain across heterogeneous wheat-growing systems. This also means that mega-environment or TPE classification should be updated regularly as irrigation expands, disease races shift and climate risk intensifies.

2.1 Yield gaps as a translation metric

Here, yield gap refers to the difference between the yield attainable within a defined TPE under currently feasible water, nutrient and crop-management conditions and the average yield realized by farmers in that same environment. Consequently, yield gaps differ among TPEs and countries according to their climatic, management and socioeconomic conditions. They are therefore not simply the difference between irrigated and rainfed systems, between experimental stations and farmers' field, or between old and new varieties. Instead, yield gap is a system-level indicator of how effectively genetics, seed, agronomy, finance, infrastructure and institutions are translated into grain. Closing these yield gaps therefore requires both higher genetic gain and greater realization of that gain through seed availability, input access, crop management, market incentives and policy coordination.

3 Challenges hindering wheat transformation in Africa

3.1 Abiotic and biotic stresses

3.1.1 Abiotic stress

Abiotic stresses, intensified by climate change, are major constraints to wheat production across Africa, particularly in rainfed systems. Drought is the dominant limitation, driving yield variability through effects on growth, grain filling and yield stability across major production zones in North, East, West and south Africa (El Idrissi et al., 2023; Ouzani et al., 2025; Tadesse et al., 2019a; Olayide et al., 2016). Heat stress frequently co-occurs with drought, especially during anthesis and grain filling, where temperatures above 30–35 °C reduce grain set, accelerate phenology and impair yield and quality (Shew et al., 2020; Musa et al., 2021). Projected warming of 3 – 4 °C, and up to 5 – 7 °C in some regions, is expected to exacerbate these constraints (Fotso-Nguemo et al., 2023).

Salinity is an increasing constraint in irrigated and coastal systems due to seawater intrusion, inefficient irrigation and high evapotranspiration, with severe impacts reported in Morocco, Senegal, and the Nile Delta of Egypt (Bouras et al., 2023; Thiam et al., 2021; Hagage et al., 2024). Additional stresses include waterlogging in highland systems (e.g., Ethiopia), which limits root function and soil degradation and nutrient imbalances that further reduce productivity (Girma, 2024; MacCarthy et al., 2021; Nyambo et al., 2025). In some irrigated areas, heavy metal contamination from wastewater and industrial sources poses additional risks to crop performance and food safety (Mohammad et al., 2025; Gelaye and Musie, 2023). The combined and spatially variable nature of drought, heat, salinity, and related stresses is a primary determinant of yield instability across African wheat systems. Their increasing intensity under climate change highlights the need to prioritize multi-stress adaptation and environment-specific resilience in wheat improvement.

3.1.2 Biotic stresses

Wheat production in Africa is strongly constrained by fungal diseases and insect pests, which cause substantial and recurrent yield losses. Rust diseases including yellow rust (*Puccinia striiformis f.* sp. *tritici*), stem rust (*P. graminis f.* sp. *tritici*, including the *Ug99* lineage) and leaf rust (*P. triticina*), are the most widespread and damaging. Yellow rust is prevalent across East and North Africa, with epidemics often causing losses exceeding 50% due to rapidly evolving pathogen populations. Stem rust remains a major transboundary threat, with *Ug99* and its variants driving periodic resistance breakdown, while leaf rust contributes additional but limited yield penalties across major production regions (Tadesse et al., 2019a; Wamalwa et al., 2022; Dehbi et al., 2024; Fetch et al., 2021; Terefe et al., 2024; Ijaz et al., 2023).

Other fungal diseases further intensify constraints. *Fusarium* head blight reduces yield and contaminates grain with mycotoxins, with losses reaching 30–70% in affected regions. *Septoria* leaf blotch (*Zymoseptoria tritici*) is particularly severe in humid highland environments such as Ethiopia, with similar pressures reported in North Africa (Shude et al., 2020; Benjamin et al., 2025; Takele et al., 2015; Teferi and Gebreslassie, 2015; Bel Hadj Chedli et al., 2020).

Insect pests also contribute to yield instability. The Hessian fly (*Mayetiola destructor*) and Russian wheat aphid (*Diuraphis noxia*) are widespread and frequently overcome host resistance, while the wheat stem sawfly (*Cephus* spp.) causes localized but significant damage in North Africa (Tadesse et al., 2022b; Jankielsohn, 2016; El Bouhssini et al., 2011). The diversity, prevalence, and rapid evolution of pathogens and pests sustain chronic yield instability across production regions. This dynamic pressure underscores the importance of durable, broad-spectrum resistance and continuous monitoring of pathogen populations. Collectively, the severity and relative importance of abiotic and biotic constraints differ considerably among Africa's major wheat production environments because of variation in climate, production systems and pathogen pressure. Consequently, breeding priorities must be tailored to the specific challenges of each target production environment. The major wheat production environments, their climatic characteristics, dominant abiotic and biotic constraints, and corresponding breeding priorities are summarized in Table 1.

3.2 Seed systems

Weak seed systems remain a major bottleneck to wheat productivity in Africa. Despite the release of many wheat varieties in the past three decades, varietal turnover is slow, with many farmers still cultivating varieties older than 20 years (Nhemachena and Kirsten, 2017; Tadesse et al., 2019a; Silva et al., 2023). Formal systems supply less than 20% of seed demand, leaving most farmers reliant on farm-saved seed and informal markets, limiting access to improved germplasm. A key constraint is early-generation seed (EGS) production, where weak coordination among breeding programs, public institutions, and private enterprises delays multiplication and dissemination (Silva et al., 2023; Tadesse et al., 2024a). Farmer-managed seed systems, critical for varietal diffusion, remain

TABLE 1 Major wheat production environments in Africa, their climatic characteristics, dominant abiotic and biotic constraints, and corresponding breeding priorities.

Major production environment	Representative countries	Climatic characteristics	Major abiotic constraints	Major biotic constraints	Priority breeding objectives
North Africa rainfed drylands	Morocco, Algeria, Tunisia	Mediterranean winter-rainfall (Nov–Jun); spring bread wheat; ~3.05 million ha	Terminal drought, heat stress, rainfall variability	Yellow rust, stem rust, Septoria, Hessian fly	High yield under drought (>10% over checks), drought tolerance, yield stability, early vigor, durable rust and Septoria resistance, Hessian fly resistance, bread-making quality
East Africa rainfed highlands	Ethiopia, Kenya, Eritrea, Tanzania, Uganda	Cool rainfed highlands (Jul–Nov); ~2.02 million ha	Moisture variability, intermittent drought	Stem rust (Ug99), yellow rust, Septoria, Russian wheat aphid	Broad adaptation, durable rust resistance, Septoria resistance, yield stability, early maturity, improved grain quality
Sub-Saharan Africa irrigated	Ethiopia, Sudan, South Africa, Tanzania, Zambia, Zimbabwe, Nigeria, Mali	Irrigated systems; high temperatures; ~2.0 million ha	Heat stress, water scarcity	Yellow rust, stem rust, Septoria, Russian wheat aphid	High yield under heat (>10% over checks), heat tolerance, irrigation adaptation, yield stability, disease resistance
North Africa irrigated	Egypt, Morocco, Algeria, Tunisia, Libya	Irrigated high-yield systems (Nov–Jun); ~1.9 million ha	Heat stress, salinity, limited irrigation water	Yellow rust, stem rust, Septoria, Hessian fly	High yield under irrigation (>10% over checks), heat tolerance, salinity adaptation, disease resistance, grain quality

insufficiently integrated into national frameworks (Vernooy et al., 2023).

Regulatory bottlenecks further slow adoption. Centralized and resource-intensive Distinctiveness, Uniformity and Stability (DUS) and Value for Cultivation and Use (VCU) testing can reject otherwise useful varieties, increase costs, delay market entry and discourage private-sector participation. Alternative approaches such as Quality Declared Seed (QDS) can provide more flexible pathways for farmer- and cooperative-based seed production but remain underutilized (Ayenan et al., 2021). Although regional harmonization initiatives (COMESA, ECOWAS, SADC) aim to facilitate seed trade, inconsistent implementation restricts cross-border movement (Lewis and Masinjila, 2018; Kuhlmann, 2015). In some countries, subsidies that favor imported or foreign-origin seed without parallel incentives for national breeding pipelines can weaken local variety adoption and reduce the return on public breeding investment (Tadesse et al., 2024a).

Institutional fragmentation compounds these constraints. Coordinated platforms, such as the National Seed Advisory Group in Ethiopia demonstrate the benefits of improved alignment but are not widely adopted (Alemu et al., 2023; McEwan et al., 2021). Overall, weak coordination and regulatory inefficiencies limit the timely delivery of improved varieties, highlighting the need for stronger, more integrated seed systems.

3.3 Farm-level yield realization and adoption gaps

Using the yield-gap definition introduced above, the main issue in Africa is not only that attainable yields differ among environments; it is that farmers capture only a fraction of the gains generated by breeding and agronomy. Farm yields of 1-2.5 t ha^{-1} in many rainfed systems represent roughly 20-40% of water-limited potential, while irrigated systems with reliable water and inputs demonstrate much higher yield ceilings. The gap therefore reflects both biophysical limits and an innovation-delivery deficit (van Ittersum et al., 2016; Silva et al., 2021, Silva et al., 2023; van Ittersum et al., 2025).

Key drivers of yield gaps include chronic water limitations, low fertilizer use, and suboptimal agronomic practices. Irrigation accounts for only about 6% of total cropland in sub-Saharan Africa, leaving the majority of wheat production heavily dependent on increasingly variable rainfall (van Ittersum et al., 2016; Mabhaudhi et al., 2018). In addition, nitrogen and phosphorus application rates remain far below agronomic recommendations in most African wheat systems, constraining biomass production and grain yield (van Ittersum et al., 2016; Silva et al., 2019).

Genetic constraints further exacerbate yield gaps. Many farmers continue to grow outdated, disease-susceptible wheat varieties, leading to yield instability and repeated resistance breakdowns under high pathogen pressure, particularly from rust diseases (Tadesse et al., 2019a; Hodson et al., 2020). Although improved and disease-resistant varieties are available in several countries, adoption remains uneven.

Socioeconomic and institutional constraints strongly limit the uptake of improved technologies. Restricted access to quality seed, fertilizers, credit, and extension services continues to impede productivity gains in countries such as Morocco, Ethiopia, Malawi, and Sudan (Yigezu et al., 2021; Makate et al., 2024; Ibrahim et al., 2024). These challenges are compounded by technology gaps, including limited mechanization and low penetration of digital agriculture tools, which reduce labor efficiency and timeliness of operations, particularly among smallholder farmers (Baudron et al., 2019; Silva et al., 2021). Higher levels of mechanization in parts of North Africa partially mitigate these constraints but do not fully offset variability in water availability and input use.

Overall, wheat yield gaps in Africa arise from interacting biophysical, management, genetic, and socioeconomic factors. Closing these gaps will require integrated intensification strategies that

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combine improved, disease-resistant varieties with better agronomy, enhanced input access, and supportive institutional frameworks.

3.4 Infrastructure and policies

Infrastructure and policy constraints remain major barriers to wheat system performance in Africa, limiting market efficiency and technology uptake. Poor rural connectivity increases transport costs, reduces farm-gate prices, and weakens incentives for intensification, contributing to fragmented markets (Ma et al., 2024; Tadesse et al., 2019a). Post-harvest losses further reduce effective supply due to inadequate storage, processing capacity, and weak logistics systems (Affognon et al., 2015; Kumar and Kalita, 2017).

Policy and regulatory bottlenecks hindered varietal deployment and seed-system performance. Fragmented seed laws, lengthy variety release procedures and inconsistent implementation of regional harmonization frameworks (COMESA, ECOWAS, SADC) delay scaling of improved varieties and limit private-sector engagement (Kuhlmann et al., 2025). Irrigation infrastructure offers both opportunity and constraint as systems in Egypt and emerging initiatives in Ethiopia demonstrate strong yield potential, but performance is often limited by inefficient water management, poor maintenance and salinization risks (Multsch et al., 2017; Senbeta and Worku, 2023). Broader agricultural policies, including subsidies, extension services and rural credit, remain uneven, limiting farmers' access to inputs and information (Jayne et al., 2018; Finizola e Silva et al., 2024). These structural problems restrict market integration and slow the diffusion of improved technologies across production systems.

4 Wheat breeding in Africa

National wheat breeding programs in Africa rely heavily on germplasm from CGIAR centers, particularly CIMMYT and ICARDA, introduced through international nurseries and evaluated in national multi-location trials before release. Although many national programs also conduct local crossing and selection, more than 95% of released varieties are originated from CGIAR-derived germplasm, emphasizing the central role of international pipelines in supplying adapted material (Tadesse et al., 2019a). The key challenge is therefore to align breeding pipelines with farmer and market demand, adapt to specific TPEs and connect them directly to seed delivery. A high performing wheat breeding pipeline should combine three forms of acceleration: I) biological acceleration through faster generation advancement; II) predictive acceleration through markers and genome-wide prediction and better phenotyping; and III) delivery acceleration through early recycling of elite parents, synchronized variety release, early-generation seed planning and deployment partnerships. Without the third component, faster breeding can increase the number of candidate varieties without increasing farmer impact. The evolution of African wheat breeding from conventional introduction and selection approaches to modern genomics-assisted and accelerated breeding systems is summarized in Table 2.

These advances in breeding strategies have resulted in the release of numerous bread wheat varieties adapted to Africa's diverse production environments. Representative cultivars released in selected African countries illustrate the successful integration of high yield potential with resistance to major diseases and tolerance to key abiotic stresses and are summarized in Table 3.

4.1 Accelerated breeding as an integrated pipeline

4.1.1 Modified shuttle breeding

Accelerated breeding approaches, particularly modified shuttle breeding, have significantly reduced breeding-cycle duration. At ICARDA, crosses are developed under controlled conditions, while early generations (F2-F4) are rapidly advanced through seasonal cycling between rainfed and irrigated environments at Merchouch, Morocco. As illustrated in Figure 3, this system integrates

TABLE 2 Major milestones in the evolution of wheat breeding in Africa (1920s–2020s).

Period	Evolution of wheat breeding approaches in Africa	References
1920s–1950s	Establishment of national wheat improvement programs through introduction, evaluation and pure-line selection of introduced and locally adapted germplasm	Tadesse et al. (2022a); Nhemachena and Kirsten (2017); Tadesse et al. (2024a)
1960s–1970s	Integration of CIMMYT semi-dwarf germplasm and Green Revolution breeding materials into African wheat breeding programs	Tadesse et al. (2019a); Tadesse et al. (2022a); Crespo-Herrera et al. (2018)
1970s–1980s	Development of collaborative CGIAR–National Agricultural Research System (NARS) breeding networks and international nursery testing	Ortiz et al. (2007); Tadesse et al. (2019a); Tadesse et al. (2024b)
1980s–1990s	Expansion of national hybridization, crossing and pedigree breeding for local adaptation and cultivar development	Tadesse et al. (2022a); Tadesse et al. (2024a); Nhemachena and Kirsten (2017)
1990s–2000s	Broadening breeding objectives to combine high yield with durable rust resistance and adaptation to drought and heat stress	Tadesse et al. (2019a); Fetch et al. (2021); Tadesse et al. (2022c)
2000s–2010s	Progressive integration of molecular breeding tools, marker-assisted selection and doubled haploid technology into breeding pipelines	Wessels and Botes (2014); Elhaddoury et al. (2012); Henkrar et al. (2016); Tadesse et al. (2024a)
2010s	Implementation of genomic-assisted breeding, high-throughput phenotyping and data-driven breeding pipelines	Alemu et al. (2021); Zaïm et al. (2020); Tadesse et al. (2023a); Tadesse et al. (2024a)
2020s	Deployment of accelerated breeding platforms integrating speed breeding, genomic prediction, DNA fingerprinting and seed-system innovations	Watson et al. (2018); Hodson et al. (2020); Habte et al. (2023); Tadesse et al. (2024a)

TABLE 3 Representative bread wheat varieties released in selected African countries, highlighting pedigree, year of release, target adaptation, stress resistance/tolerance, and yield potential.

Country	Variety	Year released	Pedigree	Main target adaptation and stress tolerance/resistance	Yield potential (t ha^{-1})	Reference
Morocco	Yakout	2025	—NA	Drought, leaf rust, yellow rust, Hessian fly	6	Ferrahi et al., 2026
Morocco	Malika	2016	—Achtar3*//'Kanz'/Ks85-8-4	Drought, leaf rust, yellow rust, *Zymoseptoria tritici* (Septoria tritici blotch)	4.2-6	Ferrahi et al., 2026
Morocco	Irchad	2023	—NA	Drought, yellow rust, Hessian fly	4.5-8	Ferrahi et al., 2026
Morocco	Snina	2017	—BT1735/ACHTAR// HUBARA-8	Leaf rust, *Zymoseptoria tritici* (Septoria tritici blotch), Hessian fly	3.5-6	Ferrahi et al., 2026
Morocco	Lina	2020	—NA	Drought, leaf rust, yellow rust, *Zymoseptoria tritici* (Septoria tritici blotch)	4.4 = 6.3	Ferrahi et al., 2026
Morocco	Ibtisam	2022	NA	Drought, leaf rust, yellow rust, *Zymoseptoria tritici* (Septoria tritici blotch)	4.5-6.5	Ferrahi et al., 2026
Ethiopia	Kakaba	2010	KIRITATI//SERI/RAYON	high yield; stem rust and yellow rust	2.5–4.7	Habte et al., 2023; Ebabu and Habteslase, 2026
Ethiopia	Danda'a	2010	KIRITATI//2*PBW65*/ 2SERI.1B	stem rust and yellow rust resistance	2.5–5.0	Habte et al., 2023; Ebabu and Habteslase, 2026
Ethiopia	Abay	2021	BOUSHODA-1/4/CROC-1/ AE.SQUARROSA(205)// KAUZ/3/SASIA	Stem rust and yellow rust resistance; rainfed adaptation	3.0–4.5	Tadesse et al., 2022a
Ethiopia	Biftu	2023	CHIPAK*2/3/KSW/SAUAL //SAUAL	disease resistance; stable high yield	5.6	Demeke et al., 2024
Ethiopia	Honqollo	2014	NJORO SD-7 (NJORO SD-7// VEE/NAC	Stem rust and yellow rust resistance; rainfed adaptation	3.0–4.5	Tadesse et al., 2022a
Ethiopia	Fentale-2	2017	QAFZAH-2/FERRIUG-2	Heat tolerance, stem rust, high yield under irrigation	4.5–6.0	Bayissa et al., 2023
Ethiopia	Hulluka	2012	UTQUE96/3/PYN/BAU// MILAN	Stem rust and yellow rust resistance; rainfed adaptation	3.0–4.5	Tadesse et al., 2022a
Egypt	Sids 17	2026	MISKEET-18/3/CBRD/ WBLL1//PANDION/5/ALD/ COC//URES/3/DUCULA/4/ METSO	Heat tolerance, Yield potential, rust resistance	8–10 t/ha	Tadesse (unpublished)
Egypt	Sids 15	2021	PARUS/PASTOR//FIDIYA- 20/3/PASTOR//MILAN/ KAUZ	Heat tolerance, yield potential, rust resistance	8-10	Tadesse et al., 2022
Egypt	Sids 14	2015	Bow"S"/Kvz"S"//7C/Seri82 /3/Giza168/Sakha61	Heat adaptation, high yield, yellow and stem rust	≈7.0–8.0	Abd El-Majeed et al., 2017
Sudan	Khidaiwi	2018	KAUZ//MON/CROW"S"/4/ SERI.1B//KAUZ/HEVO/3/ AMAD	Heat adaptation, high yield, yellow and stem rust	5-6	Tadesse et al., 2019c
Sudan	Al-Shibaik	2018	DEBEIRA/4/KAUZ//ALTAR 84/AOS/3/KAUZ	Heat adaptation, high yield, yellow and stem rust	5-6	Tadesse et al., 2019c
Sudan	Amel	2018	CROW'S'/BOW'S' -1994/95// ASFOOR-5	Heat adaptation, high yield, yellow and stem rust	5-6	Tadesse et al., 2019c
Sudan	Salah	2018	HUBARA-3*2/SHUHA-4	Heat adaptation, high yield, yellow and stem rust	5-6	Tadesse et al., 2019c
Sudan	Jawahir	2018	SHUHA-//NS732/HER	Heat adaptation, high yield, yellow and stem rust	5-6	Tadesse et al., 2019c
Nigeria	Imam	2019	ATTILA 7	Heat tolerance, high yielding under irrigation	4-6	Nigerian Seed Portal Initiative, 2026
Nigeria	LACRIWHIT-9	2017	PASTOR-2/KATILA-13// HAMAMS-5	Heat tolerance, high yielding under irrigation	4-6	Nigerian Seed Portal Initiative, 2026

(Continued)

TABLE 3 Continued

Country	Variety	Year released	Pedigree	Main target adaptation and stress tolerance/resistance	Yield potential (t ha^{-1})	Reference
Nigeria	LACRIWHIT-10	2017	KAUZ'S'/SERI/3/TEVEE'S'//CROW/VEE'S'	Heat tolerance, high yielding under irrigation	4-6	Nigerian Seed Portal Initiative, 2026
Kenya	Kenya Falcon	2016	KSW/5/2*ALTAR84/AE. SQUARROSA(221)//* 3BORL95/3/ URES/JUN/KAUZ/4/WBLL1	Excellent seedling and adult plant resistance to stem rust and yellow rust	4-5	Wanyera and Wamalwa, 2022
Kenya	Kenya Tai	2012	ND643/2*WBLL1	Resistance to stem rust and yellow rust; high-yielding bread wheat	4.5-6	Wanyera and Wamalwa, 2022

greenhouse crossing, rapid generation advancement and multi-location testing within a continuous annual cycle. Advanced yield trials represent key target conditions, including drought in Morocco, heat in Sudan, high yield potential in Egypt, cold in Lebanon and disease-prone highlands in Ethiopia. Selection based on phenotypic performance and molecular markers identifies elite germplasm for parental recycling and international nursery distribution (Tadesse et al., 2024a).

This approach enables the development and dissemination of elite germplasm within ~4 years at ICARDA and registration of varieties in the key national partners within 6–7 years, compared to 8–10 years under the previous conventional breeding scheme. Similar shuttle-based strategies are used across CGIAR and national programs exploit contrasting environments to accelerate genetic gain and improve adaptation to multiple stresses (Ortiz et al., 2007; Bhavani, 2024). This approach demonstrates how integrating contrasting environments within a single breeding cycle can substantially shorten selection time while improving adaptation to diverse stress conditions, making it a cornerstone strategy for enhancing breeding efficiency in heterogeneous agro-ecologies.

4.1.2 Speed breeding

Speed breeding is a controlled-environment breeding approach designed to accelerate genetic gain by shortening generation time through extended photoperiods, optimized temperature regimes, and intensive crop management. Originally formalized for wheat and other long-day crops, speed breeding enables the advancement of multiple generations per year and has emerged as a key component of modern accelerated breeding pipelines (Hickey et al., 2017; Watson et al., 2018).

In wheat, speed breeding typically allows the advancement of three to four generations annually, substantially reducing the time required for variety development compared with conventional field-based selection systems (Watson et al., 2018). In Africa, the establishment of speed breeding facilities, most notably by ICARDA in Morocco in collaboration with national programs, has contributed to reducing breeding cycles from approximately 10–12 years to 4–6 years, enabling more rapid delivery of improved cultivars under climate variable conditions (Tadesse et al., 2024a).

Speed breeding is particularly effective for the rapid advancement of segregating populations using single-seed descent (SSD), maintenance breeding, rapid recycling of elite germplasm and accelerated introgression of disease resistance genes, especially for wheat rusts. When integrated with molecular breeding tools such as marker-assisted selection (MAS) or genome-wide selection (GS), speed breeding can substantially enhance selection efficiency and increase realized rates of genetic gain (Hickey et al., 2019; Watson et al., 2018). Adoption of speed breeding platforms is expanding across eastern and southern Africa, including Kenya, Ethiopia and South Africa, although access remains largely restricted to

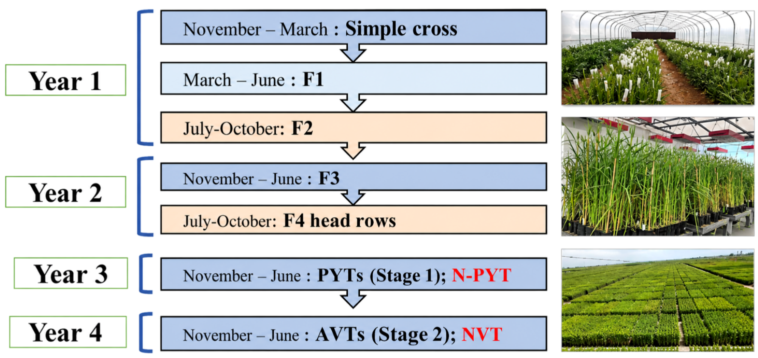

FIGURE 3
Accelerated wheat breeding pipeline integrating off-season greenhouse generation advancement with field evaluations. Simple crosses and F_1–F_4 populations are advanced within two years, followed by preliminary yield testing in year 3 and advanced/national variety trials in year 4.

specialized facilities due to infrastructure and operational costs (Mundia, 2020).

Despite its demonstrated advantages, speed breeding does not replace field evaluations as controlled environments cannot fully capture genotype × environment (GxE) interactions or complex biotic and abiotic stresses characteristic of target production environments. In addition, constraints on effective population size at early segregating generations, particularly at the F_2 stage in programs managing large numbers of crosses, may limit the capture of genetic diversity if population structure and advancement strategies are not carefully managed (Hickey et al., 2019). Consequently, speed breeding is best viewed as a complementary component of integrated breeding systems rather than a standalone solution.

4.1.3 Doubled haploids

Doubled haploid (DH) technology is a well-established approach in wheat improvement, enabling the rapid production of completely homozygous lines within a single generation. By accelerating allele fixation and allowing earlier and more effective selection, DH technology substantially shortens breeding cycles and enhances breeding efficiency compared with conventional inbreeding methods (Ren et al., 2017).

In North Africa, wheat DH platforms based on wheat × maize hybridization have been successfully implemented in Morocco and Egypt, contributing to the development of high-performing cultivars with improved adaptation to abiotic stresses, particularly drought and heat (Elhaddoury et al., 2012; El-Hennawy et al., 2011; Tadesse et al., 2024a). The wheat × maize system remains the most widely adopted method in hexaploid wheat due to its reliability and consistency across environments (Laurie & Bennett, 1988).

Integration of DH technology with molecular marker applications has further strengthened selection for complex traits, including disease resistance, stress tolerance and grain quality. This combined approach facilitates rapid fixation of favorable alleles and improves the efficiency of identifying and deploying resistance loci. In South Africa, for example, the use of DH lines alongside molecular markers has supported the development of rust resistant germplasm and contributed to breeding for durable resistance (Wessels and Botes, 2014).

Overall, DH technology increases the rate of genetic gain by enabling rapid homozygosity and more efficient selection and has played a complementary role alongside other accelerated breeding strategies. However, the recent adoption of speed breeding systems, which allow multiple generations per year, has reduced reliance on DH technology in some programs. Despite this shift, DH remains a valuable tool for trait fixation and genetic studies, particularly when integrated with MAS or GS (Watson et al., 2018).

4.1.4 Marker-assisted selection

Marker-assisted selection (MAS) is now central to wheat improvement programs enabling precise and rapid assembly of resistance and adaptive alleles. Functional markers and KASP assays are routinely used to track major rust genes (*Yr*, *Sr*, *Lr*) and key adaptive loci, shortening selection cycles and increasing selection accuracy. Across East and North Africa, MAS has validated and deployed loci for resistance to stripe, stem and leaf rust (including *Ug99*-effective loci), while also supporting selection for drought response and quality traits (Randhawa et al., 2018; Wamalwa et al., 2020; Mohamed et al., 2023). In Morocco, marker surveys indicate substantial baseline frequencies of durable adult-plant resistance (e.g., *Lr34/Yr18/Pm38*) and semi-dwarfing alleles, providing a strong foundation for targeted recombination (Henkrar et al., 2016). Increasingly, MAS is integrated both upstream (parent selection) and downstream (early-generation at F_1 or F_2 stage for gene pyramiding), at stage 1 trials (PYT) for early parental recycling and accelerating progression to Advanced yield testing across multiple locations (Tadesse et al., 2024a).

A key shift is from single-gene introgression to systematic gene pyramiding. ICARDA pipelines routinely combine multiple genes to build broad-spectrum and more durable resistance. Recent MAS efforts using conventional functional and KASP markers were specifically designed to maximize the number of favorable alleles combined within single genotypes. This strategy successfully generated elite lines carrying multiple trait combinations, integrating resistance (yellow rust, stem rust, *Septoria*) with drought and heat tolerance and grain quality.

Figure 4 illustrates the efficiency of trait pyramiding at the genotype level. A substantial proportion of lines combined two or more target trait categories, with major overlaps observed among abiotic stress adaptation, quality and disease resistance traits. Several genotypes also integrated multiple trait groups simultaneously, confirming the capacity of MAS to assemble complex and complementary allele combinations within single genetic backgrounds.

Complementary evidence comes from ICARDA's use of functional SSR markers which enabled the assembly of a stable "core" resistance backbone (*Yr10, Yr15, Yr18, Yr29/Lr46/Sr58, Sr22, Sr32*) in elite spring bread wheat genotypes. While the primary objective was to combine yellow and stem rust resistance in high-yielding backgrounds, background selection revealed additional resistance sources, particularly *Stb* genes. This allowed the identification and advancement of elite lines simultaneously carrying rust and *Septoria* resistance, indicating the efficiency of MAS for multi-disease pyramiding beyond initial breeding targets. MAS is enabling a shift from single-gene introgression to multi-trait pyramiding and facilitate the development of elite lines combining resistance, stress tolerance and quality traits within a single genetic background.

4.1.5 Genomic selection and gene editing

Genomic selection (GS) and gene editing are increasingly integrated into wheat breeding as complementary tools to accelerate genetic gain and shorten delivery timelines. GS uses genome-wide markers to predict breeding values for complex traits, enabling early-generation selection and reducing reliance on multi-season phenotyping. Gains are strongest when training populations are well designed and major QTL are incorporated as fixed effects, allowing efficient recycling of elite germplasm and tighter integration with field testing (Alemu et al., 2021, Alemu et al., 2024; Zaïm

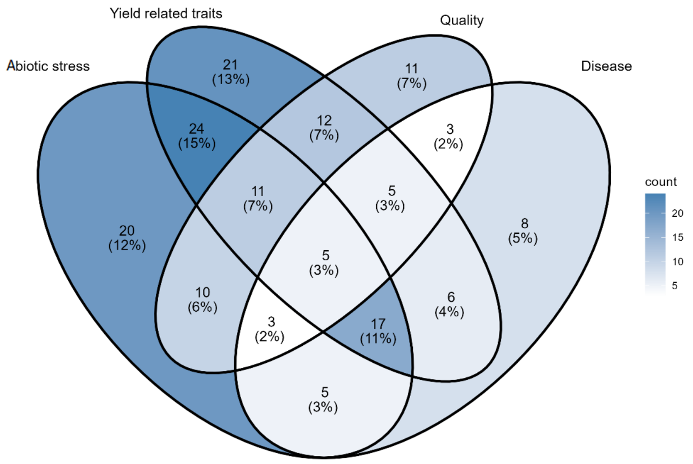

FIGURE 4
Multi-trait pyramiding in ICARDA wheat germplasm revealed by KASP-based marker-assisted selection. Distribution and overlap of elite lines combining abiotic stress adaptation, grain quality, disease resistance and yield-related traits illustrating simultaneous trait stacking achieved through MAS.

et al., 2020; Tadesse et al., 2023a). As genotyping costs decline and analytical capacity improves, GS is becoming operational for routine selection, particularly when embedded within accelerated breeding pipelines. Across programs led by CIMMYT and ICARDA (e.g., in Morocco, Ethiopia, Kenya, and South Africa), GS has improved selection accuracy for yield, quality and stress tolerance. Applications include resistance to *Septoria*, drought and heat adaptation in North Africa, and demand-led breeding in Ethiopia that combines genomic predictions with farmer preference data (Louriki et al., 2021; Gesesse et al., 2023; Tadesse et al., 2023a).

Gene editing, particularly CRISPR/Cas systems, adds a complementary layer of precision by enabling targeted modification of genes controlling stress tolerance, disease resistance and quality. For African wheat, however, gene editing remains largely at proof-of-concept, regulatory or pre-commercial stages rather than being broadly deployed across the continent. Early research includes targeted editing of stress-related genes in adapted cultivars such as 'Giza 168', while regulatory frameworks are evolving in countries such as Kenya, Nigeria and Ethiopia (Mohr et al., 2022; Tripathi et al., 2022; AUDA-NEPAD, 2023; Abdallah et al., 2025). Its near-term value will be greatest when it solves clearly defined TPE-specific constraints and is linked to biosafety clarity, seed multiplication and farmer demand.

4.2 Variety release and deployment

Wheat breeding has delivered substantial gains over the past decade, largely through CGIAR–national program pipelines that link accelerated breeding with multi-environment testing and rapid release. ICARDA and CIMMYT germplasm dominate national portfolios, with ICARDA alone contributing >80 released varieties across CWANA and Sub-Saharan Africa in the last 15 years. These varieties integrate traits for heat, drought and disease resistance and have shown strong performance across target environments (e.g., ~6 t ha^{-1} under Sudanese heat, ~5 t ha^{-1} under Moroccan drought, and up to ~11 t ha^{-1} under Egyptian irrigated environment) (Tadesse et al., 2022c; Tadesse et al., 2023b). In Ethiopia, rapid scaling of heat-tolerant irrigated wheat reached ~1 Mha by 2023 with average yields around 4 t ha^{-1}, illustrating the success of aligning breeding and deployment to translate into area-wide impact (Tadesse et al., 2023b). Rust-resistant varieties released through coordinated pipelines in East Africa further demonstrate the value of integrated testing, fast-track seed multiplication and strong extension linkages (Bishaw, 2016). More broadly, CGIAR supported programs enabled 148 wheat variety releases between 2012 and 2022 in Africa (CGIAR, 2022). Despite these advances, varietal turnover and seed reach remain uneven, limiting realized gains. Strengthening early-generation seed systems and streamlining release procedures are critical to improving adoption and impact.

4.3 Genetic gains and breeding progress

Wheat breeding in Africa has achieved measurable genetic gains over recent decades, driven by CGIAR–NARS collaboration and the adoption of accelerated and data-driven methods. Integration of rapid generation advancement, doubled haploids, shuttle and speed breeding and genomic-assisted selection has increased the rate and precision of selection, enabling development of high-yielding, stress-resilient varieties adapted to diverse agro-ecologies (Crespo-Herrera et al., 2018; Tadesse et al., 2019b). In selected breeding pipelines at ICARDA targeting key countries (e.g., Morocco and Ethiopia), annual genetic gains exceeding ~2% have been reported, alongside improvements in rust resistance, drought adaptation and end-use quality (Tadesse et al., 2024b).

Overall, wheat breeding has produced steady yield improvements, although the rate of progress differs by environment. Reported gains range from about 24–35 kg ha^{-1} yr^{-1} under irrigated conditions and 18–26 kg ha^{-1} yr^{-1} under drought stress, while semi-arid multi-environment trials have achieved gains of about 46.6 kg ha^{-1} yr^{-1}, equivalent to roughly 0.5–1% per year (Crespo-Herrera et al., 2018; Tadesse et al., 2019b). Long term evaluation of ICARDA wheat germplasm from 1980 to 2017 confirms steady breeding progress across contrasting African environments, with annual yield gains of about 1–2.5% reported in Sudan, Morocco and Egypt. These results highlight the value of testing and selecting germplasm across environments with different stress profiles, while coordinated regional trials and participatory selection in East Africa are helping to improve local adaptation and farmer adoption (Tadesse et al., 2019b; Bhavani, 2024).

Breeding priorities have expanded beyond yield to include nutrient-use efficiency, heat and drought tolerance, and resistance to major diseases (rusts, *Fusarium*, *Septoria*). Despite these advances, current genetic gain rates remain below levels required to close yield gaps and meet future demand highlighting the need for further intensification of selection schemes and improved prediction accuracy.

The integration of conventional and advanced breeding technologies described throughout this section into a single modern breeding pipeline is illustrated in Figure 5.

5 Wheat seed systems: structure, challenges and policy implications

Wheat is a strategic crop in Africa, contributing significantly to food security, dietary diversification, and national import substitution efforts. Despite sustained investments in wheat improvement by national agricultural research systems (NARS) and international centers such as CIMMYT and ICARDA, the impact of improved wheat varieties at farm level remains constrained by weaknesses in seed systems rather than limitations in breeding progress (Bishaw and van Gastel, 2009; FAO, 2010). Wheat seed systems in Africa are therefore best understood through the interaction of formal, informal and integrated seed supply pathways, with early generation seed (EGS) multiplication emerging as the principal bottleneck.

The principal constraints affecting African wheat seed systems, their implications for variety deployment and priority interventions are summarized in Table 4. The following subsections discuss each component in greater detail.

5.1 Structure of wheat seed systems

African wheat seed systems consist primarily of formal and informal systems, with emerging integrated (semi-formal) models in some countries. The formal wheat seed system operates under regulatory oversight and comprises public breeding institutions, seed certification agencies and both public and private seed producers. It relies on a defined seed class hierarchy, breeder seed, foundation seed and certified seed, to maintain varietal identity and ensure seed quality (Louwaars and Marrewijk, 1996; Tiwari, 2014). Formal systems are essential for disseminating newly released wheat varieties, particularly those with improved resistance to diseases and enhanced yield potential.

In contrast, the informal wheat seed system dominates farmer practice across much of Africa. Farmers commonly save seed from previous harvests, exchange seed locally, or purchase grain from local markets for planting. While this system enhances access and reduces costs, it often leads to declining genetic purity and slow varietal turnover decreasing long-term productivity gains (Almekinders & Louwaars, 1999; Maredia et al., 1999). Because wheat is self-pollinated and can be recycled for several seasons with limited short-term yield loss, farmer reliance on informal systems is particularly pronounced.

Integrated seed systems, involving farmer cooperatives and community-based seed producers, have shown promise in

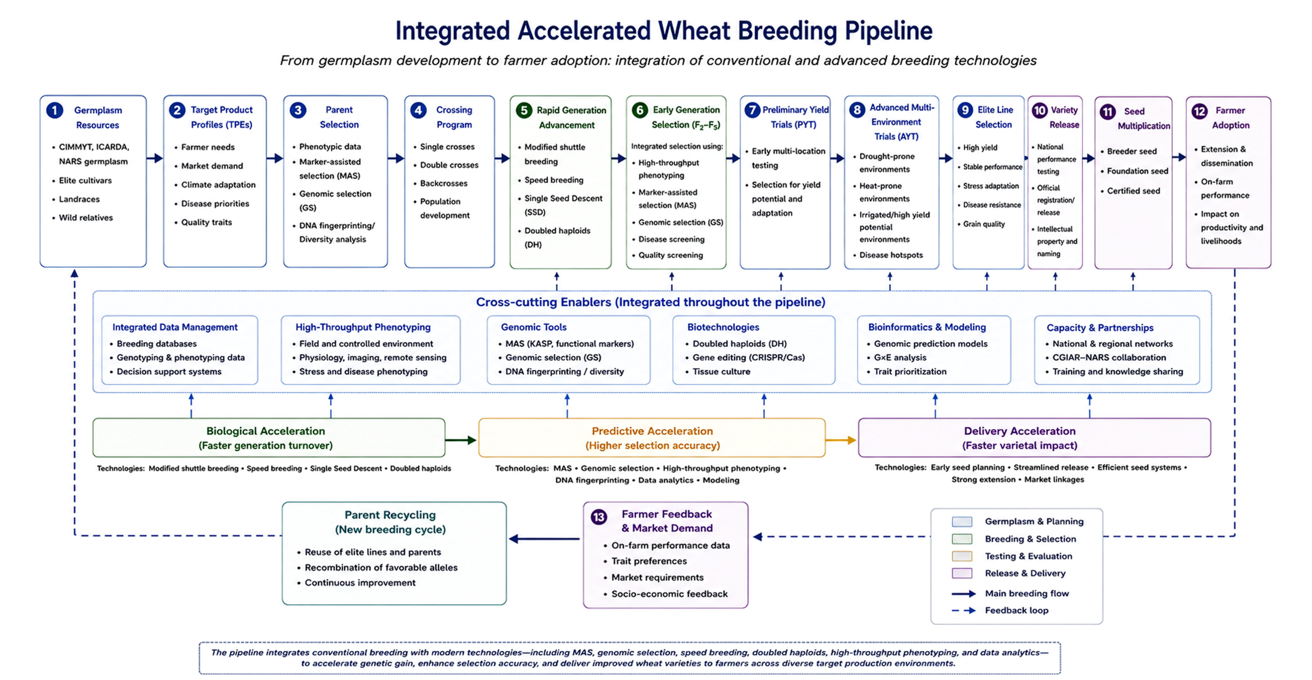

FIGURE 5
Integrated accelerated wheat breeding pipeline from germplasm resources to farmer adoption. The pipeline links TPE-based product profiling, parent selection, crossing, rapid generation advancement, genomic and phenotypic selection, multi-environment testing, variety release, seed multiplication and farmer feedback, supported by cross-cutting enablers that accelerate breeding efficiency, selection accuracy and varietal impact.

TABLE 4 Major bottlenecks affecting wheat seed systems in Africa, their implications for variety deployment, and priority interventions.

Seed system component	Main bottleneck	Implication for variety deployment	Priority action
EGS	Insufficient breeder and foundation seed production	Limits certified seed availability and delays dissemination of new varieties	Strengthen EGS capacity and public–private partnerships
Certified seed production	Weak market incentives and uncertain demand	Thin and fragmented certified seed markets	Improve seed multiplication and distribution systems
Varietal replacement	Slow turnover of released varieties	Reduces realized genetic gain on farmers' fields	Accelerate dissemination and replacement of obsolete varieties
Informal seed systems	Heavy reliance on farmer-saved seed	Slows adoption of newly released cultivars	Improve affordability and accessibility of quality seed
Quality assurance	Limited certification and inspection capacity	Reduces confidence in certified seed	Strengthen inspection and laboratory systems
Policy and regulation	Unpredictable subsidies and non-harmonized regulations	Distorts markets and slows regional variety dissemination	Develop predictable policies and harmonized seed regulations

improving access to quality wheat seed while maintaining affordability. However, their scale and impact remain limited by regulatory and institutional constraints (Sperling and Cooper, 2004).

5.2 Early generation seed multiplication

The effectiveness of wheat seed systems in Africa depends critically on the functioning of early generation seed (EGS), which includes breeder seed and foundation seed. Breeder seed is produced and maintained by breeding institutions and represents the highest level of genetic purity. Foundation seed, multiplied from breeder seed under controlled conditions, serves as the immediate source for certified seed production (Tiwari, 2014). In many African countries, however, EGS production is characterized by chronic shortages and institutional fragmentation.

Public research organizations are typically responsible for breeder seed production but often lack adequate funding, infrastructure, irrigation facilities and human capacity to produce sufficient quantities on a consistent basis (Bishaw and van Gastel, 2009). As a result, foundation seed production, which requires greater scale, investment and quality control remains severely constrained. Private seed companies generally avoid investing in foundation seed multiplication due to high costs, low margins, and uncertain demand for certified wheat seed (Minot et al., 2007). This weak link between breeding and certified seed production results in a persistent release and adoption gap, whereby officially released wheat varieties fail to reach farmers at scale (Setimela et al., 2009).

5.3 Certified seed production and adoption challenges

Certified wheat seed constitutes the final output of the formal seed system and is critical for achieving genetic gain on farmers' fields. However, demand for certified wheat seed in Africa is highly variable, influenced by rainfall patterns, grain market prices and government procurement policies. Farmer seed recycling further depresses demand, reducing incentives for sustained private sector engagement (Maredia et al., 1999; Wekundah, 2012). Available evidence from Ethiopia illustrates the scale of this challenge. The formal seed sector has been reported to directly reach only about 16% of wheat farmers, while certified seed accounted for only 7% of the cultivated wheat area in 2015/2016, despite improved wheat varieties occupying more than 50% of the national wheat area. These findings reflect low seed replacement rates, widespread reliance on farmer-saved seed and continued dependence on informal seed systems, which complicate demand forecasting, constrain certified seed production and slow varietal turnover (Habte et al., 2023). A comparable situation is observed in Morocco, where certified seed represents only about 22% of the total wheat seed planted, despite one of Africa's most developed formal wheat seed systems, indicating that seed recycling remains widespread even where seed production, certification and distribution systems are relatively well established (Yigezu et al., 2021). Recent analyses further estimate that only about 31% of the potential genetic gain generated through wheat breeding is ultimately realized on farmers' fields. This limited realization has been attributed to a modest seed replacement rate (≈35%), slow varietal turnover (≈0.045 yr^{-1}), and an adoption lag of 10–12 years, demonstrating that bottlenecks in seed multiplication, dissemination and varietal replacement remain major constraints even in comparatively advanced seed systems (Jlibene et al., 2026). Consequently, certified wheat seed markets remain thin and fragmented, with limited geographical reach and little scope for economies of scale. Collectively, these constraints result in certified wheat seed markets that remain thin and fragmented, with limited geographical reach and little opportunity for economies of scale.

Quality assurance mechanisms, including field inspections and laboratory testing, exist in most countries but are often constrained by limited institutional capacity, inadequate human and financial resources, and inconsistent enforcement of certification standards. These weaknesses undermine farmer confidence in certified seed quality and further encourage reliance on informal seed systems, ultimately reducing the rate at which improved wheat varieties are adopted and the genetic gains achieved through breeding are translated into productivity improvements.

5.4 Role of subsidies and policy frameworks

Seed subsidy programs have been widely adopted in Africa as policy instruments to promote technology adoption and enhance food security. In wheat systems, subsidies can temporarily increase demand for certified seeds and accelerate the dissemination of improved varieties when effectively targeted and well-coordinated (FAO, 2010). Although quantitative information on wheat seed subsidy levels is limited for most African countries, Morocco provides one of the few well-documented examples. Government support has included direct subsidies of 150 MAD quintal^{-1} for certified durum wheat seed and 130 MAD quintal^{-1} for certified soft wheat seed during the 2009 season, which were subsequently increased to 180 and 170 MAD quintal^{-1}, respectively, in the 2012/13 agricultural campaign, together with regulated maximum selling prices for certified seed (Ministry of Economy and Finance, 2009). These measures were intended to improve the affordability and adoption of certified seed while supporting the national seed production system. Despite these policy incentives, adoption of certified seed remains limited. In Morocco, certified seed represents only about 22% of the wheat seed planted, of which 17.8% is supplied by SONACOS and 4.2% by private seed companies. Farmers replace seed from all sources every 2.1 years on average but purchase certified seed only about once every five years, indicating that seed recycling remains widespread despite a relatively well-developed subsidy and certification system (Yigezu et al., 2021).

However, in many countries, subsidy programs remain unpredictable, politically driven and poorly aligned with long-term seed system development objectives. Poorly designed subsidies often crowd out private seed producers, distort price signals and bypass formal EGS planning processes. Emergency or short-term distribution programs may rely on limited varietal portfolios or uncertified seed sources, undermining both seed quality and system sustainability (Sperling and Cooper, 2004). The absence of stable, long-term policy commitments further discourages private investment in wheat seed systems.

Regulatory and policy environments also shape wheat seed system performance. Lengthy and non-harmonized variety release procedures across African countries increase transaction costs and slow cross-border movement of wheat varieties, despite shared agro-ecological zones (Setimela et al., 2009). Although regional initiatives have promoted harmonization, implementation remains inconsistent. Similarly, plant variety protection frameworks under UPOV and ARIPO have had limited influence on wheat seed system development, given weak enforcement and the biological characteristics of self-pollinated crops (UPOV, 2015).

Wheat seed systems in Africa are constrained less by breeding capacity than by institutional, economic and policy bottlenecks, particularly at the EGS stage. Inadequate breeder and foundation seed multiplication, weak market incentives, unpredictable subsidies and fragmented regulatory frameworks collectively limit certified seed availability and slow varietal turnover. Addressing these challenges will require targeted investment in EGS, clearer public–private role delineation, predictable and market-friendly subsidy policies and harmonized regional seed regulations. Strengthening these elements is essential for realizing the full benefits of wheat improvement and reducing Africa's growing dependence on wheat imports.

6 Future directions and prospects

In the coming decades, the wheat systems of Africa will face growing pressure as population growth and urbanization increase demand for wheat-based foods, while climate change makes production more uncertain through greater heat, drought and water stress. The strategic priority is therefore a joint transformation agenda that converts product profiles into varieties, varieties into quality seed, seed into profitable crop management, and production into food-security outcomes. We propose the following connected actions (Figure 6).

6.1 Rapid variety development and deployment

Accelerated variety development should start with a small number of clearly defined TPE-specific product profiles that combine yield potential, drought and heat tolerance, rust and Septoria resistance, grain quality, maturity, input responsiveness and farmer and market preferences. Shuttle breeding, speed breeding, doubled haploids, gene mining, marker-assisted gene pyramiding, genomic selection, gene editing, precision phenotyping and strategic multi-environment testing should then be used as complementary tools within the same pipeline. The goal is not to maximize method complexity, but to shorten the crossing to adoption interval while increasing genetic gain, resilience and varietal turnover (Tadesse et al., 2024a).

For rapid variety deployment and scaling, cluster farming approaches are highly effective, as they promote collective access to and efficient use of production technologies, including improved seed, agrochemical inputs, irrigation infrastructure, farm machinery, storage facilities and post-harvest processing, packaging and marketing services (Devaux et al., 2018). This model also facilitates farm mechanization through shared ownership or rental services, reduces production costs, and strengthens market linkages, thereby accelerating the adoption of improved varieties and enhancing productivity and profitability for smallholder farmers.

6.2 Establishing efficient seed systems

African wheat seed systems face persistent problems that limit the translation of breeding gains into farmer adoption. Overly rigid and environmentally sensitive DUS and VCU procedures slow variety registration while weak early-generation seed production restricts certified seed supply even after release (Silva et al., 2023; Tadesse et al., 2024a). A delivery-oriented seed strategy should link release decisions to breeder and foundation seed plans, quality-assured decentralized seed production, licensing and royalty arrangements that incentivize multiplication and digital traceability tools connecting breeders, seed enterprises, cooperatives and seed growers. The key accountability metric should be time from release to affordable quality seed at scale.

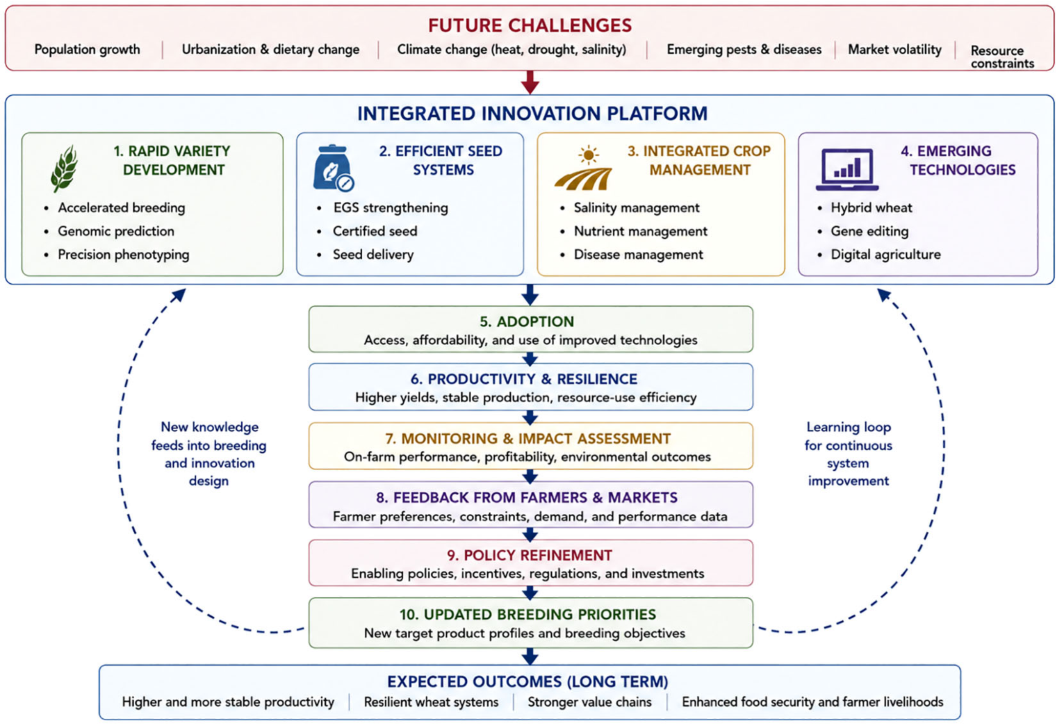

FIGURE 6
Future perspectives and strategic directions for sustainable wheat innovation in Africa. The framework demonstrates the mechanisms of addressing future pressures including population growth, urbanization, climate change, emerging pests and diseases, market volatility and resource constraints through an integrated innovation platform linking rapid variety development, efficient seed systems, integrated crop management and emerging technologies. Adoption, productivity and resilience, impact assessment, farmer and market feedback, policy refinement and updated breeding priorities form a continuous learning loop to support stable wheat productivity, resilient production systems, stronger value chains and improved food security and farmer livelihoods.

6.3 Integrated crop management practices

Improved varieties should be deployed as components of integrated crop-management packages rather than as standalone technologies. Under increasing climate variability, such packages should include locally optimized sowing dates, appropriate seed rates, balanced fertilizer and micronutrient management, conservation agriculture where appropriate, integrated pest and disease management mechanization services, post-harvest handling, and efficient water-management practices. In irrigated systems, water productivity increasingly depends on improved drainage, salinity management, irrigation scheduling, field leveling and energy-efficient pumping in addition to varietal heat tolerance. In rainfed systems, risk-reducing agronomic practices together with improved market access are essential to encourage farmers to invest in improved seed and inputs (Devaux et al., 2018; Yamini et al., 2025).

Recent evidence indicates that improved wheat cultivars achieve their full yield potential only when combined with site-specific agronomic management. Across African and Mediterranean wheat production systems, balanced nutrient management based on soil testing and integrated soil fertility management, including balanced nitrogen, phosphorus and potassium fertilization, supplemented with secondary nutrients and micronutrients where deficiencies occur, together with the combined use of mineral fertilizers and organic amendments, has been shown to improve nutrient-use efficiency, grain yield, grain protein concentration, and overall resource-use efficiency (Abdalla et al., 2023; Silva et al., 2023). Likewise, water-saving practices such as supplemental and deficit irrigation, soil moisture based irrigation scheduling, and improved water-use efficiency have become increasingly important under climate variability, particularly in water-limited production environments (Abdalla et al., 2023).

Conservation agriculture practices, including reduced tillage, crop-residue retention, and diversified crop rotations, enhance soil moisture conservation, improve soil health, reduce erosion, increase system resilience and contribute to long-term carbon sequestration. Similarly, integrated pest and disease management should combine resistant cultivars with continuous surveillance, crop rotation, residue management and judicious fungicide use to improve the durability of resistance and reduce selection pressure on pathogen populations (Rebouh et al., 2023). Emerging digital agriculture tools, including remote sensing, precision monitoring and decision support systems, can further optimize nutrient and irrigation management, support early stress detection and improve the targeting of management interventions (Rebouh et al., 2023).

Consequently, future wheat improvement strategies in Africa should increasingly integrate improved genetics with precision agronomy, climate-smart crop management and efficient resource use to ensure that genetic gains achieved through breeding are translated into sustainable on-farm productivity, climate resilience and farmer profitability (Silva et al., 2023; van Ittersum et al., 2016; van Ittersum et al., 2025).

6.4 Invest and apply emerging technologies

Hybrid wheat, gene editing, digital phenotyping and predictive breeding could become important components of African wheat transformation. However, these approaches should be deployed selectively where their benefits exceed cost and implementation complexity. Hybrid wheat may be most attractive in environments where heterosis, input access and seed replacement incentives can justify recurring hybrid seed purchase. Gene editing should focus on traits with clear breeding bottlenecks and regulatory pathways. Digital tools should strengthen decisions on stress surveillance, seed demand forecasting, irrigation scheduling and variety recommendation, rather than becoming isolated pilot projects. Public-private partnerships will be essential to test these technologies under African production and seed-system realities.

7 Conclusions

Sustainable wheat transformation in Africa requires coordinated policy action to ensure that genetic gains are efficiently converted into measurable on-farm impact. Despite major advances in germplasm development, CGIAR–NARS collaboration, accelerated breeding methods, genomic tools, and stress-resilient varieties, the realization of these gains remains constrained by systemic bottlenecks in seed systems, agronomy, input delivery, and enabling policy environments.

Priority policy actions should focus on building an integrated wheat innovation system that links breeding, seed multiplication, agronomic management, and delivery systems from the outset. Central to this transformation is strengthening early-generation seed production and ensuring reliable, scalable, and financially sustainable seed delivery systems. This requires clearer public–private roles, stronger investment in breeder and foundation seed capacity, and improved coordination between breeding programs and seed enterprises to close the release-to-adoption gap.

Policy frameworks should further prioritize faster and more harmonized variety release procedures, regional seed regulation alignment, and expansion of public–private partnerships to accelerate varietal deployment. In parallel, sustained investment in irrigation infrastructure, mechanization services, and climate-smart agronomic practices is essential to ensure that improved varieties achieve their full productivity potential under diverse agro-ecological conditions.

Future performance of wheat systems should be assessed using delivery-oriented indicators in addition to genetic gain, including time from cross to variety release, release-to-seed availability, varietal turnover rates, early-generation seed sufficiency, and the proportion of wheat area under recently released varieties. These indicators provide a practical framework for aligning national programs, regional institutions, seed enterprises, and policy actors around shared performance targets.

Overall, achieving sustainable wheat transformation in Africa requires a shift from fragmented technological interventions to a coherent, policy-driven innovation system. When breeding progress is effectively aligned with seed systems, agronomic management, and enabling policies, wheat production can move beyond incremental gains to deliver reduced import dependence, improved climate resilience, and strengthened food and nutritional security across the continent.

Author contributions

WT: Conceptualization, Writing – original draft, Investigation, Visualization, Methodology, Data curation. FH: Writing – original draft, Investigation, Visualization, Data curation, Conceptualization. KL: Writing – review & editing. AC: Writing – review & editing. AA: Data curation, Visualization, Conceptualization, Formal analysis, Writing – review & editing.

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