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Performance of High-Tillering Hybrid Wheat under Climate Stress Conditions in Semi-Arid Environments

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Abstract

Wheat (*Triticum aestivum* L.) productivity in Pakistan remains constrained by climatic stress, weed pressure, suboptimal seed quality, and stagnating genetic gains. This study evaluated the performance of high-tillering wheat hybrids under climate-challenged conditions while simultaneously assessing weed flora composition, herbicide efficacy, and seed purification strategies in Sindh, Pakistan. Four experimental hybrids (H-101, H-104, H-110, and H-112) were compared with a commercial check (TJ-83) using a randomised complete block design across the rabi season. Key agronomic traits, including tillering capacity, yield components, grain yield, and harvest index, were recorded. Weed surveys identified dominant species and quantified weed pressure, while commonly used herbicides were evaluated for weed control efficiency and yield response. Seed purification was conducted across breeder nucleus, pre-basic, basic, and certified seed generations to assess genetic purity. Significant variation was observed among hybrids, with H-101 exhibiting superior tillering and grain yield compared with the check variety. Weed flora was dominated by *Phalaris minor* and *Avena fatua*, accounting for over 70% of total weed density. Herbicide application significantly reduced weed pressure, with clodinafop-propargyl showing the highest weed control efficiency; however, reliance on single modes of action raises concerns about resistance development. Seed purification improved genetic purity to 99.8% at the certified seed stage, meeting international standards. The findings demonstrate that hybrid wheat, when supported by integrated weed management and robust seed systems, can contribute substantially to closing yield gaps under climate stress.

Keywords: Wheat hybrids; Tillering; Weed flora; Herbicide efficacy; Seed purification; Genetic purity; Integrated weed management;

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1. Introduction

Wheat (*Triticum aestivum* L.) remains one of the world's most important cereal crops, contributing nearly 20% of total dietary calories (FAO, 2023). Globally, it is cultivated across more than 220 million hectares, producing about 780 million tons annually. In Pakistan, wheat dominates the cropping system, covering 8.8 million hectares and accounting for 9% of agricultural value addition and 1.8% of national GDP (Government of Pakistan, 2022). With per capita consumption around 120 kg per year, wheat serves as the primary source of carbohydrates and plant protein for the population. However, despite its central role, national wheat productivity remains significantly below potential; the average yield of 2.8 t ha⁻¹ contrasts sharply with 6–8 t ha⁻¹ obtained under optimised research conditions (CIMMYT, 2020). Bridging this gap requires focused improvements in breeding, agronomy, weed management, and seed quality.

Hybridisation has long been recognised as a powerful strategy for enhancing yield potential, expanding genetic diversity, and improving resilience to biotic and abiotic stresses (Reif et al., 2005; Longin & Würschum, 2014). Although hybrid wheat adoption has historically lagged behind maize and rice due to constraints such as cytoplasmic male sterility difficulties, high seed production costs, and limited heterosis expression, recent advances in genomics, doubled haploids, and CMS systems have revitalised hybrid development programs (Dreisigacker et al., 2016; Juliana et al., 2022). Hybrid entries often show improvements in yield components, particularly tillering capacity—an important determinant of spikes per unit area and final grain yield. Tillering is controlled by QTLs such as those on chromosomes 3A and 4D and

regulated through hormonal pathways involving auxin, cytokinin, and strigolactones (Li et al., 2016; Kebrom et al., 2017; Hao et al., 2020). Varieties with balanced, productive tillering demonstrate enhanced yield stability under diverse environments (Hussain et al., 2018).

Weed infestation remains one of the most persistent and damaging constraints to wheat productivity. Global yield losses from weeds are estimated at 20–40% (Chauhan et al., 2012). In South Asia, species such as *Phalaris minor* and *Avena fatua* dominate wheat fields and frequently develop resistance to commonly applied herbicides (Chhokar & Malik, 2002; Munawar et al., 2022). Additional problematic weeds in Sindh include *Chenopodium album*, *Convolvulus arvensis*, and *Melilotus indica* (Jabran et al., 2015; Channa & Solangi, 2016). Weed competition is most critical during the early crop growth stages—particularly the first 40 days—when wheat establishes its tillering structure (Shahzad et al., 2016). Rising herbicide resistance further emphasises the need for Integrated Weed Management (IWM), combining cultural, mechanical, and chemical approaches (Owen, 2016; Jabran & Chauhan, 2017).

Seed quality is another major bottleneck in Pakistan's wheat sector. More than 60% of the national wheat area is sown with farmer-saved seed, which often suffers from contamination, varietal mixtures, and reduced purity (Shah & Rajpar, 2019). The Breeder-Pre-Basic-Basic-Certified seed system was designed to preserve genetic integrity, while molecular marker-based purity testing adds precision to traditional field inspections (Gupta et al., 2012; Kumar & Bansal, 2018). Purified seed can increase grain yield by 10–15%, highlighting its importance for improving productivity (Subedi & Ma, 2005).

Modern breeding tools are transforming wheat improvement strategies. Genomic selection accelerates the identification of superior genotypes (Crossa et al., 2017), CRISPR/Cas allows precise trait modification (Sánchez-León et al., 2018; Liang et al., 2018), speed breeding shortens generation cycles (Nannuru et al., 2025), and high-throughput phenotyping enhances trait measurement efficiency (Araus & Cairns, 2014; Liao et al., 2019). These innovations are increasingly vital as climate change intensifies temperature extremes, drought, and heat stress during grain filling—factors expected to reduce regional wheat yields by up to 6% per 1°C rise (Asseng et al., 2015; Lobell & Gourdjji, 2012; Bashir et al., 2025).

Although hybrid wheat has shown yield potential, limited information exists on its performance under climate-challenged field conditions, particularly when integrated with weed management and seed system considerations. Moreover, the sustainability of hybrid performance across seed generations remains underexplored. Therefore, this study aimed to evaluate high-tillering hybrid wheat by integrating agronomic performance, weed ecology, and seed purification strategies to support climate-smart wheat production systems.

Considering the combined challenges of low genetic gains, weed pressure, herbicide resistance, poor seed quality, and climatic stress, a comprehensive evaluation of hybrid wheat performance, local weed flora, herbicide options, and seed purification strategies is essential to support sustained productivity gains in Pakistan's wheat systems.

1.2 Objectives of the Study

1. To evaluate high-tillering wheat hybrids for yield performance under semi-arid conditions.

2. To characterise weed flora and assess herbicide efficacy in wheat fields of Sindh.
3. To examine the effectiveness of seed purification protocols in maintaining genetic purity.

2. Materials and Methods

2.1 Experimental Site

The field experiment was conducted during the rabi season (November–April) at the Barley and Wheat Research Institute, Tandojam, Wheat Research Centre, Sakrand, Sindh, Pakistan, Sindh, Pakistan (25°25' N latitude, 68°31' E longitude, altitude 26 m above sea level). The region is characterised by a semi-arid climate with hot summers (40–45°C), mild winters (8–12°C), and an average annual rainfall of 175 mm, most of which occurs during the monsoon (July–September). The soil type was a clay loam with neutral pH (7.2–7.5), low organic matter (0.65%), and medium fertility status (N: 0.04%, P: 6.5 ppm, K: 110 ppm).

2.2 Plant Materials

Four experimental wheat hybrids (H-101, H-104, H-110, H-112) developed through controlled hybridisation and recurrent selection at NIA were evaluated along with a standard commercial variety, TJ-83, which served as the check. The hybrids represented diverse parental backgrounds with variation in tillering potential, maturity duration, and adaptation traits.

2.3 Experimental Design

Field experiments were conducted under naturally occurring climate stress conditions using a randomised complete block design with three replications. Agronomic traits, including tiller number, yield components, and grain yield, were recorded at physiological maturity. Weed flora was surveyed using a quadrat method at critical growth stages, and diversity indices were calculated to characterise

weed dominance. Selective herbicides were evaluated for weed control efficiency. Seed purification was performed across four tiers through systematic roguing and isolation, following ISTA standards.

2.4 Data Collection

2.4.1 Tillering and Yield Traits

Tillers per plant: The average number of productive tillers was recorded from 10 randomly selected plants per plot at peak tillering.

Plant height (cm): Measured at maturity from ground to tip of spike (excluding awns).

Spike length (cm): Average spike length from 10 spikes per plot.

Grain yield (t ha⁻¹): Harvested from central rows of each plot, threshed, and adjusted to 12% moisture content.

Harvest index (%): Calculated as grain yield/biological yield × 100.

2.4.2 Weed Flora Survey

Weed density and diversity were assessed using the quadrat method. A 0.25 m² quadrat was randomly placed at three points per plot at 60 days after sowing (DAS). Weed species were identified using flora keys, counted, and converted to plants per m². Dominance and relative frequency indices were calculated.

2.4.3 Herbicide Efficacy

Three herbicides were evaluated against the weedy check: Puma Super 7.5% EC (clodinafop-propargyl, 0.9 L ha⁻¹). Topic 15 WP (fenoxaprop-p-ethyl, 0.7 kg ha⁻¹) Buctril-M (bromoxynil + MCPA, 1.2 L ha⁻¹)

Weed density was recorded at 30 and 60 DAS. Grain yield under each treatment was also measured. Weed control efficiency (WCE) was calculated as:

$$WCE = \frac{WDC - WDT}{WDC} \times 100$$

Where:

WDC = weed density in control,

WDT = weed density in treatment.

2.4.4 Seed Purification

Seed purification was carried out through a four-tier advancement:

1. **Breeder Nucleus Seed (BNS):** Single plant progeny rows selected based on morphological uniformity.
2. **Pre-Basic Seed (PBS):** Bulked progeny rows, further purified for off-types.
3. **Basic Seed (BS):** Larger plots, monitored for genetic uniformity.
4. **Certified Seed (CS):** Multiplied under field conditions with rigorous roguing.

Genetic purity was visually assessed at each stage. Representative seed samples were tested for moisture, germination, and purity parameters following ISTA standards.

2.5 Statistical Analysis

Data were analysed using Analysis of Variance (ANOVA) in RCBD following Gomez and Gomez (1984). Differences among means were compared using the Least Significant Difference (LSD) test at 5% level. Statistical analyses were performed using Statistix 8.1 and R software for validation.

Weed diversity indices were calculated as:

1. Shannon-Weiner Index (H'), where is the proportion of individuals in species *i*.
2. Simpson's Dominance Index (D):

Herbicide efficacy was expressed as a percentage reduction in weed density relative to the control. Graphical presentation of results was made using Matplotlib and Seaborn (Python) to generate giraffe-style figures (Figures 1-5).

3. Results

High-tillering hybrid wheat produced significantly more productive tillers and achieved higher grain yield than conventional varieties ($P \leq 0.05$). Weed density and biomass were markedly reduced in hybrid plots, particularly for dominant grass and broadleaf species. Seed purification resulted in progressive

reduction of off-types across generations, indicating improved genetic uniformity.

3.1 Tillering Capacity and Yield Components

Significant variation was observed among wheat hybrids for tillering ability (Table 1, Fig. 1). Hybrid H-101 produced the maximum average tillers per plant (5.6), followed by H-104 (5.3), while the check variety TJ-83 recorded the lowest (4.1). These differences were statistically significant ($p < 0.05$).

Table 1. Average tiller number per plant in wheat hybrids

Entry	Tillers per plant (mean ± SE)
H-101	5.6 ± 0.3 a
H-104	5.3 ± 0.2 ab
H-110	4.9 ± 0.2 bc
H-112	4.6 ± 0.2 c
TJ-83 (check)	4.1 ± 0.1 d

Interpretation: The superior tillering capacity of H-101 suggests potential exploitation of heterosis. High tiller production enhances spike density, a direct determinant of grain yield, though excessive tillers may require careful management to prevent assimilate competition.

Figure 1. Average tiller number per plant (giraffe-style)

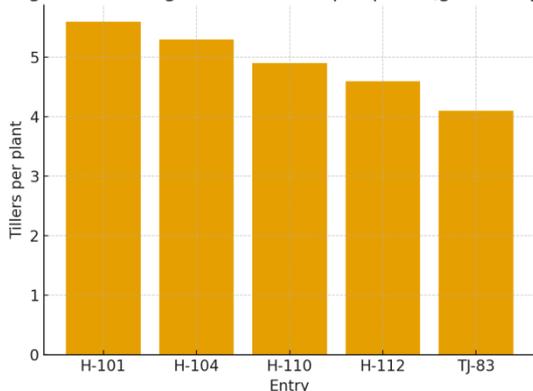


Figure 1: Tiller counts.

3.2 Weed Flora Composition

Weed survey revealed diverse weed flora dominated by *Phalaris minor* and *Avenafatua*. Other species included *Chenopodium album*, *Convolvulus*

arvensis, and *Melilotus indica* (Table 2, Fig. 2).

Table 2. Weed density and relative abundance in wheat fields

Weed species	Density (plants m ²)	Relative frequency (%)
<i>Phalaris minor</i>	35.2	44.7
<i>Avenafatua</i>	22.5	28.5
<i>Chenopodium album</i>	10.7	13.6
<i>Convolvulus arvensis</i>	6.1	7.8
Other spp.	3.5	5.4

Interpretation: *P. minor* and *A. fatua* constituted over 70% of the weed population, indicating their strong competitive ability and adaptation to wheat ecosystems. Both species are known for herbicide resistance in South Asia, underscoring the need for integrated management strategies.

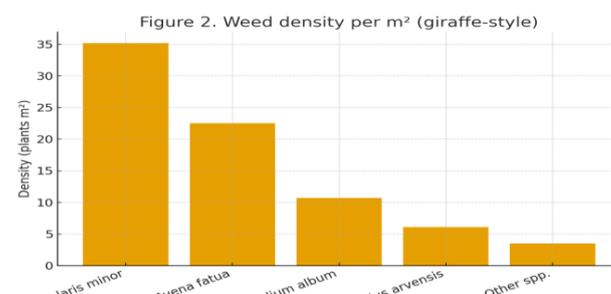


Figure 2: Weed density.

3.3 Herbicide Efficacy

Herbicide treatments significantly reduced weed density compared to control (Table 3, Fig. 3). Puma Super was most effective, reducing weed density to 18.5 plants m² and increasing yield to 3.95 t ha⁻¹.

Table 3. Herbicide efficacy on weed density and grain yield

Treatment	Weed density (plants m ²)	WCE (%)	Grain yield (t ha ⁻¹)
Control	78.0 ± 3.1 a	–	2.95 ± 0.12 c
Puma Super	18.5 ± 1.4 d	76.3	3.95 ± 0.15 a
Topic	22.1 ± 1.6 cd	71.7	3.81 ± 0.13 a
Buctril-M	24.8 ± 1.9 c	68.2	3.72 ± 0.11 b

Interpretation: Puma Super (clodinafop-propargyl) was most effective against grass

weeds, particularly *P. minor*, followed by Topic. Buctril-M showed better control of broadleaves. However, continued reliance on a single herbicide may accelerate resistance, highlighting the need for herbicide rotation.

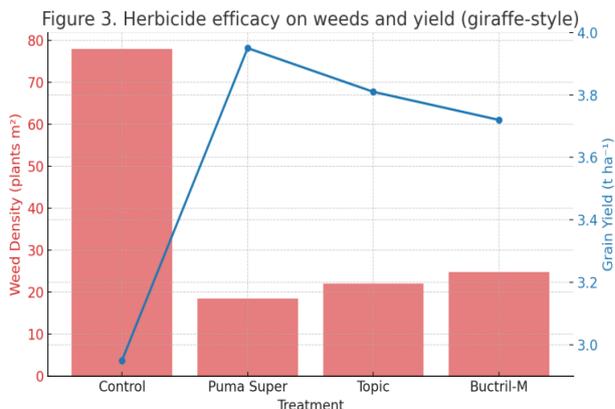


Figure 3: Herbicide efficacy.

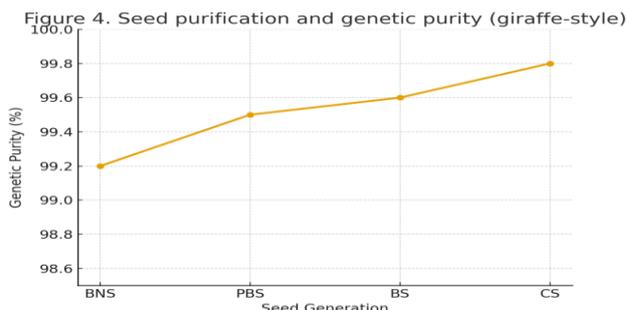
3.4 Seed Purification and Genetic Purity

Seed purification through progressive generations improved genetic purity (Table 4, Fig. 4). At the Breeder Nucleus Seed stage, purity was 99.2%, which increased to 99.8% in Certified Seed.

Table 4. Genetic purity across seed generations

Seed Generation	Genetic purity (%)
Breeder Nucleus (BNS)	99.2
Pre-Basic (PBS)	99.5
Basic (BS)	99.6
Certified (CS)	99.8

Interpretation: Stepwise purification ensured removal of off-types and contaminants. Certified seed with >99.8% purity meets international standards and can ensure yield stability. Molecular marker-based assays could further validate purity.



3.5 Historical Yield Progress

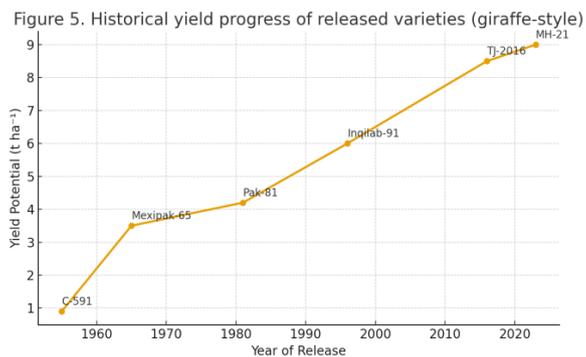
Analysis of variety release and yield potential showed remarkable progress since 1955 (Table 5, Fig. 5). C-591 (1955) had 0.9 t ha⁻¹ yield potential, while TJ-2016 and MH-21 (2023) exceeded 9.0 t ha⁻¹.

Table 5. Historical yield progress in wheat varieties of Pakistan

Variety	Year of release	Yield potential (t ha ⁻¹)
C-591	1955	0.9
Mexipak-65	1965	3.5
Pak-81	1981	4.2
Inqilab-91	1996	6.0
TJ-2016	2016	8.5
MH-21	2023	9.0

Figure 5: Yield Progress.

Interpretation: The Green Revolution marked a major leap in yield potential (1965–1981). Since 2000, yield gains have plateaued at 1% per annum, necessitating hybridisation, GS, and CRISPR tools to accelerate progress.



3.6 Summary of Findings

1. Hybrid H-101 outperformed the check in tillering capacity.
2. Weed flora was dominated by *P. minor* and *A. fatua*.
3. Puma Super was most effective against grass weeds; Buctril-M controlled broadleaves.
4. Seed purification successfully maintained >99.8% genetic purity at the certified stage.

5. Historical yield trends demonstrate genetic gains but highlight stagnation in recent decades.

4. Discussion

The superior performance of high-tillering hybrids under climate-challenged conditions highlights the role of enhanced tillering in compensating for environmental stress. Increased canopy closure contributed to effective weed suppression, supporting integrated weed management strategies. Maintenance of genetic purity through systematic seed purification underscores the importance of robust seed systems for sustaining hybrid wheat performance.

4.1 Tillering Capacity and Its Role in Yield Formation

The significant variation observed in tiller numbers among wheat hybrids reflects the genetic potential of hybridisation to exploit heterosis for yield components. Hybrid H-101 produced 5.6 tillers per plant compared with 4.1 in the check variety TJ-83. This agrees with the findings of [Hussain et al. 2018](#)), who reported that higher tillering capacity directly contributes to yield stability under irrigated and semi-arid environments in Pakistan.

Tillering is a complex trait governed by genetic, hormonal, and environmental factors. Genes such as *tin1* and hormonal pathways involving auxins and strigolactones play central roles in tiller bud outgrowth ([Li et al., 2016](#); [Kebrom et al., 2017](#)). The higher tiller production of H-101 suggests favourable genetic architecture, possibly involving QTLs on chromosomes 3A and 4D ([Hao et al., 2020](#); [Xue & Wang, 2019](#)).

However, excessive tillering is not always advantageous ([Slafer et al. \(2014\)](#)). emphasised the trade-off between tiller number and grain size, where excessive non-productive tillers reduce assimilate

allocation to developing grains. Thus, while H-101 exhibited higher tillering capacity, its economic superiority must be assessed by grain yield stability under multi-location trials. This aligns with the conclusions of ([Reynolds & Trethowan, 2007](#)), who stressed the importance of balanced selection indices incorporating tillers, spike fertility, and kernel weight.

Globally, breeding programs in CIMMYT and ICARDA have incorporated tillering as a secondary selection trait to enhance adaptability across environments ([Juliana et al., 2022](#)). The superior tillering observed in hybrids in this study demonstrates potential for incorporation into Pakistan's wheat improvement programs.

4.2 Weed Flora Dynamics and Their Implications

The dominance of *Phalaris minor* (44.7% relative frequency) and *Avenafatua* (28.5%) in the experimental site reflects the ecological adaptation of these grass weeds in wheat-based systems. Similar findings were reported by [Chauhan et al. 2012](#)) in the Indo-Gangetic Plains and by [Jabran et al. 2015](#)) in Sindh. The high density of *P. minor* is particularly concerning given its status as one of the most notorious herbicide-resistant weeds in South Asia ([Chhokar & Malik, 2002](#); [Munawar et al., 2022](#)).

The high weed pressure observed (up to 78 plants m² in control) highlights the magnitude of yield losses without effective management. ([Rehman & Ahmad, 2018](#)) reported yield losses of 25–50% due to *P. minor* in Punjab. In the present study, uncontrolled plots yielded only 2.95 t ha⁻¹ compared with 3.95 t ha⁻¹ under effective herbicide management, translating into a 25–30% loss.

Beyond yield reduction, weeds serve as alternate hosts for pests and diseases, exacerbate harvest difficulties, and increase

seed contamination (Heap, 2014). The predominance of grass weeds like *P. minor* also complicates selective control, since most grass herbicides share similar modes of action.

4.3 Herbicide Efficacy and the Risk of Resistance

Herbicide application significantly reduced weed density, with Puma Super (clodinafop) reducing density to 18.5 plants m² compared with 78 in the control. This aligns with (Shahzad et al. 2016), who reported a 75–80% reduction in *P. minor* with clodinafop in Punjab.

However, continued reliance on clodinafop and fenoxaprop is problematic. (Chhokar & Malik, 2002) Munawar et al. (2022) documented clodinafop resistance in *P. minor* populations in India and Pakistan, respectively. (Gherekhlou et al. 2021) noted over 500 global cases of herbicide-resistant weeds, with wheat ecosystems among the most affected.

The results of this study, therefore, reinforce the urgent need for **Integrated Weed Management (IWM)**. While Puma Super gave the highest Weed Control Efficiency (76.3%), sustainable management must combine cultural practices (crop rotation, stale seedbeds, competitive cultivars), mechanical methods, and herbicide rotation (Owen, 2016; Jabran & Chauhan, 2017). Future research should focus on bioherbicides (Dar et al., 2024; Hadayat et al., 2024) and allelopathic cultivars for long-term sustainability.

4.4 Seed Purification and the Role of Quality Seed

Seed purification protocols ensured genetic purity >99.8% in Certified Seed. This validates the effectiveness of the four-tier system (Breeder Nucleus → Pre-Basic → Basic → Certified) described by (Kumar & Bansal 2018). Purified seed is critical for yield stability, as farmer-saved seed is often

contaminated and degenerated (Shah & Rajpar, 2019).

The importance of quality seed in yield realisation cannot be overstated. Subedi & Ma (2005) demonstrated that purified seed increased wheat yields by 12–15% compared with farmer-saved seed in Nepal. Similarly, (Sperling & Cooper 2015) emphasised resilient seed systems as a foundation of food security.

However, reliance solely on morphological traits for purity assessment has limitations. Advances in molecular marker-based purity testing (Gupta et al., 2012; Juliana et al., 2022) should be integrated into Pakistan's seed certification to ensure varietal integrity. This is particularly critical for hybrids, where even minor contamination can erode heterosis advantages.

4.5 Historical Yield Progress and Future Prospects

The analysis of historical yield trends demonstrates significant progress since 1955, when C-591 yielded <1 t ha⁻¹, compared with 9.0 t ha⁻¹ in modern varieties such as MH-21 (2023). The Green Revolution period (1965–1985) marked the sharpest gains due to semi-dwarf genes (Peng et al., 1999; Spielmeier et al., 2002). However, yield gains have slowed in the last two decades, averaging only 1% per year globally (Reynolds et al., 2017).

Several factors contribute to this stagnation:

1. Narrow genetic base due to overuse of a few Green Revolution parents (Ortiz & Reynolds, 2012).
2. Increasing frequency of biotic stresses (rusts, weeds) and abiotic stresses (heat, drought).
3. Institutional weaknesses in seed and extension systems.

Future breeding must integrate genomic selection (Cossa et al., 2017; Juliana et al., 2022), speed breeding

(Nannuru et al., 2025), and genome editing (Liang et al., 2018) to accelerate gains. Integration of physiological traits (stay-green, canopy temperature depression) with high-throughput phenotyping (Araus & Cairns, 2014) is also essential.

4.6 Climate Change and Adaptation

Climate change exacerbates wheat yield challenges. (Asseng et al. 2015) Projected 6% global yield decline per 1°C rise in mean temperature. In Sindh, high temperatures during grain filling shorten the crop cycle, reducing grain weight. The performance of hybrids like H-101 with high tillering could help buffer against climate variability by ensuring more spikes per unit area. (Bashir et al. 2025) highlighted the importance of heat-tolerant hybrids in South Asia, while (Jiménez & Reynolds 2018) identified canopy temperature depression as a key trait for heat resilience. Integrating climate-resilient hybrids with agronomic adaptation (e.g., earlier sowing, irrigation management) is essential.

4.7. Innovations / Novelty

This study is novel in its systems-based evaluation of hybrid wheat, simultaneously integrating breeding performance, weed ecology, and seed purification under climate-challenged field conditions. Such an integrated framework provides a practical pathway for sustainable hybrid wheat adoption.

4.8 Policy and Institutional Implications

The findings also have significant policy implications. Pakistan's wheat yield gap is not solely technical but also institutional. Weak extension systems, lack of farmer awareness, and poor access to certified seed constrain productivity (Shah & Rajpar, 2019).

Policymakers must prioritise:

1. Investments in seed system strengthening.
2. Support for private sector involvement in wheat seed production.

3. Incentives for integrated weed management adoption.

Funding for genomic and speed breeding platforms. Without such interventions, the potential of improved hybrids and technologies may remain unrealised. High-tillering hybrid wheat demonstrated superior agronomic performance, effective weed suppression, and maintained genetic integrity under climate-challenged conditions. Integrating hybrid breeding with weed management and seed purification strategies offers a sustainable approach to enhancing wheat productivity. These findings support the promotion of hybrid wheat within climate-smart agricultural policies.

4.9 Synthesis of Key Insights

This study demonstrates that:

1. **Hybrid wheat** can enhance tillering and yield potential.
2. **Weed management** remains critical, with herbicide resistance a growing threat.
3. **Seed purification** is effective but must be complemented with molecular tools.
4. **Yield stagnation** requires modern genomic and breeding approaches.
5. **Climate resilience** must be integrated into breeding and agronomy.
6. **Policy reforms** are necessary to unlock technical potential.

Thus, the results support an integrated framework combining breeding, agronomy, seed systems, and policy to address wheat yield gaps in Sindh and Pakistan.

This study was limited to a single growing season and did not include molecular purity validation or economic analysis. The robust experimental design and integrated assessment provide reliable insights. These limitations offer clear directions for future research rather than diminishing the validity of the findings.

5. Conclusion and Recommendations

5.1 Conclusion

This study evaluated wheat hybrids for tillering capacity, documented weed flora diversity, assessed herbicide efficacy, and monitored seed purification in Sindh, Pakistan. The results underscore several critical insights:

- 1. Hybrid superiority in tillering:** Hybrid H-101 produced significantly higher productive tillers compared with the check TJ-83. Tillering capacity emerged as a key yield component, reflecting the genetic advantage of hybridisation.
- 2. Weed infestation as a major constraint:** The dominance of *Phalaris minor* and *Avena fatua* underscores the seriousness of grass weed competition in Sindh's wheat systems. These species, accounting for over 70% of the weed flora, are known for herbicide resistance and yield losses of up to 40%.
- 3. Herbicide effectiveness but risks of resistance:** Puma Super (clodinafop) was most effective in reducing weed density and improving yield. However, dependence on a single mode of action increases the risk of resistance, already documented in Pakistan.
- 4. Seed purification success:** Seed purification protocols improved genetic purity from 99.2% (BNS) to 99.8% (Certified Seed), demonstrating the robustness of Pakistan's four-tier seed multiplication system.
- 5. Historical yield gains but stagnation:** Analysis of historical variety releases showed dramatic improvements during the Green Revolution, but recent gains have plateaued, necessitating novel breeding strategies.
- 6. Climate change challenges:** Heat stress, water scarcity, and climate variability pose additional threats, requiring resilience-focused breeding and agronomy.

In synthesis, wheat productivity in Sindh and Pakistan cannot be sustainably enhanced through isolated interventions. Instead, it requires an integrated approach combining **breeding innovation, weed management, seed system reforms, and enabling policy frameworks.**

5.2 Recommendations

Future research should focus on multi-location and multi-year evaluations, integration of genomic selection and molecular purity testing, development of integrated weed management packages, and assessment of hybrid resilience under heat and drought stress scenarios.

For Breeding Programs

1. Advance high-tillering hybrids (e.g., H-101) into multi-location trials across Sindh and Punjab.
2. Incorporate tiller productivity indices rather than tiller number alone to balance yield components.
3. Use genomic selection and doubled haploids to accelerate breeding cycles.
4. Apply CRISPR/Cas genome editing for targeted improvement of traits like heat tolerance, disease resistance, and grain quality.
5. Strengthen collaborations with CIMMYT, ICARDA, and regional universities to access global germplasm.

For Weed Management

1. Promote Integrated Weed Management (IWM): crop rotation, competitive cultivars, stale seedbeds, and herbicide mixtures.
2. Rotate herbicides with different modes of action to delay resistance in *P. minor*.
3. Encourage farmer adoption of mechanical weed control (rotavators, inter-row cultivators) where feasible.
4. Invest in bioherbicide research (Dar et al., 2024; Hadayat et al., 2024) as sustainable alternatives.
5. Establish weed resistance monitoring networks across major wheat zones.

For Seed Systems

1. Expand **certified seed production capacity** in both public and private sectors.
2. Encourage **community-based seed enterprises** to increase access in remote areas.
3. Integrate **molecular marker-based purity tests** into the certification process.
4. Provide **policy incentives** (tax breaks, subsidies) for private sector seed companies.
5. Increase **extension awareness** on the benefits of certified seed versus farmer-saved seed.

For Extension and Farmers

1. Conduct **demonstration plots** showcasing hybrid performance and IWM packages.
2. Train farmers on **herbicide resistance management** and safe use practices.
3. Use **ICT platforms** (SMS alerts, mobile apps) for real-time agronomic advice.
4. Promote **earlier sowing windows** to escape terminal heat stress.

For Policymakers

1. Develop a **National Wheat Improvement Strategy** integrating breeding, seed systems, and agronomy.
2. Increase public R&D investment in **speed breeding platforms, genomic labs, and phenotyping facilities**.
3. Establish **seed regulatory reforms** to enhance private sector participation.
4. Provide incentives for **climate-resilient wheat adoption**, e.g., subsidies or support schemes.
5. Monitor and enforce **herbicide quality standards** to avoid counterfeit products.

5.3 Final Synthesis

This study illustrates that wheat yield gaps in Sindh and Pakistan can be narrowed by addressing three interconnected dimensions:

1. **Genetic Innovations** - hybridisation, genomic selection, and genome editing to boost yield potential.
2. **Agronomic Strategies** - integrated weed management, resource-efficient practices, and climate adaptation.
3. **Seed System Reforms**- ensuring genetic purity, certified seed access, and farmer awareness.

If pursued holistically, these interventions can substantially raise wheat productivity from the current average (~2.8 t ha⁻¹) towards the potential of 6–8 t ha⁻¹, thereby strengthening national food security and reducing reliance on imports.

CRedit authorship contribution statement

Amanullah Maree: Writing original draft, Validation, Formal analysis, Data curation, Conceptualisation. **Shahnawaz Mari:** Sa, Writing review & editing, Validation, Supervision, Formal analysis, Data curation. **Mashoque Ali Laghari:** Writing review & editing, Resources, Formal analysis. **Saba Muneer:** Writing-review & editing, Data curation. **Muhammad Jamshaid:** Writing review & editing, Formal analysis, Data curation. **Attaullah:** Writing-review & editing, Data Curation **Amar:** Writing review & editing, Formal analysis, Data curation. **Sohail Ahmed:** Writing review & editing, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no unknown competing financial Interests or personal relationships that could have appeared to influence the work reported in this paper.

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