Original Research

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Screening and Adaptability of Wheat Varieties for Growth and Yield Traits Under the Rainfed Conditions of Azad State of Jammu and Kashmir

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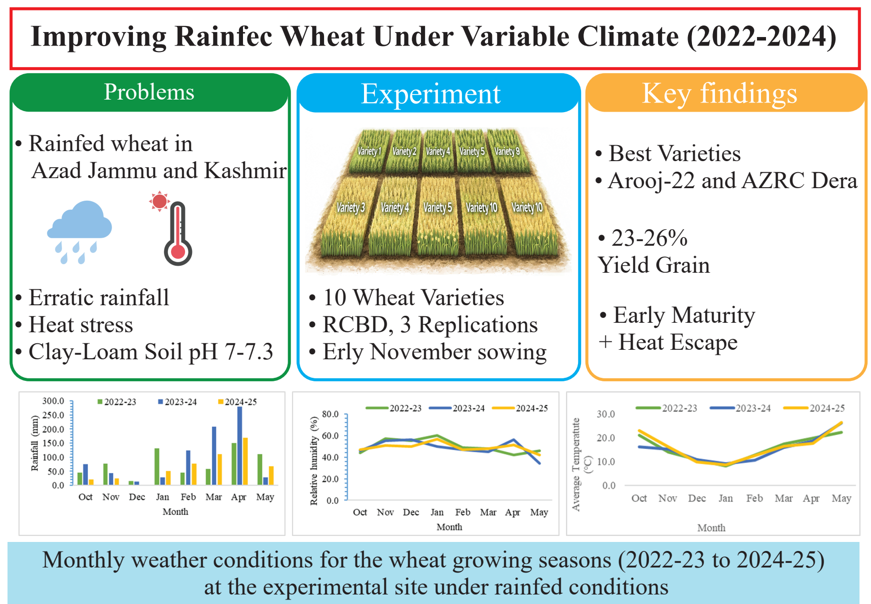
Highlights

- Rainfed climatic variability drives wheat growth and yield performance.
- Arooj-22 and AZRC Dera showed stable, high yield under rainfed stress.
- Early sowing and variety selection enhance rainfed wheat productivity.

Graphical Abstract



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Abstract

Wheat productivity in rainfed regions of Azad Jammu and Kashmir is constrained by erratic rainfall, temperature fluctuations, and genotype-environment interactions. This study evaluated ten wheat varieties (Akbar-2019, NARC-Super, Pakistan-2013, Markaz-2019, Borlough, Zincol, Arooj-22, Anaj-17, AZRC Dera, and MH-2021) over three Rabi seasons (2022-2024) at the Adaptive Research Farm, Muzaffarabad (73.37° E, 34.13° N, 817 m elevation), with a clay-loam soil (pH 7.1-7.3, low organic matter 1.31-1.37 %). A randomized complete block design with three replications was used, with sowing in early November and application of 115 kg N ha^{-1} and 85 kg P ha^{-1}. Significant differences were observed in phenology, with MH-2021 heading earliest (82 days) and NARC-Super latest (138 days). Growth traits varied: Zincol produced the most tillers in 2022 (19), Arooj-22 set the most grains per spike (59), and AZRC Dera was tallest (82 cm). Arooj-22 and AZRC Dera achieved top grain yields in 2022 (3.58 and 3.63 t ha^{-1}), Anaj-17 in 2023 (3.27 t ha^{-1}), and Borlough in 2024 (2.89 t ha^{-1}). Harvest index was highest for Arooj-22 and AZRC Dera across years. Early-maturing varieties (Akbar-2019, MH-2021) escaped terminal heat, while high-yielding lines (Arooj-22, AZRC Dera) demonstrated stable performance under variable rainfall. Adopting Arooj-22 for high grain number and AZRC Dera for tillering and straw yield, with early November sowing, can enhance productivity. Integrated nutrient management and site-specific variety selection are advised for rainfed wheat systems.

Keywords: Wheat, Rainfed, Genotypes, Environment, Grain yield

1. Introduction

Wheat (*Triticum aestivum* L.) is a staple crop in many parts of the world, including Azad Jammu and Kashmir (AJK), Pakistan. It plays a vital role in the region's food security and economy, with a significant portion of the population relying on agriculture for their livelihood (El Hanafi et al., 2021). However, wheat production in AJK faces numerous challenges, including limited irrigation facilities, erratic rainfall patterns, and soil degradation (Khatoon et al., 2016). Among these challenges, rainfed conditions pose a significant threat to wheat productivity, as the crop is often exposed to water stress, which can lead to reduced growth, lower yields, and decreased grain quality (Lobell et al., 2012; Wassmann et al., 2009).

Climate change impacts wheat production through rising temperatures and changing precipitation patterns, threatening crop yields and food security (Gourdji et al., 2013; Knox et al., 2012). Drought and heat stress are major abiotic stresses that can significantly reduce wheat productivity, particularly in rainfed areas (Mahpara et al., 2022; Upadhyaya et al., 2021). The development of wheat varieties that can tolerate these stresses is crucial for improving crop yield and stability under rainfed conditions.

Plant breeding plays a critical role in developing crop varieties that can tolerate abiotic stresses, such as drought and heat stress (Farooq et al., 2015; Sattar et al., 2020). In the context of wheat production in AJK, breeding for drought tolerance is a key objective, as it can help improve crop yield and stability under rainfed conditions (Sadaf et al., 2017). However, breeding for drought tolerance is a complex process, requiring a thorough understanding of the physiological and genetic mechanisms underlying drought tolerance in wheat (Abdelsalam et al., 2022).

Several studies have evaluated the performance of wheat varieties under rainfed conditions in different parts of the world (Munaro et al., 2020). These studies have identified various traits associated with drought tolerance in wheat, including early maturity, deep root system, and osmotic adjustment (Ibrahim and Said 2020; Sabit et al., 2017). However, the performance of wheat varieties can vary significantly across different environments, highlighting the need for location-specific research to identify genotypes that are well-suited to the specific conditions of AJK.

Despite the importance of wheat production in AJK, there is a lack of research on the screening and adaptability of wheat varieties for growth and yield traits under rainfed conditions. Most studies on wheat production in the region have focused on irrigated conditions, with limited attention to rainfed areas (Kashif and Khaliq, 2004).

As a result, a significant knowledge gap exists regarding the performance of wheat varieties under rainfed conditions in Azad Jammu and Kashmir (AJK), which limits the development of effective breeding programs and crop management strategies. There is limited understanding of how different wheat varieties respond to rainfed environments in AJK, particularly in terms of water-stress tolerance, growth performance, and yield potential. To address this gap, the present study was designed with the following objectives:

1. To assess the performance of different wheat varieties for growth and yield traits under rainfed conditions in AJK.

2. To identify wheat varieties that exhibit improved tolerance to water stress, enhanced growth characteristics, and increased yield potential under rainfed conditions.

3. To provide insights into the physiological and genetic mechanisms underlying drought tolerance in wheat, which can inform breeding programs aimed at developing drought-tolerant wheat varieties.

2. Materials and Methods

2.1. Experimental Site, Soil, and Climate

The experimental study was conducted at the Adaptive Research Farm (ADR) Training and Adaptive Research Unit (TARU) Garhi Dopatta (Fig. 1), Muzaffarabad, Azad State of Jammu and Kashmir, from 2022 to 2024 during the Rabi season (November to June). The farm is situated at 73.37° E longitude, 34.133° N latitude, and 817 meters above sea level. Before the execution of the experiment, soil samples up to 30 cm (0-15 cm and 15-30 cm) depth were collected using a soil auger following a zig-zag pattern of soil sampling from different locations, and a composite sample was prepared (Cardina et al., 1991). Soil samples were analyzed for various properties (Table 1) using the method of Estefan et al. (2013). The initial soil analysis indicated that the soil had a pH ranging from 7.1 to 7.3, saturation percentage ranging from 45% to 46%, organic matter content ranging from 1.31% to 1.37% (low), available phosphorus (P) ranging from 15 ppm to 19 ppm (medium), and available potassium (K) ranging from 171 ppm to 193 ppm (high). The soil texture was classified as clay loam. Garhi Dupatta, Muzaffarabad, has a temperate climate with significant precipitation throughout the year (Fig. 2). The temperature varies considerably, with summer highs reaching up to 38.7°C and winter lows around 1.5°C (Fig. 2). The area receives substantial rainfall, with the wettest month typically exceeding 280 mm of precipitation. The relative humidity ranges from 30% to 68%, indicating a moderate level of humidity throughout the year (Fig. 2).

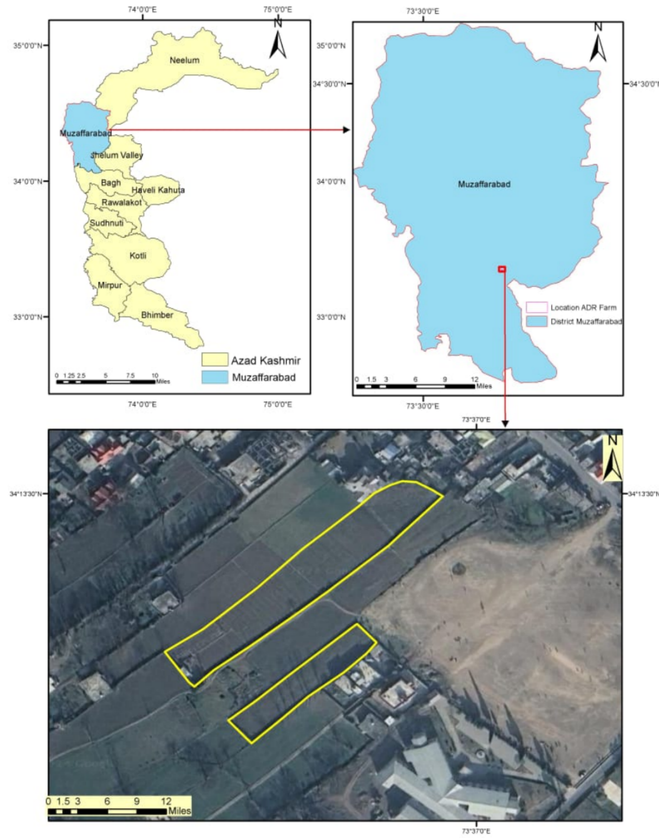

Fig. 1. Map of experimental location.

2.2. Plant Material

Wheat cultivars were procured from the Wheat Research Institute, Faisalabad. Germination potential and moisture contents of seeds were determined according to ISTA (2015) and were >90% and 12%, respectively.

2.3. Experimental Details

The experiment was laid out in a randomized complete block design (RCBD) with three replicates per group. Ten approved varieties of wheat, viz., V1 = Akbar, V2 = NARC Super, V3 = Pak 2013, V4 = Markaz 2019, V5 = Borlough, V6 = Zincol, V7 = Arooj, V8 = Anaj, and V9 = Azrc-Dera, and V10 = MH-2021 were used for screening and adaptability. The characteristics of each variety are elaborated in Table 2. Each variety was randomly assigned to an experimental unit, and the size of each subplot was 6.5 x 3.6 meters.

2.4. Crop Husbandry

After the rain, the soil was ploughed twice, and the remains of the maize crop and weeds were removed. At the field capacity level, the Rotavator was used to cut the subsoil surface to make it porous and reduce soil compaction. Line sowing of each variety in three replications was accomplished by using a hand drill on 3rd November 2022, 6th November 2023, and 30th October 2024. The crop was cultivated in lines (09 cm apart) using the seed rate of each variety of 48 kg ha^{-1}. Based on soil test, fertilizers were applied at 115:85 N:P kg ha^{-1}, respectively. Nitrogen (115 kg ha^{-1}) and phosphorus (85 kg ha^{-1}) were applied according to the recommendation in the form of urea and Di-Ammonium Phosphate (DAP). Phosphorus was applied as a basal dose along with 20% of the total N at the time of sowing. The remaining 80% N (urea) was applied in two splits. The second dose of nitrogenous fertilizer was applied at the active tillering stage (BBCH identification code = 23) and the third dose at the anthesis stage (BBCH identification code = 41) (Meier, 2001).

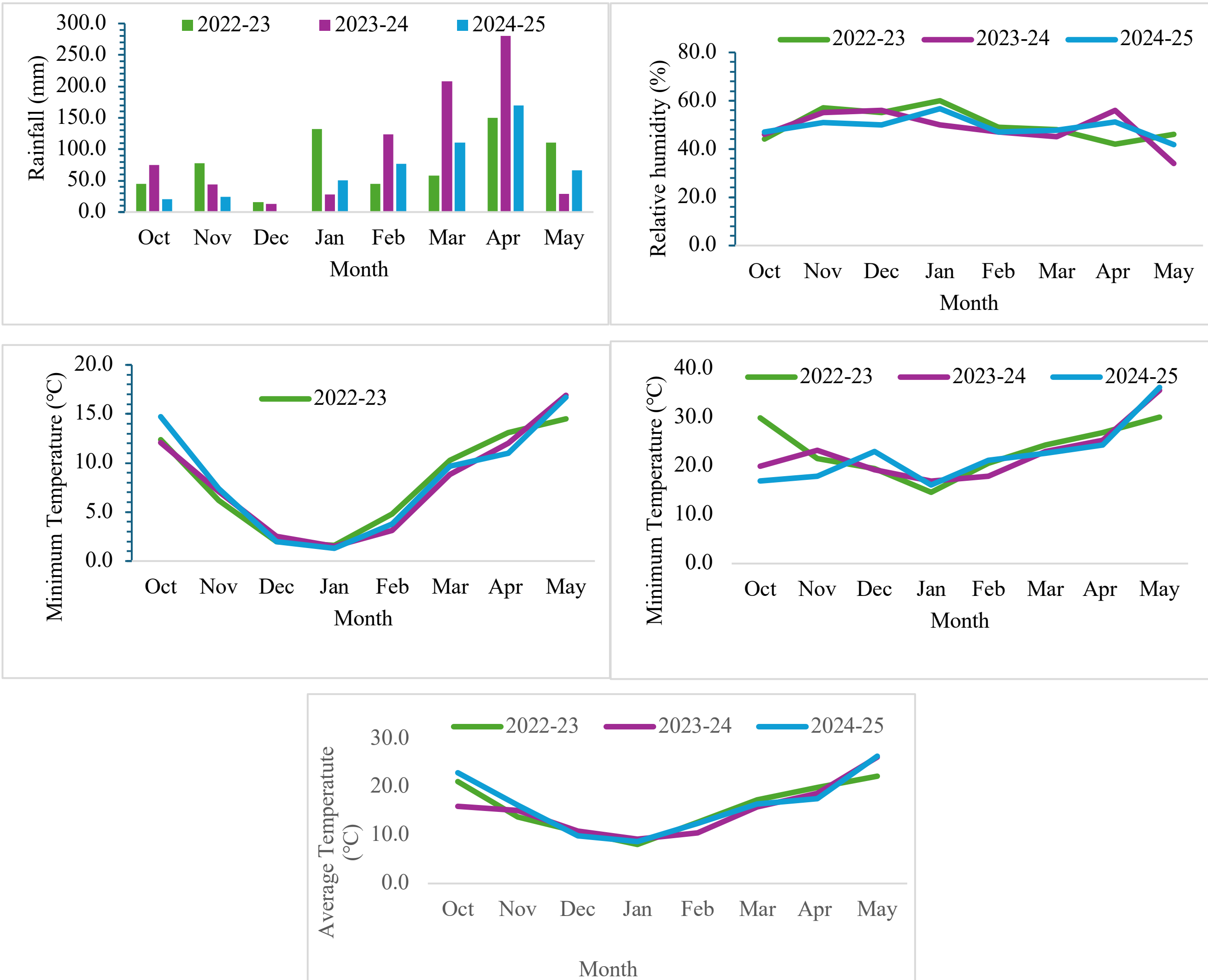

Fig. 2. Relative humidity (RH), rainfall, minimum temperature (temp. min.), average temperature (temp. avg.), and the maximum temperature (temp. max.) of the experimental site during the course of study in 2022-23, 2023-24, and 2024-25.

Weeds were controlled by applying the herbicides, with Axial (pinoxaden) for narrow-leaf weeds and Ally max (metsulfuron methyl + tribenuron methyl) for broadleaf weeds at 38 days after sowing. The crops were harvested on the 20th, 26th, and 31st of May in 2023, 2024, and 2025, respectively, when the grain moisture content was ~19%. The grain moisture content was determined using a grain moisture meter (MC-7825G, Swastik Scientific Co.).

2.5. Data Collection

Data were collected on various crop phenological, growth, and yield parameters. Days to germination were counted according to the guidelines of the Association of Official Seed Analysts (AOSA, 1990). Days to physiological maturity were recorded when 90% of all plants per plot lost chlorophyll and turned yellow, determined visually. Days to maturity were determined as the number of days from sowing to harvesting. Plant height was measured from the base to the tip of the spike (awns excluded) of 20 randomly pre-tagged plants from the net plot area at physiological maturity, following the method described by Tesfaye et al. (2021).

The number of tillers was counted on 20 randomly selected plants and averaged. Spike length and number of grains per spike were measured and averaged for 20 randomly selected spikes. Thousand-grain weight was determined by weighing 1000 grains sampled from the grain yield of each treatment using an electronic seed counter and balance, as explained by Farooq et al. (2015). Grain yield was harvested manually from a 1 m² area, sun-dried, and threshed. Grain yield ($t \cdot ha^{-1}$) was calculated and adjusted to 12.5% moisture content using the formula:

$$\text{Grain Yield} = \text{Actual Yield} \times \frac{(100 - \text{M})}{(100 - \text{D})} - - - - - - - - - - 1$$

where M is the measured moisture content and D is the designated moisture content (Mulvaney and Devkota, 2020).

Straw yield was calculated as the difference between total above-ground plant biomass and grain yield, converted to tons per hectare. The harvest index was computed as the ratio of dry seed yield to above-ground dry biomass yield, using the formula given by Wheeler et al. (1996).

$$\text{HI (\%)} = \frac{\text{Grain Yield}}{\text{Biomass}} \times 100 - - - - - - - - - -$$

2.6 Statistical Analysis

The data were analyzed using the statistical software Statistics 10 student version. One-way analysis of variance (ANOVA) was conducted with fine-grain varieties as the factor. For post-ANOVA mean separation, the Tukey test at a 5% probability level was used (Steel et al., 1997). The Fisher analysis of variance (ANOVA) technique was used to determine the significance of the treatment effects.

Table 1. Physico-chemical properties of the soil.

Characteristics	Year 2022	Status	Year 2023	Status	Year 2024	Status
Physical analysis						
Soil Texture	Clay Loam		Clay Loam		Clay Loam	
Chemical analysis						
pH	7.3	Neutral	7.1	Neutral	7.2	Neutral
Saturation %age (%)	46	Saturated	45	Saturated	46	Saturated
Organic matter (%)	1.37	Low	1.31	Low	1.37	Low
Available P (ppm)	17	Medium	15	Medium	19	Medium
Available K (ppm)	181	High	193	High	171	High

Table 2. Characteristics of wheat varieties used in the experiment.

Variety	Year of release	Crop duration (Days)	Plant height (cm)	Yield potential (t ha^{-1})	Salient features
Akbar	2019	200-210	120	7.41	Resistant to Rust, contains 14-15% proteins and 50-54 grains per spike
NARC Super	2009	170-190	95-98	6.92	Resistant to rust and smut, drought-tolerant, suitable for barani areas cultivation
Pak 2013	2013	200-220	112	7.11	Rust-resistant and heat-tolerant
Markaz 2019	2019	180-190	107	6.42	Rust-resistant, medium-sized plants, suitable for early sowing, and contain a protein content 15%
Borlough	2016	200-210	103	7.11	Rust-resistant, suitable for barani and irrigated lands, good for making bread and chapatti
Zincol	2016	190	110	6.42	Contains 35 ppm zinc element, but other varieties contain 25 ppm, disease-resistant, suitable for barani and irrigated lands
Arooj	2022	140-150	110	7.41	Suitable for both irrigative and rain field zones, having strong resistance against leaf rust, moderate resistance against yellow rust, and high in protein, starch, and gluten.
Anaj	2017	140-150	105	7.21	Tolerate stress conditions (drought, salinity, and waterlogging), disease resistance, high crude fat content, excellent color, and texture.
Azrc-Dera	2022	140-145	105	6.92	Good rust resistance, moderate to good straw yield, moderately heat-tolerant, and suitable for warmer climates.
MH-2021	2021	110-130	110	6.92	Rust-resistant, suitable for irrigated lands, good for making bread and chapatti.

Data source: https://aari.punjab.gov.pk/crop varieties rice; t ha^{-1} = tons per hectare

3. Results

3.1. Weather Indices

The weather conditions during the study period (2022-23, 2023-24, and 2024-25) are presented in Fig. 1. The total rainfall received during the growing seasons varied across the three years, with the highest rainfall recorded in 2022-23 (632.1 mm) and the lowest in 2023-24 (578.5 mm). Monthly rainfall distribution showed that most of the rainfall occurred during January, February, March, and April. The mean minimum temperature ranged from 1.3°C to 16.9°C, while the mean maximum temperature ranged from 14.6°C to 36.1°C. A consistent increase in maximum temperature was observed from January to May. Relative humidity ranged from 34% to 60%, with the highest averages in December (54.3%) and January (55.6%). The variable rainfall and temperature patterns during the study period can impact wheat growth and yield, providing valuable insights into environmental conditions that inform agricultural practices and decision-making.

3.2. Phenological Traits of Wheat Varieties

The analysis of variance revealed significant differences ($p \leq 0.05$) among wheat varieties for days of germination, heading, physiological maturity, and harvest maturity.

3.2.1. Days of Germination

The days of germination varied from 12 to 23 days across the three years. Akbar-2019 took 20 days, 18 days, and 19 days to germinate in 2022, 2023, and 2024, respectively. In comparison, Arooj-2022 took the longest time to germinate with 23 days in 2022, which is 15% longer than Akbar-2019. On the other hand, MH-2021 and Anaj-17 took 13.0 days to germinate in 2023, which is 26.6% shorter than Akbar-2019 (Table 3).

3.2.2. Days of Heading

The days of heading ranged from 82 to 138 days across the three years. NARC-Super took 117.0 days, 118 days, and 138 days in 2022, 2023, and 2024, respectively. In comparison, MH-2021 took the shortest time to head with 82 days in 2023, which is 31.1% shorter than NARC-Super. On the other hand, Zincol took the longest time to head with 120.0 days, 118 days, and 133.0 days in 2022, 2023, and 2024, respectively, which is 2.6% longer than NARC-Super in 2022 (Table 3).

3.2.3. Days to Physiological Maturity

The days to physiological maturity ranged from 135 to 175 days across the three years. Akbar-2019 took 135 days, 145 days, and 159 days to physiological maturity in 2022, 2023, and 2024, respectively. In comparison, NARC-Super took 12.4% longer to mature than Akbar-2019 in 2022. On the other hand, Markaz-2019 took 140 days, 145 days, and 175 days to physiological maturity, which is 3.7% longer than Akbar-2019 in 2022 (Table 3).

3.2.4. Days to Harvest Maturity

The days to harvest maturity ranged from 167 to 207 days across the three years. Akbar-2019 took 167 days, 177 days, and 191 days to reach maturity in 2022, 2023, and 2024, respectively. In comparison, NARC-Super took 10.1% longer to mature than Akbar-2019 in 2022. On the other hand, Markaz-2019 took 172 days, 177 days, and 207 days to reach maturity, which is 3.1% longer than Akbar-2019 in 2022 (Table 3).

3.3. Growth Traits of Wheat Varieties

The growth traits of wheat varieties were evaluated under rainfed conditions. The results revealed significant differences among the varieties for the number of tillers, plant height, spike length, and grains per spike.

3.3.1. Number of Tillers

The number of tillers is a critical growth trait that affects wheat yield. The analysis of variance revealed significant differences ($p \leq 0.05$) among wheat varieties for the number of tillers in 2022. However, no significant differences were observed in 2023 and 2024. In 2022, the number of tillers ranged from 12 to 19. Zincol produced the highest number of tillers (19), which was significantly higher than Akbar-2019 (14), NARC-Super (12), Borlough (14), Anaj-17 (13), and AZRC Dera (14). In 2023, although no significant differences were observed, Anaj-17 produced the highest number of tillers (13), followed by Borlough (12) and Pakistan-2013 (12). While in 2024, the number of tillers ranged from 10 to 14. Markaz-2019 produced the highest number of tillers (14), followed by Akbar-2019 (13). Zincol was the best-performing variety in terms of tiller number, producing the highest number of tillers in 2022. Zincol produced 35.0% more tillers than NARC-Super in 2022. Pakistan-2013 and Markaz-2019 also showed promising results. The results suggest that Zincol has a higher potential for producing more tillers, which can lead to higher grain yields (Table 4).

3.3.2. Plant Height

Plant height is a crucial growth trait that can significantly impact wheat yield and lodging resistance. The analysis of variance revealed significant differences ($p \leq 0.05$) among wheat varieties for plant height in all three years. In 2022, the plant height ranged from 67.7 to 81.7 cm. The tallest plants were recorded in AZRC Dera (81.7 cm) and NARC-Super (81.3 cm), which were statistically similar to Markaz-2019 (79.7 cm) and MH-21 (78.3 cm). Akbar-2019 produced the shortest plants (67.7 cm), which were significantly shorter than the tallest varieties. In 2023, the plant height ranged from 61.7 to 76.3 cm. Pakistan-2013 produced the tallest plants (76.3 cm), although statistically similar to several other varieties, including Zincol (74.3 cm), Anaj-17 (74.0 cm), and MH-21 (74.0 cm). Borlough produced the shortest plants (61.7 cm), which were significantly shorter than several other varieties. In 2024, the plant height ranged from 68.6 to 79.3 cm. Akbar-2019 produced the tallest plants (79.3 cm), although statistically similar to several other varieties, including MH-21 (77.3 cm), AZRC Dera (76.3 cm), and Zincol (75.0 cm). NARC-Super produced the shortest plants (68.6 cm). The results suggest that there is significant variation among wheat varieties for plant height, and some varieties have a potential for better lodging resistance due to their height. The best performing varieties in terms of plant height were AZRC Dera, NARC-Super, and MH-21 (Table 4).

3.3.3. Spike Length

The spike length is a crucial growth trait that affects wheat yield. The analysis of variance revealed no significant differences ($p \leq 0.05$) among wheat varieties for spike length in all three years, except for some minor variations. In 2022, the spike length ranged from 8.7 to 11.3 cm. Borlough, NARC-Super, Pakistan-2013, and Markaz-2019 produced longer spikes, with lengths of 11.3 cm, 11.3 cm, 11.3 cm, and 11.3 cm, respectively. Akbar-2019 produced the shortest spikes (8.7 cm), which were 23.0% shorter than Borlough. In 2023, the spike length ranged from 10.0 to 12.3 cm. Zincol and Borlough produced longer spikes, with lengths of 12.3 cm and 12.0 cm, respectively. Akbar-2019 produced a spike length of 10.7 cm. In 2024, the spike length ranged from 9.0 to 12.0 cm. NARC-Super and Borlough produced longer spikes, with lengths of 12.0 cm. Akbar-2019 produced a spike length of 9.0 cm. The results suggest that Borlough, NARC-Super, and Zincol are promising varieties in terms of spike length (Table 4).

3.3.4. Grains per Spike

The number of grains spike^{-1} is a crucial yield component that significantly impacts wheat productivity. The analysis of variance revealed significant differences ($p \leq 0.05$) among wheat varieties for grains spike^{-1} in all three years. In 2022, the number of grains spike^{-1} ranged from 38.7 to 58.7. Arooj-22 produced the highest number of grains spike^{-1} (58.7), which was 29.6% higher than Akbar-2019 (45.3). Varieties, including Zincol, Anaj-17, and Borlough, produced significantly lower grains spike^{-1} compared to Arooj-22. In 2023, although the analysis of variance showed non-significant differences, Arooj-22 and Anaj-17 produced a higher number of grains spike^{-1}, with 49.3 and 49.7, respectively. In 2024, the number of grains spike^{-1} ranged from 39.7 to 51.7. Arooj-22 and Zincol produced the highest number of grains spike^{-1}, with 51.7 and 51.0, respectively. These values were significantly higher than Pakistan-2013 (39.7). The results suggest that Arooj-22 is a promising variety in terms of grains spike^{-1}, consistently producing a higher number of grains across the three years. Other varieties, such as Zincol and Anaj-17, also showed potential for higher grains spike^{-1} (Table 4).

3.4. Yield Traits of Wheat Varieties

The ANOVA results show significant differences among wheat varieties for various traits. For 1000-grain weight, the differences were highly significant in 2022 ($p < 0.001$) and significant in 2023 ($p = 0.007$), but non-significant in 2024 ($p = 0.093$). However, for grain yield, straw yield, and harvest index, the differences among varieties were highly significant across all three years, with p-values < 0.001 in 2022 and 2023, and $p = 0.002$ in 2024 for grain yield and harvest index, while straw yield remained highly significant with $p < 0.001$ in all years.

3.4.1. 1000-grain Weight

The 1000-grain weight is a crucial yield component in wheat, influenced by various factors such as genotype, environmental conditions, and agricultural practices. In 2022, the 1000-grain weight ranged from 41.7 g to 54.3 g. Arooj-22 performed exceptionally well with a weight of 54.3 g, followed closely by AZRC Dera at 53.3 g and Markaz-2019 at 49.7 g. In 2023, the 1000-grain weight ranged from 40.0 g to 52.0 g. Markaz-2019 excelled with a weight of 52.0 g, while Anaj-17 and Borlough had weights of 49.8 g and 47.0 g, respectively. For 2024, the 1000-grain weight ranged from 47.0 g to 55.0 g. Markaz-2019 again topped the list with a weight of 55.0 g, followed by Anaj-17 at 52.0 g and Arooj-22 at 49.0 g. These results indicate that different wheat varieties performed variably across the three years in terms of 1000-grain weight. Some varieties, such as Markaz-2019 and Arooj-22, consistently showed high performance (Table 5).

3.4.2. Grain Yield

In 2022, the grain yield ranged from 2.47 t ha^{-1} (Akbar-2019) to 3.63 t ha 1 (AZRC Dera). AZRC Dera and Arooj-22 showed exceptional performance with grain yields of 3.63 t ha^{-1} and 3.58 t ha^{-1}, respectively. Other top-performing varieties included Zincol (3.32 t ha^{-1}) and MH-21 (3.33 t ha^{-1}). In 2023, the grain yield ranged from 1.68 t ha^{-1} (NARC-Super) to 3.27 t ha^{-1} (Anaj-17). Anaj-17 excelled with a grain yield of 3.27 t ha 1, followed by Arooj-22 (2.78 t ha^{-1}) and Markaz-2019 (2.40 t ha^{-1}). Pakistan-2013 also performed well with a grain yield of 2.43 t ha^{-1}. In 2024, the grain yield ranged from 2.28 t ha^{-1} (Zincol) to 2.89 t ha^{-1} (Borlough). Borlough and AZRC Dera showed consistent performance with grain yields of 2.89 t ha^{-1} and 2.79 t ha^{-1}, respectively. Other top-performing varieties included Anaj–17 (2.69 t ha^{-1}) and Arooj-22 (2.68 t ha^{-1}). The highly significant differences among varieties across the three years indicate that the selection of wheat varieties can substantially impact grain yield (Table 5).

3.4.3. Straw yield

The straw yield performance of wheat varieties varied across the three years. In 2022, AZRC Dera and Arooj-22 excelled with straw yields of 3.21 t ha^{-1} and 3.16 t ha^{-1}, respectively. Akbar-2019 had the lowest straw yield at 2.05 t . In 2023, Anaj-17 topped the list with a straw yield of 2.85 t ha^{-1}, while Zincol and NARC-Super had the lowest yields at 1.23 t ha^{-1} and 1.26 t ha^{-1}, respectively. In 2024, Borlough and AZRC Dera performed well with straw yields of 2.47 t ha^{-1} and 2.37 t ha^{-1}, respectively. Zincol and Markaz–2019 had relatively lower yields. Overall, the top-performing varieties for straw yield were AZRC Dera, Arooj-22, Anaj-17, and Borlough, which demonstrated consistent and high yields across the three years (Table 5).

Table 3. Phenological Traits of Wheat Varieties for Screening and Adaptability under the Rainfed Conditions in Azad Jammu and Kashmir

Treatment		Days of Germination (Days)			Days of Heading (Days)			Days to Physiological Maturity (Days)			Days to Harvest Maturity (Days)		
		2022	2023	2024	2022	2023	2024	2022	2023	2024	2022	2023	2024
Akbar-2019		20.0^{b}	17.7^{ab}	19.0^{a}	100.3^{h}	110.3^{a}	123.7^{e}	135.3^{h}	145.3^{a}	158.7^{e}	167.3^{h}	177.3^{a}	190.7^{e}
NARC- Super		21.7^{ab}	16.0^{bc}	18.0^{ab}	117.0^{b}	118.3^{a}	138.0^{a}	152.0^{b}	153.3^{a}	173.0^{a}	184.0^{b}	185.3^{a}	205.0^{a}
Pakistan-2013		20.7^{ab}	16.0^{bc}	15.3^{c}	112.0^{d}	121.0^{a}	133.0^{b}	147.0^{d}	156.0^{a}	168.0^{b}	179.0^{d}	177.0^{a}	200.0^{b}
Markaz-2019		21.0^{ab}	15.3^{c}	16.0^{bc}	105.3^{f}	110.0^{a}	140.0^{a}	140.3^{f}	145.0^{a}	175.0^{a}	172.3^{f}	177.0^{a}	207.0^{a}
Borlough		21.3^{ab}	18.7^{a}	18.0^{ab}	115.0^{c}	119.0^{a}	130.3^{bc}	150.0^{c}	154.0^{a}	165.3^{bc}	182.0^{c}	186.0^{a}	197.3^{bc}
Zincol		22.3^{ab}	15.7^{c}	16.0^{bc}	120.0^{a}	117.7^{a}	133.0^{b}	155.0^{a}	152.7^{a}	168.0^{b}	187.0^{a}	184.7^{a}	200.0^{b}
Arooj-2022		23.0^{a}	12.0^{d}	18.0^{ab}	106.0^{f}	118.0^{a}	122.0^{e}	141.0^{f}	153.0^{a}	157.0^{e}	173.0^{f}	185.0^{a}	189.0^{e}
Anaj-17		22.0^{ab}	13.0^{d}	15.0^{c}	108.0^{e}	120.0^{a}	130.0^{c}	145.0^{e}	155.0^{a}	156.0^{c}	177.0^{e}	187.0^{a}	197.0^{c}
AZRC Dera		22.0^{ab}	15.0^{c}	16.0^{bc}	103.0^{g}	111.7^{a}	127.0^{d}	138.0^{g}	146.7^{a}	162.0^{d}	170.0^{g}	178.7^{a}	194.0^{d}
MH-2021		22.0^{ab}	13.0^{d}	17.0^{abc}	115.0^{c}	81.7^{a}	132.0^{bc}	150.0^{c}	116.7^{a}	167.0^{bc}	182.0^{c}	148.7^{a}	199.0^{bc}
HSD ($p \leq 0.05$)		*2.71*	*1.74*	*2.63*	*1.24*	*54.3*	*<0.001*	*1.24*	*54.3*	*2.98*	*1.24*	*54.3*	*2.98*
Analysis of variance													
Source	DF												
Varieties	9	*0.037*	*0.004*	*<0.001*	*<0.001*	*0.361*	*0.02*	*<0.001*	*0.361*	*<0.001*	*<0.001*	*0.361*	*<0.001*

HSD = Honestly Significant Difference; Values sharing different lettering for a parameter are significantly different (p ≤ 0.05) by the Tukey's HSD test; DF = Degree of Freedom; P value for varieties

Table 4. Growth Traits of Wheat Varieties under the Rainfed Conditions in Azad Jammu and Kashmir.

Treatment		Number of Tillers			Plant Height (cm)			Spike Length (cm)			Grains Spike^{-1}		
		2022	2023	2024	2022	2023	2024	2022	2023	2024	2022	2023	2024
Akbar-2019		14.3^{bc}	10.7^{a}	13.3^{a}	67.7^{b}	71.7^{a}	79.3^{ab}	8.7^{a}	10.7^{a}	9.0^{a}	45.3^{b}	47.3^{a}	45.3^{ab}
NARC- Super		12.3^{c}	10.0^{a}	12.0^{a}	81.3^{a}	71.0^{ab}	68.6^{b}	11.3^{a}	12.0^{a}	12.0^{a}	42.7^{b}	45.7^{a}	48.7^{ab}
Pakistan-2013		18.3^{ab}	12.0^{a}	12.6^{a}	77.7^{a}	76.3^{a}	74.0^{ab}	11.3^{a}	11.0^{a}	9.7^{a}	38.7^{b}	47.0^{a}	39.7^{b}
Markaz-2019		16.0^{abc}	10.0^{a}	14.0^{a}	79.7^{a}	71.0^{ab}	73.7^{ab}	11.3^{a}	11.3^{a}	11.3^{a}	38.7^{b}	42.7^{a}	44.0^{ab}
Borlough		14.0^{c}	12.3^{a}	10.3^{a}	73.3^{ab}	61.7^{b}	73.0^{ab}	11.3^{a}	12.0^{a}	12.0^{a}	38.7^{b}	44.3^{a}	48.3^{ab}
Zincol		19.3^{a}	10.0^{a}	11.3^{a}	77.7^{a}	74.3^{a}	75.0^{ab}	10.3^{a}	12.3^{a}	10.0^{a}	42.0^{b}	49.0^{a}	51.0^{a}
Arooj-22		15.0^{bc}	11.7^{a}	10.7^{a}	73.3^{ab}	73.3^{a}	74.7^{ab}	10.3^{a}	11.3^{a}	11.3^{a}	58.7^{a}	49.3^{a}	51.7^{a}
Anaj-17		13.0^{c}	13.3^{a}	12.0^{a}	73.0^{ab}	74.0^{a}	71.0^{ab}	9.0^{a}	11.0^{a}	11.0^{a}	38.7^{b}	49.7^{a}	51.3^{a}
AZRC Dera		13.7^{c}	11.0^{a}	12.0^{a}	81.7^{ab}	73.3^{a}	76.3^{ab}	10.7^{a}	11.0^{a}	11.0^{a}	41.7^{b}	45.7^{a}	46.7^{ab}
MH-21		14.7^{bc}	11.0^{a}	11.0^{a}	78.3^{a}	74.0^{a}	77.3^{a}	9.0^{a}	10.0^{a}	10.0^{a}	41.0^{b}	44.0^{a}	44.0^{ab}
HSD ($p \leq 0.05$)		*5.06*	*4.47*	*4.07*	*9.27*	*9.86*	*8.37*	*3.31*	*3.45*	*3.34*	*8.38*	*10.12*	*9.49*
Analysis of variance													
Source	DF												
Varieties	9	*<0.001*	*0.183*	*0.087*	*0.001*	*<0.001*	*0.023*	*0.034*	*0.710*	*0.057*	*<0.001*	*0.237*	*0.006*

HSD = Honestly Significant Difference; Values sharing different lettering for a parameter are significantly different (p ≤ 0.05) by the Tukey's HSD test; DF = Degree of Freedom; P value for varieties.

On the other hand, Zincol and NARC-Super consistently ranked lower in straw yield performance. These results highlight the importance of selecting suitable wheat varieties for specific environments to optimize straw production.

3.4.3. Harvest Index

The harvest index (HI) of wheat varieties varied across the three years. In 2022, Arooj-22 and AZRC Dera excelled with HI values of 1.88%, while Akbar-2019 had a relatively lower HI of 1.83%. In 2023, Anaj-17 topped the list with an HI of 1.87%, and Arooj-22 and AZRC Dera also performed well. In 2024, Borlough and AZRC Dera had high HI values of 1.85%. Overall, the top-performing varieties for harvest index were Arooj-22 and AZRC Dera, which consistently ranked high across the three years. Anaj-17 also showed strong performance, particularly in 2023. These results indicate that these varieties have a higher capacity to allocate biomass to grain production, making them more efficient in terms of grain yield (Table 5).

4. Discussion

4.1. Weather Indices

The study period exhibited variable weather conditions, with total rainfall during the growing seasons ranging from 578.5 mm in 2023-24 to 632.1 mm in 2022-23. Most rainfall was concentrated in January through April, aligning with the crop's critical water-requirement phase. The mean minimum temperature was 1.3-16.9°C, and the maximum was 14.6-36.1°C. Winter months were cool enough for vernalization. A steady rise from December to May likely accelerated development after heading. Relative humidity remained moderate (34-60%), with peaks in December and January suggesting occasional foggy mornings that may reduce evapotranspiration. These climatic fluctuations are known to influence wheat phenology and yield, as reported by Gulino and Lopes, (2024), who found that temperature extremes shorten grain-filling duration, reduce solar radiation interception, and lower photosynthetic activity. Favorable climatic conditions promoted greater plant performance. These included higher temperatures, increased solar radiation, and a prolonged vegetative phase (Qasim et al., 2022; Gulino and Lopes, 2024). The observed weather patterns thus provide a realistic backdrop for interpreting genotypic performance.

4.2. Soil and Amendments

The soil was classified as clay loam with a neutral pH (7.1-7.3), high saturation (45-46%), low organic matter (1.31-1.37%), medium available phosphorus (15-19 ppm), and high potassium (171-193 ppm). Such characteristics suggest adequate nutrient reserves but limited organic carbon, which can affect microbial activity and nitrogen use efficiency. Fertilizer was applied at 115 kg N ha^{-1} and 85 kg P ha^{-1}, with phosphorus and a starter dose of nitrogen supplied at sowing, and the remainder of N split at tillering and anthesis, a practice consistent with recommendations for wheat in similar agro-climatic zones (Derebe et al., 2022). The uniform soil texture across years ensures that observed varietal differences are more likely due to genotype rather than edaphic variation.

4.3. Phenological Traits

Days of germination ranged from 12 to 23 days. Akbar-2019 germinated in about 18-20 days, while Arooj-2022 took the longest (23 days in 2022), possibly reflecting slower emergence under cooler early-season temperatures.

Table 5. Yield and Efficiency Traits of Wheat Varieties under the Rainfed Conditions in Azad Jammu and Kashmir.

Treatment	1000-grain weight (g)			Grain Yield (t ha^{-1})			Straw Yield (t ha^{-1})			Harvest Index		
	2022	2023	2024	2022	2023	2024	2022	2023	2024	2022	2023	2024
Akbar-2019	45.7^{bcd}	46.7^{ab}	49.3^{a}	2.47^{f}	2.02^{cde}	2.61^{abc}	2.05^{f}	1.60^{cde}	2.19^{abc}	1.83^{e}	1.79^{d}	1.84^{abc}
NARC- Super	47.3^{abcd}	44.3^{b}	49.0^{a}	3.11^{cd}	1.68^{de}	3.14^{a}	2.69^{cd}	1.26^{de}	2.72^{a}	1.86^{bc}	1.75^{e}	1.87^{c}
Pakistan-2013	41.7^{cd}	48.3^{ab}	50.3^{a}	2.88^{de}	2.43^{bc}	2.65^{abc}	2.46^{de}	2.01^{bc}	2.23^{abc}	1.85^{cd}	1.83^{bcd}	1.84^{abc}
Markaz-2019	49.7^{abc}	52.0^{a}	55.0^{a}	3.26^{c}	2.40^{bc}	2.34^{bc}	2.84^{c}	1.98^{bc}	1.92^{bc}	1.87^{ab}	1.82^{bcd}	1.82^{bc}
Borlough	43.0^{cd}	47.0^{ab}	48.0^{a}	2.77^{e}	2.39^{bc}	2.89^{ab}	2.35^{e}	1.97^{bc}	2.47^{ab}	1.85^{d}	1.82^{bcd}	1.85^{ab}
Zincol	47.7^{abcd}	48.0^{ab}	47.3^{a}	3.32^{bc}	1.65^{e}	2.28^{c}	2.90^{bc}	1.23^{e}	1.86^{c}	1.87^{ab}	1.74^{e}	1.81^{c}
Arooj-22	54.3^{a}	49.3^{ab}	49.0^{a}	3.58^{ab}	2.78^{b}	2.68^{abc}	3.16^{ab}	2.36^{b}	2.26^{abc}	1.88^{a}	1.85^{ab}	1.84^{abc}
Anaj-17	41.0^{d}	49.8^{ab}	52.0^{a}	2.90^{de}	3.27^{a}	2.69^{abc}	2.48^{de}	2.85^{a}	2.27^{abc}	1.86^{cd}	1.87^{a}	1.84^{abc}
AZRC Dera	53.3^{ab}	45.7^{a}	49.0^{a}	3.63^{a}	2.60^{b}	2.79^{abc}	3.21^{a}	2.18^{b}	2.37^{abc}	1.88^{a}	1.84^{abc}	1.85^{ab}
MH-21	46.7^{abcd}	40.0^{ab}	47.7^{a}	3.33^{bc}	2.10^{cd}	2.48^{bc}	2.91^{bc}	1.68^{cd}	2.06^{bc}	1.87^{ab}	1.80^{cd}	1.83^{bc}
HSD ($p \leq 0.05$)	*8.25*	*10.12*	*8.16*	*0.297*	*0.421*	*0.567*	*0.297*	*0.421*	*0.567*	*0.014*	*0.041*	*0.035*

Analysis of variance

Source	DF												
Varieties	9	*<0.001*	*0.007*	*0.093*	*<0.001*	*<0.001*	*0.002*	*<0.001*	*<0.001*	*0.002*	*<0.001*	*<0.001*	*0.002*

HSD = Honestly significant difference; Values sharing different lettering for a parameter are significantly different ($p \leq 0.05$) by the Tukey's HSD test; DF = Degree of Freedom; P value for varieties; g = grams; t ha-1 = ton per hectare

MH-2021 and Anaj-17 germinated fastest (13 days in 2023), indicating better early-season vigor, a trait useful for early sowing windows. Days to heading varied widely (82-138 days). NARC-Super required the most thermal time to head (117-138 days), whereas MH-2021 headed earliest (82 days in 2023), suggesting a photoperiod-insensitive, early genotype. Zincol was consistently late, which may relate to its genetic background adapted to longer growing periods. Earlier heading under higher spring temperatures agrees with findings that temperature accelerates reproductive development in wheat (Qasim et al., 2022; Gulino and Lopes, 2024). Physiological maturity occurred between 135 and 175 days. Akbar-2019 matured earliest (135 days in 2022), while Markaz-2019 and NARC-Super took longer, reflecting differences in grain-fill duration. Longer maturity under higher accumulated heat units in 2024 likely explains the extended cycle that year. Harvest maturity followed a similar trend, ranging from 167 to 207 days. Akbar-2019 again reached harvest faster, whereas Markaz-2019 and NARC-Super required up to 10% more days, suggesting that early-maturing varieties like Akbar-2019 could fit better into double-cropping systems. Variable rainfall, increasing maximum temperatures, and consistent fertilizer regimes produced significant phenological differences among varieties. Early genotypes like MH-2021 and Akbar-2019 showed rapid germination, early heading, and shorter life cycles. This may confer resilience to terminal heat stress, a growing concern with climate change. Conversely, late varieties (e.g., NARC-Super, Zincol) exhibited longer vegetative phases that could maximize yield under favorable water supply but risk exposure to late-season heat. The clay loam soil with neutral pH supported uniform establishment, while low organic matter underscores the importance of integrated nutrient management.

4.3. Growth Traits

Significant varietal differences appeared only in 2022, with Zincol producing the highest tiller count (19), 35% more than NARC-Super. In 2023 and 2024, differences were non-significant, yet Anaj-17 and Markaz-2019 showed modest advantages. Tillering depends on the green photosynthetic area that fuels carbohydrate production and grain filling (Saleem et al., 2016; Dautani et al., 1997). Year-to-year fluctuation was observed, likely due to weather variability. Higher early-season temperatures can reduce tiller survival in late-sown crops (Khalifa et al., 1977). Genetic variation also explains why some cultivars tiller more (Shah et al., 2006; Khan et al., 1999). Similarly, plant height varied significantly across years. AZRC Dera and NARC-Super were tallest in 2022, Pakistan-2013 in 2023, and Akbar-2019 in 2024. Improved temperature, solar radiation, and an extended vegetative phase promote increased height (Qasim et al., 2022). Significant positive correlations between height and grain yield have been reported (Chaves and Oliveira, 2004). However, Upadhyay et al. (2001) found no significant genotypic differences, underscoring that environment modulates expression. The variation likely stems from both genotype and environmental interaction (Shahzad et al., 2016; Ashiq et al., 2007; Hassan et al., 2007).

Spike length remained stable except for minor fluctuations. Borlough, NARC-Super, and Zincol consistently produced longer spikes, while Akbar-2019 recorded the shortest. Although differences were mostly non-significant, spike length contributes to grain number per spike, a key yield component. Grains per spike differed significantly each year. Arooj-22 topped the list in 2022 (58.7) and maintained superiority in 2023-24, indicating stable sink potential. Calderini et al. (2003) noted that increased kernels per spike raise durum and bread wheat yield. The critical period for kernel set is from floral initiation to anthesis, when water stress can limit grain number (Ali et al., 1999).

4.2. Yield Traits

The 1000-grain weight showed highly significant differences in 2022 and significant differences in 2023, but not in 2024. Arooj-22, AZRC Dera, and Markaz-2019 achieved the highest weights, aligning with Peltonen-Sainio et al. (2007), who identified kernel weight as a predictor of final grain yield. Warm, dry winds in March-April can force maturity and reduce test weight (Dhaliwal et al., 2013). Grain yield varied markedly. AZRC Dera (3.63 t ha^{-1}) and Arooj-22 (3.58 t ha^{-1}) excelled in 2022; Anaj-17 (3.27 t ha^{-1}) led in 2023, and Borlough (2.89 t ha^{-1}) in 2024. The range reflects genotype × environment interaction, a complex trait noted by Mondal and Khajuria, (2001). Positive associations of yield with tillers m^{-2}, grains per spike, and thousand-grain weight support previous findings (Saleem et al., 2016; Dhonde et al., 2000; Ali et al., 1999). Straw yield was highest for AZRC Dera in 2022, Anaj-17 in 2023, and Borlough in 2024. Varieties like Zincol and NARC-Super consistently yielded less straw. Harvest index (HI) mirrored grain performance; Arooj-22 and AZRC Dera achieved the best HI, indicating efficient biomass partitioning to grain (Fellahi et al., 2013; Mahpara et al., 2022). From the study, it could be synthesized that varietal performance was driven by both genetics and environment. Zincol and Arooj-22 showed strong tillering and grain-set traits, respectively. While early-maturing varieties (e.g., Akbar-2019, MH-2021) escaped terminal stress, consistent with Hassan et al. (2007). Positive correlations among tillers m^{-2}, grains spike^{-1}, and grain yield confirm prior studies (Saleem et al., 2016; Dhonde et al., 2000; Ullah et al., 2007).

5. Conclusion

The three-year field study evaluated wheat phenology, growth, and yield traits under rainfed conditions in Azad Jammu and Kashmir, revealing strong genotype × environment interactions. Rainfall varied from 578.5 mm (2023-24) to 632.1 mm (2022-23), with most precipitation occurring in January-April. Temperatures ranged from 1.3-16.9 (minimum) and 14.6-36.1 (maximum), while relative humidity stayed between 34-60%. The clay-loam soil was neutral, low in organic matter, and fertilized uniformly at 115 kg N ha^{-1} and 85 kg P ha^{-1}. Significant differences were observed for days to germination, heading, physiological maturity, and harvest maturity. Early varieties such as Akbar-2019 and MH-2021 exhibited rapid germination and early heading, escaping terminal heat stress, whereas late varieties like

NARC-Super and Zincol displayed longer vegetative phases that maximized yield when water was adequate but increased exposure to late-season heat. In terms of growth traits, Zincol produced the highest tiller number in 2022 (19), and Arooj-22 consistently set more grains per spike (up to 59). For yield, AZRC Dera and Arooj-22 recorded the highest grain yields in 2022 (3.63 and 3.58 t ha^{-1}, Anaj-17 led in 2023 (3.27 t ha^{-1}), and Borlough topped in 2024 (2.89 t ha^{-1}). Harvest index was highest for Arooj-22 and AZRC Dera across years, indicating efficient biomass partitioning. Hence, in summary, early-maturing, high-tillering varieties (e.g., Akbar-2019, MH-2021) and stable high-yielding varieties (e.g., Arooj-22, AZRC Dera) are recommended for rainfed wheat systems to improve productivity and climate resilience. Integrated nutrient management and timely sowing should be adopted to exploit the favorable early-season rainfall.

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IH, SRH, and MI: conceptualization and drafting of the manuscript; NBK and MH: literature review and drafting of the manuscript. WA and MI: critical review and expert view; All authors contributed to the research article and approved the final version.

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Data availability

All data generated or analyzed during this study are included in this article.

Additional Information

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