ÇOMÜ Zir. Fak. Derg. (COMU J. Agric. Fac.)
2024: 12 (2): 253-262
ISSN: 2147–8384 / e-ISSN: 2564–6826
doi: 10.33202/comuagri.1582025

OPEN ACCESS

Research Article

Evaluation of Initial Yield Performances of Perennial Wheat Genotypes and Their F_1 Hybrids

Burcu Gökbulut[1] **Deniz Istipliler [*1]**

[1]Ege University, Faculty of Agriculture, Department Crops Science, İzmir, Türkiye
*Corresponding author: deniz.istipliler@ege.edu.tr

Received Date: 09.10.2024 Accepted Date: 20.11.2024

Abstract

The rising demand for sustainable food production due to climate challenges has increased the interest in perennial crops as a potential solution. Perennial wheat improves soil structure thanks to its deep root structure and can contribute to reducing agricultural inputs and carbon emissions through reduced tillage. This study evaluates the first-year yield performances of 20 perennial wheat genotypes and 23 F_1 hybrids obtained from intraspecific crosses among these lines, with two commercial bread wheat cultivars. The field experiments were conducted over two consecutive growing seasons (2021-2022 and 2022-2023) at experimental fields of Ege University, Faculty of Agriculture and Department of Field Crops. Key agronomic traits measured were plant height (PH), grain number per spike (GNS), thousand kernel weight (TKW), and plot yield (PY). The ANOVA indicated significant genotypic effects on all traits ($p<0.01$), and year effect was significant for PH ($p<0.05$) and TKW ($p<0.01$). Heritability estimates were high for all four traits, particularly for PH (H^2=0.93), TKW (H^2=0.82), and GNS (H^2=0.77), demonstrating substantial genetic influence on these traits. There was considerable variation observed in PH, with genotypes derived from *Thinopyrum ponticum* exhibiting the tallest growth, while commercial varieties (checks or control) displayed a relatively shorter stature. The commercial cultivars excelled in yield-related traits, consistently ranking in the highest statistical groups for TKW, GNS, and PY. Promising genotypes included G18 (sourced from *Th. intermedium*) and G19 (sourced from *Th. ponticum*), which close to commercial standards in TKW and PY across both years showed that these lines are promising for future breeding studies aiming to improve the yield. The findings demonstrate that specific perennial wheat genotypes can be employed in breeding programmes to achieve high yields, whereas the yield performance of lines is influenced by their genetic resources.

Keywords: perennial wheat, yield, plant height, heritability, heterosis.

Çok Yıllık Buğday Genotiplerinin ve F_1 Hibritlerinin Ön Verim Performanslarının Değerlendirilmesi

Öz

İklim değişikliği nedeniyle sürdürülebilir gıda üretimine olan talebin artması, çok yıllık bitkilere olan ilgiyi arttırmaktadır. Çok yıllık buğday derin kök yapısı sayesinde toprak yapısını iyileştirir ve daha az toprak işleme ile tarımsal girdilerin ve karbon emisyonunun azaltılmasına katkıda bulunabilir. Bu çalışmada, 20 farklı çok yıllık buğday genotipinin ve bu genotipler arasında yapılan tür içi melezlemelerden elde edilen 23 F_1 melezinin, iki ticari ekmeklik buğday çeşidi ile birlikte, verim performansları değerlendirilmiştir. Tarla denemeleri, Ege Üniversitesi Tarla Bitkileri Bölümü deneme alanlarında, 2021-2022 ve 2022-2023 buğday yetiştirme sezonlarında yürütülmüştür. Araştırmada bitki boyu (PH), başakta tane sayısı (GNS), bin tane ağırlığı (TKW) ve parsel verimi (PY) (g/plot) özellikleri incelenmiştir. Varyans analiz sonuçları, tüm özellikler için genotipik etkilerin önemli olduğunu ($p<0.01$) göstermiş ve yıl etkilerinin PH ($p<0.05$) ve TKW ($p<0.01$) için anlamlı olduğunu ortaya koymuştur. İncelenen dört özellik için yüksek geniş anlamda kalıtım dereceleri gözlenmiştir. Özellikle PH (H^2=0.93), TKW (H^2=0.82) ve GNS (H^2=0.77) karakterleri için genetik etkinin önemli olduğu yüksek kalıtım derecelerinden anlaşılmaktadır. Bitki boyu *Thinopyrum ponticum* kaynaklı genotiplerde yüksek olarak bulunmuş, ticari çeşitler ise nispeten daha kısa boy değerlerine sahip olmuşlardır. Ticari çeşitler, verimle doğrudan ilişkili özelliklerde üstünlük göstermiş ve TKW, GNS ve PY için en yüksek istatistiksel gruplarda yer almışlardır. G18 (*Th. intermedium* kaynaklı) ve G19 (*Th. ponticum* kaynaklı) her iki yılda da ticari çeşitlere yakın verim performasları ile umut verici genotipler arasında yer almışlardır. Bu

sonuçlar, belirli çok yıllık buğday genotiplerinin yüksek verim için ıslah programlarında kullanılabileceğini vurgularken, hatların verim performanslarının genetik kaynaklarından etkilendiğini göstermiştir.
Anahtar Kelimeler: Çok yıllık buğday, verim, bitki boyu, kalıtım derecesi, heterosis

Introduction

The annual grain crops supply 70% of the global calorie demand in daily consumption and occupy 70% of the world's arable land (Glover et al., 2010). The environmental challenges sourced from climate change are affecting the global agricultural production and the sustainability of current food systems are increasingly questioned (Erenstein et al., 2022). Perennial wheat, a novel agricultural innovation, represents a significant advancement in the quest for sustainable food production systems. This crop is derived from hybridization between traditional wheat species and their perennial relatives, particularly those from the genus *Thinopyrum*. The development of perennial wheat aims to combine the desirable traits of both annual and perennial plants, thereby addressing pressing agricultural challenges such as soil degradation, nutrient loss, and the need for sustainable farming practices. The cultivation of perennial wheat is gaining attention due to its potential to enhance soil health, improve carbon sequestration, and provide a reliable source of food while minimizing environmental impact (Kane et al., 2016; Cassman and Connor, 2022; Bell et al., 2010). The environmental benefits of perennial wheat are particularly noteworthy. Unlike annual crops, which require tillage and replanting each season, perennial wheat maintains a continuous root system that enhances soil structure and stability. This characteristic significantly reduces soil erosion and nutrient leaching, contributing to improved soil fertility over time (Kurmanbayeva, 2024; Tyl and Ismail, 2018).

Agronomically, perennial wheat presents unique challenges and opportunities. While it is still in the developmental stages, ongoing research is focused on improving its yield and resilience. Initial assessments have indicated that perennial wheat may produce lower biomass than its annual counterparts; however, its dual-purpose potential as both a grain and forage crop is being explored (Jaikumar et al., 2012; Abbasi et al., 2020). The integration of perennial wheat into existing agricultural systems could enhance biodiversity and provide additional forage for livestock, thereby supporting mixed farming operations (Newell and Hayes, 2017; Ryan et al., 2018). Moreover, the genetic diversity introduced through hybridization with perennial species may confer advantages such as disease resistance and drought tolerance, which are increasingly critical in the face of climate variability (Morgan, 2023; Turner et al., 2013). Numerous studies have investigated the performace of the perennial wheat lines based on the yield related morphological traits. Murphy et al. (2009) assessed the nutritional and quality characteristics of 31 perennial wheat breeding lines. They reported significant variability in agronomic traits, including grain yield and thousand grain weight, among the lines evaluated. This variability highlights the potential for selecting superior lines that could perform better under specific environmental conditions. Pogna et al. (2014) recorded the spike length of the perennial wheat nearly 3 cm longer than the common annual wheat. Jaikumar et al. (2012) reported the perennial wheat lines grain yield values ranged from 1.0 to 1.6 tons/ha which coincides 50% less than bread wheat.

The aims of this study were i) to investigate the yield performance of 20 perennial wheat lines along with 23 F_1 hybrids derived from the crosses between perennial wheat lines ii) to compare the effects of different genetic backgrounds on measured traits iii) to assess the hybrid vigour in F_1 hybrids by calculating better parent heterosis (BPH).

Material and Methods

Experimental Site and plant material

The research was conducted during the 2021-2022 and 2022-2023 wheat growing seasons at the experimental fields of Ege University, Faculty of Agriculture, Department of Field Crops. The trial location, situated in Izmir/Bornova, is located at an elevation of 6 meters above sea level (38°34'45" N, 27°1'22" E). The soil profile of the research area is characterised by a silt-clay composition with a pH of 8.2 at depths of 0-20 cm, and a clay-loamy composition with a pH of 7.8 at depths of 20-40 cm.

Twenty perennial wheat genotypes sourced from different *Thynopyrum* spp. species (*Thinopyrum intermedium*, *Th. ponticum*, *Th. Elogantum*, and *Th. Junceiforme*) were used along with 23 F_1 hybrids derived from the intraspecific crosses between the perennial wheat lines (Table 1). Two commercial bread wheat (*Triticum aestivum* L.) cultivars as Basribey and Masaccio were used as checks in both years of the study.

Experimental Design

The perennial wheat lines were sown according to randomized complete block design with three replications in both years. To evaluate the hybrids, randomized incomplete block design was used with three blocks due to the low amount of F_1 seeds obtained from the first year. One row plots were used with 50 cm distance between two rows and 25 seeds were sown in each row (approx. 5 cm distance between each seed on the row) in both years by hand according to Hayes et al. (2018). The sowings were done on 11 November 2021 in first year and 28 December 2022 in the second year of the study. The late sowing in the second year occurred due to an excessive amount of water in the soil caused by precipitation that made the sowing impossible. Fertilization was applied in the form of NPK (15-15-15) with the rate of 90 kg pure N per ha at the time of sowing in both years. At the end of tillering stage, the second fertilizer was applied as 60 kg pure N per ha of ammonium sulphate (21%). Weed control was performed by hand in both years when it was necessary.

Table 1. The perennial wheat genotypes and F_1 hybrids used in the study.

Accession Number	Genotype No	Name	Origin	Donor Wheatgrass
160018	G1	WHEAT-AGROPYRON PONTICUM PARTIAL AMPHIPLOID	OTHER	*Th.ponticum*
160020	G3	WHEAT-AGROPYRON PONTICUM PARTIAL AMPHIPLOID	USA	*Th.ponticum*
160008	G4	PI573182/BFC2-4//BFC2-N/3/PI440048/4/(TAM110/PI401201//JAGand 2137)/5/(PI636500/PI414667//PI414667/3/(PI573182/PI314190//BFC1-FF))	US-TLI	*Th.intermedium*
160012	G5	(KEQIANG/NANDA2419)/AG.INTERMEDIUM//WHEAT	CHINA	*Th.intermedium*
160009	G8	PI634318/PI414667	US-TLI	*Th.junceiforme*
160022	G9	WHEAT-AGROPYRON INTERMEDIUM PARTIAL AMPHIPLOID	RUSSIA	*Th.intermedium*
160019	G10	VILMORIN 27*2/AG.INTERMEDIUM	FRANCE	*Th.intermedium*
160014	G11	WHEAT-AGROPYRON INTERMEDIUM PARTIAL AMPHIPLOID	RUSSIA	*Th.intermedium*
160011	G12	(KEQIANG/NANDA2419)/AG.INTERMEDIUM//WHEAT	CHINA	*Th.intermedium*
160017	G13	WHEAT-AGROPYRON PONTICUM PARTIAL AMPHIPLOID	US-OSU	*Th.ponticum*
160006	G14	TAM110/PI401201//JAG and 2137	US-TLI	*Th.intermedium*
160021	G15	T.DURUM/AG.ELONGATUM	CIMMYT	*Th.elongatum*
160004	G16	MADSEN//CHINESE SPRING/PI531718	US-WSU	*Th.elongatum*
160007	G17	TAM110/PI401201//JAG and 2137/3/PI520054/4/PI401168/5/(TAM110/PI401201//JAG and 2137)	US-TLI	*Th.intermedium*
160013	G18	HEZUO#2/AG.INTERMEDIUM//WHEAT	CHINA	*Th.intermedium*
160015	G19	WHEAT-AGROPYRON PONTICUM PARTIAL AMPHIPLOID	RUSSIA	*Th.ponticum*
160017	G20	WHEAT-AGROPYRON PONTICUM PARTIAL AMPHIPLOID	US-OSU	*Th.ponticum*
160017	G21	WHEAT-AGROPYRON PONTICUM PARTIAL AMPHIPLOID	US-OSU	*Th.ponticum*
160017	G22	WHEAT-AGROPYRON PONTICUM PARTIAL AMPHIPLOID	US-OSU	*Th.ponticum*
160017	G23	WHEAT-AGROPYRON PONTICUM PARTIAL AMPHIPLOID	US-OSU	*Th.ponticum*
***Th.intermedium* × *Th.intermedium* F1 Hybrids**		G12 × G5, G5 × G12, G11 × G12, G11 × G10, G17 × G4, G10 × G17, G4 × G9, G11 × G5, G10 × G11, G14 × G9, G9 × G14, G9 × G4, G10 × G4, G12 × G10, G4 × G12		
***Th.ponticum* × *Th.ponticum* F1 Hybrids**		G22 × G19, G20 × G3, G21 × G3, G21 × G22, G3 × G13, G3 × G1, G3 × G20, G1 × G19		

The crosses were done in the first year of the study to obtain the F_1 hybrids. The emasculation and pollination were done in the lines randomly based on the availability of the male and female parents. The lines from the same genotypic sources were used in hybridization process. Four yield-related morphological traits were measured as plant height (PH), grain number per spike (GNS), thousand kernel weight (TKW) and plot yield (PY)

Statistical analyses

All statistical analyses were done using R statistical software v4.2.0. The aov function was used to obtain the analysis of variance table (ANOVA) to control the significance of the variance sources in the study. Fisher's least significant difference (LSD) test was applied to determine the minimum significant differences between the effects. The broad sense heritability (H^2) was calculated for each trait by using the following formula (1):

$$H^2 = \frac{\sigma_g^2}{\sigma_g^2 + \frac{\sigma_e^2}{n}} \quad (1)$$

Where the H^2 is broad sense heritability, the σg^2 is genotypic variance, the σe^2 is the residual variance and the n is the number of replications. The best linear unbiased estimations (BLUEs) were extracted for each genotype to compare the hybrids and their parents. To calculate BLUEs a linear model was fit to dataset in which the genotypic effect was considered as fixed and year and block were used as random effects. Then the fixef function of the lme4 package in R was used to center BLUEs around the mean. All plots were generated by using the ggplot2 package (Wickham, 2016) in R.

Results

Genotypic variations are shaping agronomic traits with high heritability

ANOVA results (Table 2) showed that the genotypic effects are statistically important on forming all morphological traits measured in perennial wheat genotypes ($p<0.01$). The effects of two years were found significant for two traits PH ($p<0.05$) and TKW ($p<0.01$), while no year effect was observed for GNS and PY. Genotype by year interaction effect was found significant only for GNS of perennial wheat lines.

Table 2. The mean squares from the ANOVA table for the measured agronomic traits.

Source/Trait	*PH*	*TKW*	*GNS*	*PY*
Genotype	2269.27**	239.14**	855.12**	14943.2**
Year	367.46*	935.97**	7.96^{ns}	3613.5^{ns}
G x Y	79.08^{ns}	22.76^{ns}	137.49**	1266.2^{ns}
Block	137.44^{ns}	14.18^{ns}	175.56*	6956.1**

**: p<0.01, * : p<0.05 , ns: non-significant, PH: plant height (cm), TKW: Thousand kernel weight (g), GNS: Grain number per spike (g/spike), PY: plot yield ($g/0.5m^2$)

The H^2 values showed that all four measured traits are highly heritable (>0.50) and the variance values observed for these traits are mainly explained by the genotypic effects (Figure 1). The most heritable trait was PH (H^2= 0.93) followed by TKW (H^2= 0.82) and GNS (H^2= 0.77). Although PY was found as the least heritable trait with a 0.65 H^2 value, it still indicates a sufficient genetic effect forming the yield in perennial wheat lines.

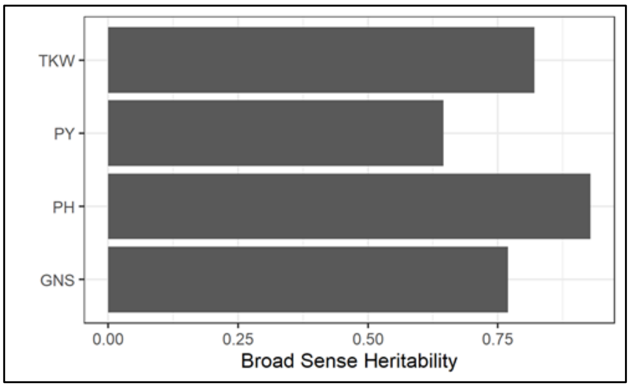

Figure 1. The broad sense heritability values (H^2) of measured traits. PH: Plant height, PY: Plot yield, GNS: Grain number per spike, TKW: Thousand kernel weight.

Different genetic sources in perennial wheat affect yield-related traits

The plant height of the perennial wheat lines from different genetic sources and the commercial check cultivars (Basribey: BAS and Masaccio: MAS) showed a wide range of variation (LSD: 13.94) (Figure 2a). Although the year effect was significantly important, it can be seen that a similar patterns among the genotypes weree observed for PH in both years, which confirmed the insignificant G × E effect (Table 2) for plant height. The G23 sourced from *Th. ponticum* had the highest plant height in the first (147.2 cm) and the second (138.3 cm) years of the study, followed by G15 (sourced from *Th. elongatum*), while G17 had the shortest PH for both the years of 2023 (66.0 cm) and (64.8 cm). Notably, the genotypes from *Th. ponticum* generally had taller heights than the other perennial wheat lines. The lines had the *Th. intermedium* as perennial genitor was found shorter in PH than *Th. ponticum* lines. The check cultivars BAS and MAS had relatively shorter PH values (~75 cm) in both years (Figure 2a).

Despite the PH, the commercial checks came into prominence when the yield-related traits were evaluated such as TKW (Figure 2b), GNS (Figure 2c), and PY (Figure 2d). The genotypes BAS and MAS were consistently placed in the first group in terms of TKW values in both years. The check cultivars were followed by two genotypes, G19 (33.2g) and G18 (32.0 g) in 2022, and G18 (39.5 g) and G13 (34.7 g) in 2023. No clear separation was observed between different sources in terms of TKW (Figure 2b). However, the genotypes G18 (*Th. intermedium*) and G19 (*Th. ponticum*) showed promising TKW values in both years consistently. It can be seen that both G18 and G19 are in the same statistical groups with commercial checks for TKW in both years (LSD: 6.59).

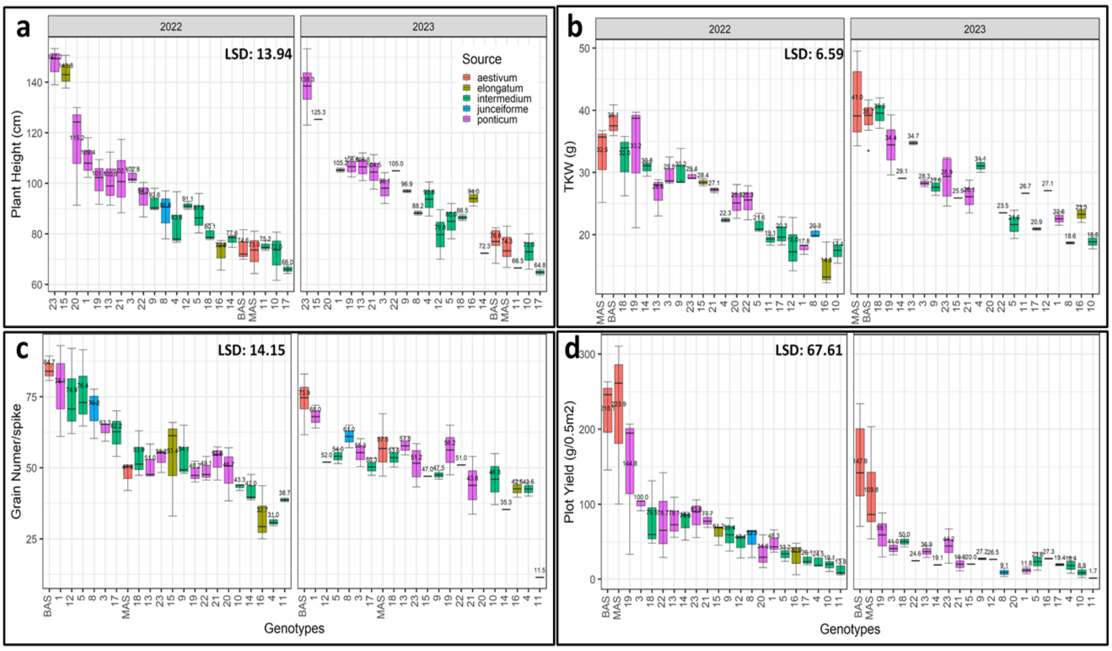

Figure 2. Comparison of the perennial wheat genotypes from different genetic backgrounds, *T. intermedium, T. ponticum, T. junceiforme, T. elongatum* based on four agronomic traits; plant height (a), Thousand Kernel Weight (b), Grain Number per Spike (c), and Plot yield (d).

For GNS, the cv. BAS showed a superior performance in both 2022 (84.7) and in 2023 (73.9) followed by G1 which is in the same statistical group (LSD: 14.15) (Figure 2c). Significant year and G × E effects can be observed for GNS (Figure 2c). Generally, the GNS values obtained in the first year were higher than those of the second year for each genotype. Moreover, changes in the order of the genotypes across two years indicated a crossover genotype by environment interaction for GNS. For example, G14 had the least mean GNS (31.0) in the first year, while G11 showed the lowest GNS value (11.5) in the second year. From different *Thinopyrum spp*. sources, two perennial wheat lines belonging to *Th. intermedium* group (G12 and G5) and one belonging to *Th. ponticum* group (G1) were in the same statistical group with cv. BAS in 2022. On the other hand, for 2023, G8 from the group *Th. junceiforme* and G1 from *Th. ponticum* was in the same statistical group with cv. BAS. It is notable that the other check cv. MAS didn't show a similar performance with CV. BAS for GNS in both 2022 and 2023 (Figure 2c).

For PY, two check genotypes cv. BAS and cv. MAS showed superior performance in two years followed by G19 (*Th. ponticum*) which showed the closest performance to the checks (Figure 2d). The lowest yield was obtained from G11 (*Th. intermedium*) in both 2022 and 2023. Although the difference between two years was not found significant from ANOVA (Table 2), relatively lower PY values for 2023 are drawing attention (Figure 2d). Although it was not as clear as PH, the separation between two different sources, *Th. intermedium* and *Th. ponticum* was observed for PY. Especially in 2022, the three most yielded perennial wheat genotypes (G19, G3, G23) were *Th. ponticum* derivatives, while the least yielded genotypes (G11, G10, G4) were sourced from *Th. intermedium*.

Genotypic Performance and Hybrid Vigor Assessments

The best linear unbiased estimates (BLUEs) of perennial wheat lines and the F_1 hybrids used in the study are shown in Figure 3. Each point in the figure represents one genotype for one trait. The colors of the points separate the genotypes based on whether they are hybrids or lines (parents). The x-axis separates two different sources *(intermedium* or *ponticum)*. The lines between the two dots represent the BPH for each hybrid that connects the hybrid's value with the superior parent. If the angle the line makes with the x-axis is greater than zero, that means that the hybrid showed better performance than the superior parent involved in the cross.

Similar to their parents, the *ponticum* × *ponticum* hybrids had greater PH values than those of intermedium × intermedium hybrids (Figure 3a). For *Th. intermedium* hybrids the highest PH was observed in 12 ×10 cross (103.7 cm), while the lowest PH was observed in the 10 × 4 (77.4 cm) cross. Out of 15 *Th. intermedium* hybrids, 11 of them showed positive BPH indicating the high possibility to obtain hybrid vigor in *Th. intermedium* crosses for PH. Similarly for the *Th. ponticum* crosses, five hybrids out of eight showed a positive BPH. 3 × 1 (122.7 cm) and 21 × 22 (94.4 cm) crosses had the highest and lowest plant heights respectively.

The hybrids of different *Thinopyrum spp*. derivatives showed a wide range of TKW values and it is not possible to conclude that one group is superior to another (Figure 3b). The hybrids, 4 × 9 and 11 × 10 had the highest (40.0 g) and the lowest (16.2 g) TKW values respectively in *Th. intermedium* crosses. For the *Th. ponticum* crosses, 22 × 19 (40.2 g) had the highest and 1 ×19 (18.3 g) hybrid had the lowest TKW values. Eight crosses from a total of 15 in *Th. intermedium* and similarly four hybrids out of eight for *Th. ponticum* showed a positive BPH indicating a lower possibility to obtain a hybrid vigor in TKW compared to PH in perennial wheat hybrids.

For GNS, similar to TKW there was no clear difference between the hybrids from different sources (Figure 3c). The highest GNS values were observed from 12 × 5 (73.8) and 1 × 19 (89.5) hybrids for *Th. intermedium* and *Th. ponticum* groups respectively. On the other hand 12 × 10 from *Th. intermedium* and 3 × 20 from *Th. ponticum* groups showed the lowest GNS values of 19.9 and 22.2 respectively. Notably, most of the hybrids in both groups didn't show a positive BPH for GNS trait. For *Th. intermedium* × *Th. intermedium* hybrids, only three combinations out of 15 showed a positive BPH. Similarly for the *Th. ponticum* group, five combinations out of eight showed positive BPH values.

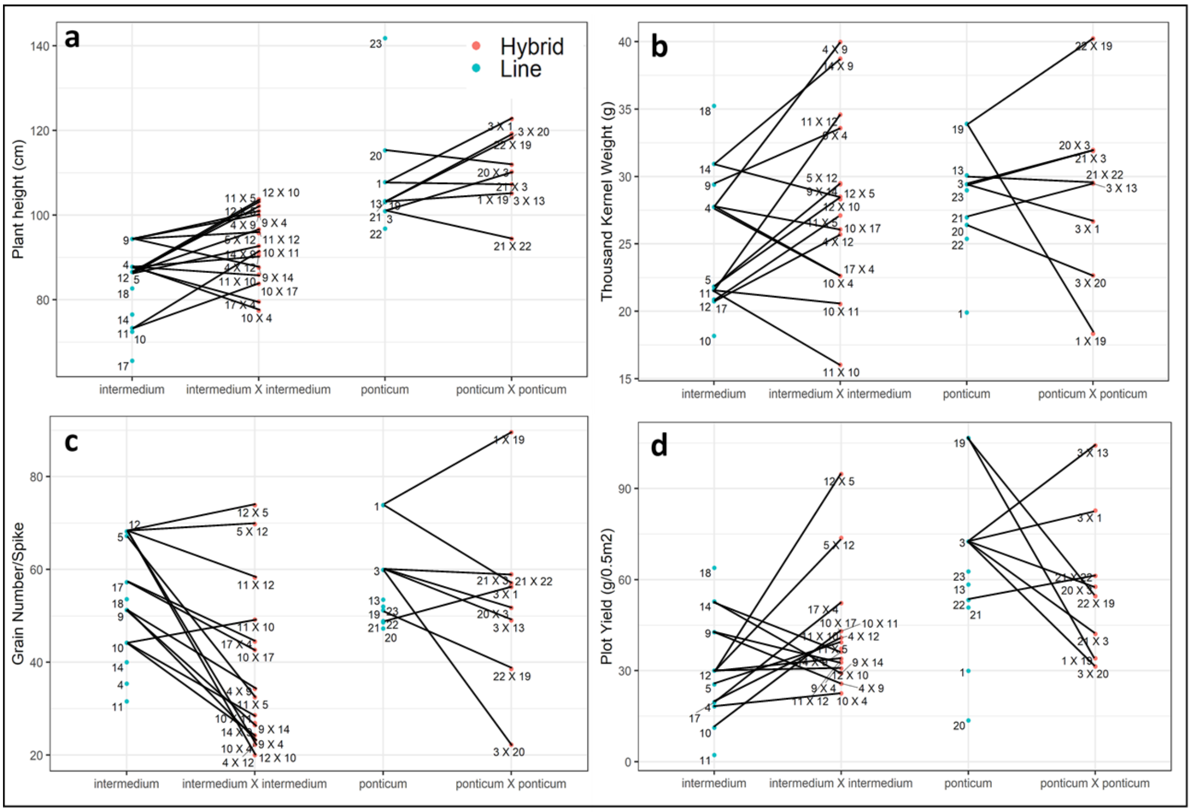

Figure 3. The comparison of perennial wheat lines and their hybrids for the species of *Th. intermedium* and *Th. ponticum* separately. Each dot represents an individual genotype with its label. Blue colour represents the lines (parents) and red for the hybrids obtained from these lines. The stripes connecting two genotypes are in between the hybrid and its superior parent representing the magnitude of the better parent heterosis.

Plot yield values of the F_1 hybrids and their parents are shown in Figure 5d. Overall, the *Th. ponticum* × *Th. ponticum* hybrids had a higher PY mean (58.5 g $0.5m^{-2}$) than the *Th. intermedium* × *Th. intermedium* hybrids (42.2 g $0.5m^{-2}$). The 12 × 5 (94.7 g $0.5m^{-2}$) hybrid combination in *Th. intermedium* group had the highest yield value as it was for GNS. On the other hand lowest plot yield was observed for 10 × 4 cross (22.54 g $0.5m^{-2}$). For *Th. ponticum* hybrids, the highest and lowest PY values were obtained from the hybrids 3 × 13 (104.1 g $0.5m^{-2}$) and 3 × 20 (31.3 g $0.5m^{-2}$) respectively. Nine hybrids out of 15 in *Th. intermedium* group and three hybrids out of eight in *Th. ponticum* group showed positive BPH values.

Discussion

This study investigated the agronomic performances of perennial wheat lines and their F_1 hybrids derived from various derivatives of *Thinopyrum spp*., focusing on four key agronomical traits as PH, TKW, GNS, and PY. The H^2 values exceed 0.50 for all traits. Previous research stated that traits with high heritability are often more amenable to selection, particularly in the context of wheat breeding (Gashaw et al., 2011). Furthermore, high H^2 values in this study highlight the predominance of genetic variance over environmental influences, with PH showing the highest heritability at 0.93. This aligns with findings in other crops, where high heritability is often associated with traits that are primarily controlled by genetic factors (Khan, 2022; Wu et al., 2019). The relatively lower heritability of PY (0.65) suggests that while genetic factors play a role, environmental interactions may also significantly affect yield outcomes in perennial wheat genotypes, as noted in other study conducted by Akbarpour et al. (2015) in bread wheat.

The significant variation in PH among the perennial wheat genotypes, especially with G23 sourced from *Th. ponticum* exhibiting the tallest PH which underscores the potential of utilizing diverse genetic resources to enhance specific agronomic traits. This finding aligns with previous research that emphasizes the importance of genetic diversity in breeding programs aimed at improving crop characteristics (DeHaan et al., 2018). The commercial bread wheat checks had relatively lower PH values than *Thinopyrum spp*. species. This result is parallel with the research conducted by

Coleman et al. (2010) indicated that perennial grasses, including perennial wheat, can produce higher dry matter yields than annual wheat in certain conditions.

In terms of yield-related traits, the commercial check cultivars, cv. BAS and cv. MAS, performed consistently better than perennial wheat lines. In parallel to our results, Morgan et al. (2023) found that the grain yield of perennial wheat lines ranged from 50% to 70% of the annual control check. The superior performance of these checks highlights their established genetic backgrounds. On the other hand, it was indicated that perennial wheat is still under development, and there is ongoing research on its agronomic performance to reach the yield performance of commercial wheat cultivars (Morgan et al., 2023). For TKW, The presence of G18 and G19 in the same statistical group as the commercial checks indicates that these perennial wheat lines could be promising candidates for breeding programs aimed at improving yield potential. The significant genotype-by-environment (G × E) interactions observed GNS in perennial wheat lines highlight the complexity of breeding for stability in this trait across varying growing conditions. This complexity can confound the selection process, as the ranking of genotypes may change depending on the environmental conditions experienced during growth (Khazratkulova et al., 2015).

The PY results further support the notion that *Th. ponticum* derivatives generally outperformed those from *Th. intermedium*, especially in the first year. In parallel with our results, Hayes et al. (2018) showed that genotypes derived from *Th. ponticum* often exhibit enhanced vigor and biomass accumulation compared to those from other *Thinopyrum* species, such as *Th. intermedium* in lower latitude sites. This separation in performance may be attributed to inherent genetic differences between the species, as noted in other studies focusing on the agronomic characteristics of perennial wheat (Liu et al., 2023; DeHaan et al., 2018).

Singh et al. (2021) emphasize that hybrid in bread wheat breeding programs can effectively exploit hybrid vigor to develop high-yielding varieties. In the context of perennial wheat, the ability to harness heterosis could lead to significant improvements in yield, which is essential for meeting global food demands. The analysis of BPH among hybrids indicates a potential for hybrid vigor, particularly in PH, although the results for TKW and GNS were less conclusive. The presence of positive BPH in a majority of the F_1 hybrids suggests that there is room for improvement through hybridization, which could lead to enhanced performance in subsequent generation. However, the lack of clear superiority among hybrid groups for TKW and GNS indicates that further research is needed to optimize hybrid combinations for these traits.

Conclusion

In conclusion, this study provides valuable insights into the agronomic performance of perennial wheat lines and their F_1 hybrids derived from *Thinopyrum spp.* The H^2 observed for traits such as PH and TKW underscores the significant influence of genetic factors, suggesting that these traits are suitable for selection in breeding programs. The variability in PH, particularly the notable performance of G23 from *Th. ponticum*, demonstrates the potential for utilizing genetic diversity to enhance specific traits. The high TKW and PY performance of certain perennial wheat genotypes, such as G18 and G19, further indicates promising candidates for future breeding efforts focused on yield improvement. The yield performance results showed the slight yield advantage of *Th. ponticum* derivatives over *Th. intermedium* under Mediterranean climate conditions. Continued research focusing on hybrid optimization, and stability across environments is essential to advance perennial wheat breeding and meet the demands of sustainable agriculture.

Acknowledgment

This study is a part of the master thesis of Burcu Gökbulut.

Researchers' Contribution Declaration

The authors declare that they have contributed equally to the article.

Conflict of Interest Declaration

The authors of the article declare that there is no conflict of interest between them.

References

Abbasi, J., Dehghani, H., Dvořák, J., McGuire, P., 2020. Perennial growth and salinity tolerance in wheat × wheatgrass amphiploids varying in the ratio of wheat to wheatgrass genomes. Plant Breeding. 139(6): 1281-1289.

Akbarpour, O., Dehghani, H., Rousta, M., 2015. Evaluation of salt stress of Iranian wheat germplasm under field conditions. Crop and Pasture Science. 66(8): 770-781.

Bell, L., Wade, L., Ewing, M., 2010. Perennial wheat: A review of environmental and agronomic prospects for development in Australia. Crop and Pasture Science. 61(9): 679-690.

Cassman, K., Connor, D., 2022. Progress towards perennial grains for prairies and plains. Outlook on Agriculture. 51(1): 32-38.

Coleman, S. W., Rao, S. C., Volesky, J. D., Phillips, W. A., 2010. Growth and nutritive value of perennial C3 grasses in the southern Great Plains. Crop Science. 50(3): 1070-1078.

DeHaan, L., Christians, M., Crain, J., Poland, J., 2018. Development and evolution of an intermediate wheatgrass domestication program. Sustainability. 10(5): 1499.

Erenstein, O., Poole, N., Donovan, J., 2022. Role of staple cereals in human nutrition: Separating the wheat from the chaff in the infodemics age. Trends in Food Science and Technology. 119: 508-513.

Gashaw, A., Mohammed, H., Singh, H., 2011. Genotypic variability, heritability, genetic advance and associations among characters in Ethiopian durum wheat (*Triticum durum Desf.)* accessions. East African Journal of Sciences. 4(1): 27-33.

Glover, J. D., Reganold, J. P., Bell, L. W., Borevitz, J., Brummer, E. C., Buckler, E. S., Cox, C.M., Crews T.E., Culman, S.W., Dehaan, L.R., Eriksson, D., Gill, B. S., Holland, J., Hu, F., Hulke, B. S., Ibrahim, A.M. H., Jakson, W., Jones, S. S., Murray, S. C., Paterson A.H., Ploschuk, E., Sacks, E. J., Snapp, S., Tao, D., Van Tassel, D. L., Wade, L. J., Wyse, D. L., Xu, Y., 2010. Increased food and ecosystem security via perennial grains. Science. 328(5986): 1638-1639.

Hayes, R. C., Wang, S., Newell, M. T., Turner, K., Larsen, J., Gazza, L., Anderson, J. A., Bell, L. W., Cattani, D. J., Frels, K., Galassi, E., Morgounov, A. I., Revell, C. K., Thapa, D. B., Sacks, E. J., Sameri, M., Wade, L. J., Westerbergh, A., Shamanin, V., Amanov, A., Li, G., 2018. The performance of early-generation perennial winter cereals at 21 sites across four continents. Sustainability. 10(4): 1124.

Jaikumar, N., Snapp, S., Murphy, K., Jones, S., 2012. Agronomic assessment of perennial wheat and perennial rye as cereal crops. Agronomy Journal. 104(6): 1716-1726.

Kane, D., Rogé, P., Snapp, S., 2016. A systematic review of perennial staple crops literature using topic modeling and bibliometric analysis. Plos One. 11(5): e0155788.

Khan, M., 2022. Devising selection strategy for increase in sesame yield based on variability heritability and genetic advance studies. Pure and Applied Biology. 11(1).

Khazratkulova, S., Sharma, R. C., Amanov, A., Ziyadullaev, Z., Amanov, O., Alikulov, S., Ziyaev, Z., Muzafarova, D., 2015. Genotype × environment interaction and stability of grain yield and selected quality traits in winter wheat in Central Asia. Turkish Journal of Agriculture and Forestry. 39: 920-929.

Kurmanbayeva, M., 2024. Anatomical and morphological features, and productivity of six perennial wheat varieties in the agroecological conditions of the Almaty region, Kazakhstan. Bio Web of Conferences. 100: 04048.

Liu Y., Song W., Song A., Wu C., Ding J., Yu X., Song J., Liu M., Yang X., Jiang C., Zhao H., Li X., Cui L., Li H., Zhang Y., 2023. Hybridization domestication and molecular cytogenetic characterization of new germplasm of Thinopyrum intermedium with SMGISH at Northeastern China. Research Square.

Morgan, R., Danilova, T., Newell, M., Cai, X., Jones, S., 2023. Agronomic evaluation and molecular cytogenetic characterization of Triticum aestivum × Thinopyrum spp. derivative breeding lines presenting perennial growth habits. Plants. 12(18): 3217.

Murphy, K. M., Hoagland, L., Reeves, P. G., Baik, B., Jones, S. S., 2009. Nutritional and quality characteristics expressed in 31 perennial wheat breeding lines. Renewable Agriculture and Food Systems. 24(4): 285-292.

Newell, M., Hayes, R., 2017. An initial investigation of forage production and feed quality of perennial wheat derivatives. Crop and Pasture Science. 68(12): 1141.

Pogna N, Galassi E, Ciccoritti R, De Stefanis E, Sgrulletta D, Cacciatori P, Gazza L, Bozzini A. 2014. Evaluation of nine perennial wheat derivatives grown in Italy. In: C Batello, L Wade, S Cox, N Pogna, A Bozzini, J Choptiany, eds. Perennial crops for food security – Proceedings of the FAO expert workshop. Rome, Italy: FAO, 54–71.

Ryan, M., Crews, T., Culman, S., DeHaan, L., Hayes, R., Jungers, J., Bakker, M. G., 2018. Managing for multifunctionality in perennial grain crops. Bioscience. 68(4): 294-304.

Singh, M., Albertsen, M., Cigan, A., 2021. Male fertility genes in bread wheat (Triticum aestivum L.) and their utilization for hybrid seed production. International Journal of Molecular Sciences. 22(15): 8157.

Turner, M., DeHaan, L., Jin, Y., Anderson, J., 2013. Wheatgrass–wheat partial amphiploids as a novel source of stem rust and fusarium head blight resistance. Crop Science. 53(5): 1994-2005.
Tyl, C., Ismail, B., 2018. Compositional evaluation of perennial wheatgrass (Thinopyrum intermedium) breeding populations. International Journal of Food Science and Technology. 54(3): 660-669.
Wickham, H., ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York, 2016.
Wu, X., Liang, S., Byrne, D., 2019. Heritability of plant architecture in diploid roses (Rosa spp.). HortScience. 54(2): 236-239.