

Comparison of conventional and speed breeding systems for wheat and barley based on growth stages

Merve Bayhan¹*, Remzi Özkan², Levent Yorulmaz¹, Ahmet Can Akinci¹ and Mehmet Yildirim¹

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Abstract: Conventional and speed breeding experiments were conducted in a polycarbonate-enclosed greenhouse at the Faculty of Agriculture, Dicle University, Turkey. The objective was to evaluate the potential of speed breeding systems to shorten the crop breeding process and enhance the efficiency of breeding programs by examining their effects on wheat and barley genotypes. The responses of four bread wheat, four durum wheat, and five barley genotypes under speed breeding conditions were measured according to the Zadoks scale. Results revealed that durum wheat completed its vegetative phase the quickest, followed by barley and bread wheat. Under speed breeding conditions, the number of growth cycles achievable per year was 4.13 for bread wheat, 4.26 for barley, and 4.64 for durum wheat. Thus, the time required to obtain viable seeds in these three cereal species was reduced by an average of 37%. In obtaining viable seeds, barley showed the fastest growth rate.

Keywords: Speed breeding, Zadoks scale, generation, cereal

INTRODUCTION

The rapidly evolving threat of climate change and emerging pests has underscored the need for innovative approaches to crop breeding (Hickey et al. 2017). Speed breeding has been proposed as an important technique for accelerating genetic progress and food production by dramatically shortening the time required for crops to mature (Pandey et al. 2022). Reducing the duration of the breeding cycle is widely recognized as one of the most straightforward methods for enhancing genetic gain (Atlin et al. 2017). Speed breeding has emerged as a highly effective approach for controlling environmental factors, making it suitable for both short- and long-day crops. Its adaptability allows speed breeding to be employed year-round, allowing multiple generations annually.

Extensive research on the response of crops to constant light has been conducted. Notable early experiments were conducted by NASA in the 1980s, in which crops such as wheat, soybean, lettuce, and potato were grown under constant light. These studies found that biomass production is closely linked to light availability. Later research explored the effects of continuous light and developed techniques to shorten crop generation time (O'Connor et al. 2013). Building on these findings, Watson et al. (2018) introduced the concept of "speed breeding," which extends photoperiods to accelerate the generation time of long-day crops, achieving up to six generations per year for species such

***Corresponding author:**
E-mail: merveybayhan21@gmail.com

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¹ Dicle University, Fetih, Dicle Üniversitesi
Rektörlüğü, 21280 Sur/Diyarbakır, Turkey

² Hakkari University, Yüksekova VHS, 30300
Yüksekova, Hakkari, Türkiye

as wheat and barley. Recent advancements by Jähne et al. (2020) and Liu et al. (2022) have extended speed breeding to short-day crops, including soybean, rice, amaranth, and hot peppers, with mixed results depending on crop-specific conditions, such as light intensity and photoperiod. However, further research is needed to optimize the speed breeding in greenhouse settings and fully understand the genetic and molecular mechanisms involved in this technique.

This study investigates how speed breeding techniques, utilizing an extended photoperiod, affect the growth stages and overall development time of wheat and barley genotypes. The ultimate goal is to determine if speed breeding can effectively shorten breeding cycles and enhance the efficiency of developing improved varieties in these crops.

MATERIAL AND METHODS

This study was conducted in 2020 in a single polycarbonate-covered greenhouse at the Faculty of Agriculture, Dicle University (lat 37° 53' 20" N, long 40° 16' 21" E), Turkey, to evaluate the growth stages of four durum (*Triticum durum*), four bread wheat (*Triticum aestivum*), and five barley (*Hordeum vulgare*) genotypes under speed breeding and control conditions (Table 1). Both the speed breeding and control groups were grown in the same greenhouse to ensure consistent environmental conditions. Temperature, humidity, drip irrigation, and fertilization were kept identical for both groups, isolating the light conditions as the only variable. The temperature was maintained at 18 ± 2 °C using air conditioners and water-ventilated cooling systems. The only difference between the groups was the photoperiod and light spectrum. The control group was grown under natural daylight, which varied seasonally, whereas the speed breeding group received natural light supplemented with artificial lighting to maintain a 22-hour photoperiod. Artificial light was supplied by strip LEDs (316.15 μmol m² s⁻¹) emitting red, yellow, blue, and purple spectra positioned 20 cm above the plants. The dark period for the speed breeding group was set between 00:00 and 02:00.

In April 2022, seeds of each genotype were sown in pots (17.5 × 17.5 × 25 cm) using a randomized plot design with four replications, ensuring four plants per pot. There were no weed or disease problems during the development of the wheat plants. Chemical control with deltamethrin was applied once during the emergence period to control insects. The experimental soil was characterized by low organic matter and an alkaline, clayey texture (Table 2).

Temperature and humidity were monitored daily using a Trotec BL30 data logger, with averages of 17.3 °C and 47.2% under speed breeding conditions. The cumulative growing degree days (°C) from sowing to harvest were 1283 °C for durum wheat, 1428 °C for bread wheat, and 1395 °C for barley (Figure 1). Drip irrigation maintained soil moisture near field capacity until heading, after which it gradually decreased to accelerate grain filling. The fertilization program supplied 1600 kg ha⁻¹ nitrogen and 80 kg ha⁻¹ phosphorus in six applications (Sowing, two leaves, tillering, stem elongation, heading and anthesis stages). The composite fertilizer was applied in two parts until the tillering period, while the urea fertilizer was applied in four equal parts until the flowering period. Both fertilizers were diluted with water, with the composite fertilizer (20-20-0) at a rate of 0.36 g per 100 mL and urea (46%) at 0.15 g per 100 mL. Wheat and barley growth stages

Table 1. Genotypes tested under speed breeding conditions

	Genotype	Breeding organization	Heading time (days)	varieties	References	
Triticum durum	Firat-93	GAP Agricultural Research Center	146.00	Mid-early	Spring	Özkan (2024)
	Gündaş	GAP Agricultural Research Center	145.60	Mid-early	Spring	Özkan (2024)
	Hasanbey	GAP Agricultural Research Center	145.50	Mid-early	Spring	Özkan (2024)
	Hat-300	Dicle University Faculty of Agriculture	149.62	Mid-early	Alternative	Özkan (2024)
Triticum aestivum	Empire	Teknobiltar	147.25	Early	Spring	Bayhan (2024)
	Ceyhan-99	Eastern Mediterranean Agricultural Research Institute	146.50	Mid-early	Spring	Bayhan (2024)
	Dinç	GAP Agricultural Research Center	145.75	Early	Spring	Bayhan (2024)
	LOK-1	Dicle University Faculty of Agriculture	144.70	Early	Spring	Bayhan (2024)
Hordeum vulgare	Barış	GAP Agricultural Research Center	137.25	Mid-early	Spring	Bayram et al. (2023)
	Kendal	GAP Agricultural Research Center	132.75	Mid-late	Spring	Bayram et al. (2023)
	Önder	Dicle University Faculty of Agriculture	133.75	Mid-late	Alternative	Dogan and Yildirim (2024)
	Keçiburcu	Dicle University Faculty of Agriculture	132.75	Early	Spring	Dogan and Yildirim (2024)
	TBT16-14	Dicle University Faculty of Agriculture	133.00	Early	Spring	Dogan and Yildirim (2024)

*The data are under field conditions, and the varieties were grown in a conventional way.

(seedling, tillering, stem elongation, booting, heading, milk, and maturity) were recorded under both speed breeding and control conditions using the Zadoks scale (Zadoks et al. 1974). The formula for the growth rate differences of barley, bread wheat, and durum wheat:

$$GRD (\%) = \frac{CC}{SB} = \frac{GS2 - GS1}{GS2 - GS1} \times 100$$

GRD: Growth rate differences (%) between speed breeding (SB) and control conditions (CC), showing how much faster plants grew under SB at the same stages. GS1 and GS2: days after sowing at the first and second growth stages, respectively.

One-way analysis of variance was conducted using the JMP 13.0 Pro package program (Jones and Sall 2011). The least significant difference (LSD) was used to evaluate the differences between genotype means for the recorded traits. The significance levels used in the study were $p < 0.01$ and $p < 0.05$.

Table 2. Physical and chemical traits of the soil sample used in the experiment

Analysis name	Results	
Saturation (%)	63.00	Clay Loam
Salinity (Saturation Sludge) (dS/m)	0.92	No salt
% Salt (With Calculation) TS 8334	0.04	No salt
pH (Saturation Sludge)	8.11	Slightly Alkaline
Lime (Calcimetric) (%)	11.24	Medium
Organic Matter (Walkley Black) (%)	0.71	Low
Nitrogen (by Calculation) (%)	0.04	Low
Phosphorus (Olsen Spectrometer) (ppm)	4.00	Low
Potassium (A. Acetate-ICP) (ppm)	314.45	high
Calcium (A. Acetate-ICP) (ppm)	10717.89	Very high
Magnesium (A. Acetate-ICP) (ppm)	471.78	Medium
Sodium (A. Acetate-ICP) (ppm)	26.65	Low
Iron (DTPA-ICP) (ppm)	9.29	Very high
Copper (DTPA-ICP) (ppm)	1.61	Medium
Manganese (DTPA-ICP) (ppm)	16.50	Medium
Zinc (DTPA-ICP) (ppm)	0.08	Low

RESULTS AND DISCUSSION

The cumulative growing degree days from sowing to 15 days after anthesis for durum wheat, bread wheat, and barley under speed breeding conditions were 1283, 1428, and 1395, respectively. Under speed breeding conditions, durum wheat exhibited the shortest vegetative period, followed by barley and bread wheat (Table 4, Figures 1 and 3). Harvesting in the speed breeding system occurs approximately 15 days after anthesis (Ghosh et al. 2018). This study showed that speed breeding enables multiple growth cycles within a single year. Specifically, harvesting 20 days after heading permits 4.13 cycles of bread wheat, 4.26 cycles of barley, and 4.64 cycles of durum wheat annually. (Table 4).

The differences in growth rates of cereal varieties under speed breeding conditions were compared to the control conditions (Figure 2). In all three cereal species, the growth pattern under speed breeding conditions generally followed a linear curve, whereas it exhibited a quadratic curve under control conditions. The responses to speed breeding, from most to least favorable, were ranked as barley, durum wheat, and bread wheat. The seedling stage in all three cereals occurred 1.3 times faster under speed breeding conditions than under control conditions (Table 3).

During the tillering stage, bread wheat maintained a growth rate approximately 1.3 times faster, while slower growth rates were observed for durum wheat (1.19) and barley (1.13). The stem elongation stage exhibited a sharp increase in the growth rate, reaching 5.17 times for barley, 2.75 times for bread wheat, and 2.91 times for durum wheat (Figure 3). At this stage, barley grew significantly faster than the other two wheat species. In all three cereals, the growth rate peaked during the stem elongation stage compared with the control conditions. During the heading stage, barley had a slightly increased growth rate, bread wheat slowed down, and durum wheat showed a noticeable decline. During the milk development stage, the growth rate of bread wheat increased, whereas it continued to decrease in the other cereals. After the milk development stage, the growth rate slowed for all three cereals. At this stage, the differences in the growth rate of barley, bread wheat, and durum wheat were 0.55, 0.74, and 0.88, respectively (Table 4).

On average, barley genotypes headed in 65.6 days and reached the milk stage, the harvest point in speed breeding, in 81.1 days. The average time taken to reach physiological maturity was 98.1 days. Under speed breeding conditions, barley genotypes reached the heading, milk, and physiological maturity stages 58.5, 62.5, and 54.9 days earlier, respectively, compared to control growing conditions. Overall, speed breeding under greenhouse conditions reduced the growth cycle of barley genotypes by an average of 60 days (Table 4).

Significant differences in growth rate emerged among the barley genotypes starting from the stem elongation stage and persisted until physiological maturity (Figure 3). The variation in the growth rate of barley genotypes under speed

breeding was quite high. For instance, despite having the same heading date under control conditions, the Barış, Kendal, and TBT16-14 genotypes showed a difference of 25 days in heading time under speed breeding (Table 4). This difference can be explained by the fact that different genetic mechanisms govern early anthesis under speed breeding or reflect a negative response to full photoperiodism. In general, bread and durum wheat genotypes did not show such sharp differences in response to speed breeding as the barley genotypes.

Every crop responded differently under speed breeding conditions, emphasizing the extent that genotype can affect developmental timing. Table 4 shows that, under controlled conditions, the barley varieties Kendal and Barış grew at

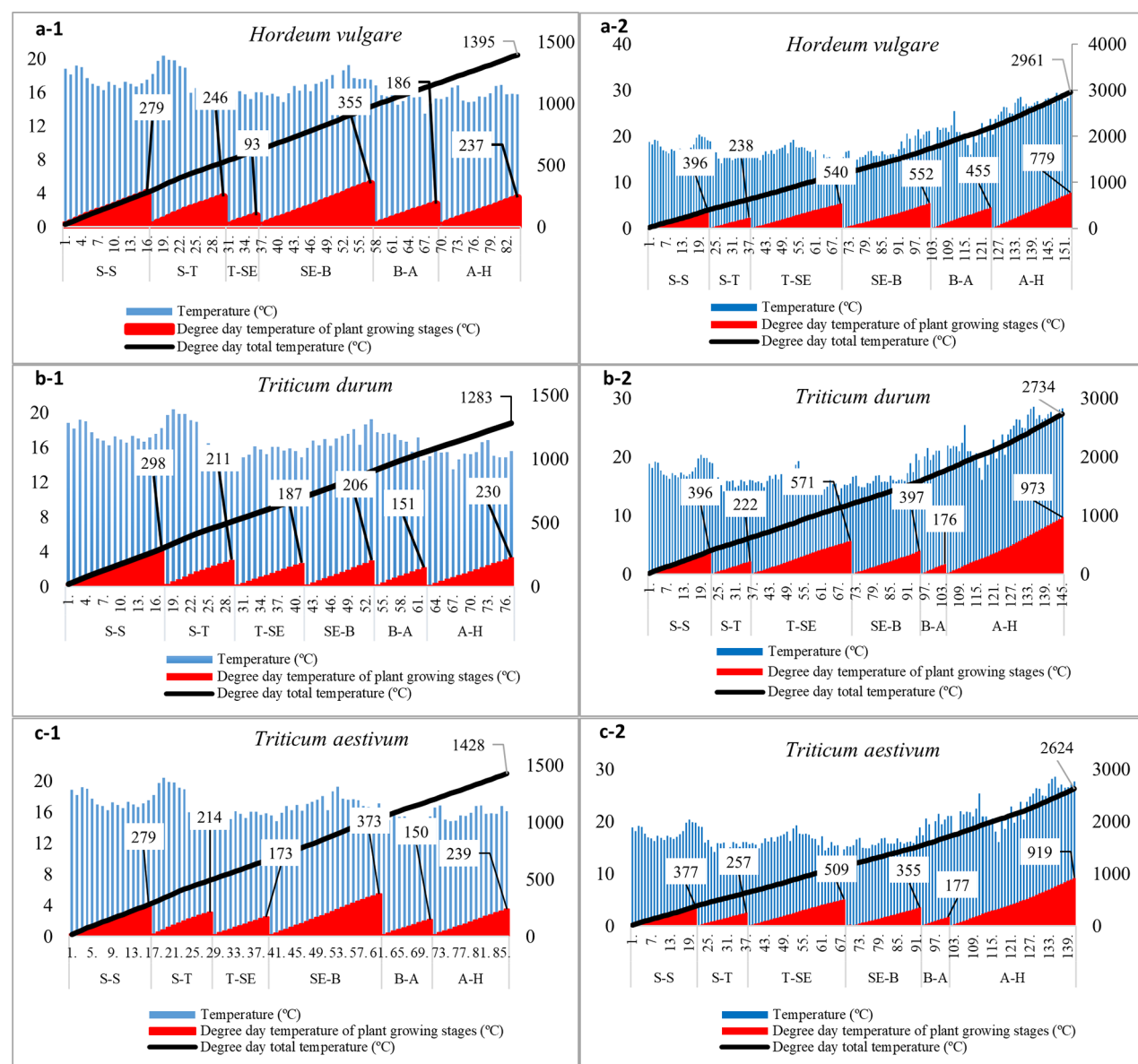


Figure 1. Daily average temperature at greenhouse and average growing degree-day temperature of genotypes from sowing to physiological maturity. $DDT = \sum [((T_{max} + T_{min}) / 2) - T_{base}]$ (Berti and Johnson 2008), T_{max} and T_{min} are daily maximum and minimum air temperatures in degrees centigrade, respectively. T_{base} is the 0 °C base temperature for mustard development (Stannard et al. 2000). S-S: Sowing-Seedling, S-T: Seedling-Tillering, T-SE: Tillering-Stem Elongation, SE-B: Stem Elongation-Booting, B-A: Booting-Anthesis, A-H: Anthesis-Harvesting.

similar times - about 121 days. However, Kendal matured later (83.5 days) than Barış (68.8 days) during speed breeding. The 14.7-day difference shows how speed breeding can improve small genetic variations in flowering time.

The response of bread wheat varied. For instance, under both control and speed breeding conditions, the variety Empire routinely reached the seedling stage earlier - mean of 17.9 days - than Ceyhan-99 (mean of 19.8 days) (Table 3). This difference continued during the booting process; Empire reached maturity in 79.3 days while Ceyhan-99 took 83.8 days. Thus, Empire naturally requires a shorter growing time, independent of the farming conditions.

Although durum wheat genotypes showed less variation in their overall developmental timing, differences can still be observed. For example, Hasanbey clearly reached the stem elongation stage later than other durum wheat genotypes (Table 3). The differences in reaction to speed breeding draw attention to the need to consider genotypic variation in breeding programs since various types may respond differently to changed environmental conditions, thereby influencing the effectiveness of speed breeding for certain breeding goals.

In bread wheat genotypes, differences in growth rates were observed during the stem elongation and booting stages under speed breeding conditions. However, no significant differences were observed among the genotypes during the heading and milk stages. Under control conditions, bread wheat genotypes headed 3.2 days earlier than durum wheat genotypes. In contrast, under speed breeding conditions, bread wheat genotypes headed 9.5 days later (Table 4 and Figure 3). This suggests that certain mechanisms may be activated in bread wheat that prevent a positive response to maximum day length. On the other hand, no significant differences were observed among durum wheat genotypes under either control or speed breeding conditions throughout all growth stages.

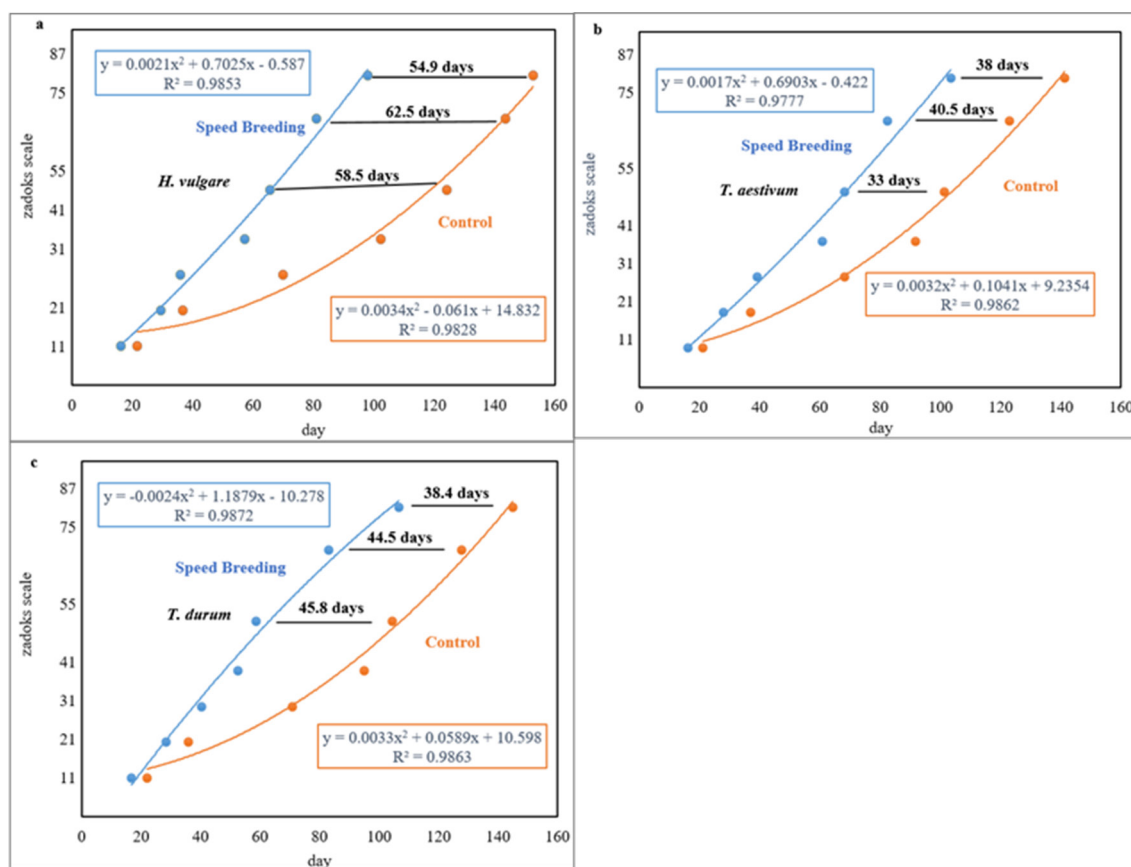


Figure 2. Growth curves of barley (a), bread wheat (b), and durum wheat (c) under speed breeding and control growing conditions by regression and differences in flowering, milking, and physiological maturity periods in days.

In similar studies, Ghosh et al. (2018) determined the anthesis time as 49.6 ± 5.0 days for bread wheat, 46 ± 1.9 days for durum wheat, and 38.4 ± 13.9 days for barley. Similarly, Watson et al. (2018) found the anthesis time to be 38.1 days for bread wheat, 35.7 days for durum wheat, and 37.5 days for barley. Özkan et al. (2022) reported the anthesis time of durum wheat under speed breeding conditions as 53.38 days. Bayhan et al. (2022), in a study aimed at optimizing the speed breeding technique, highlighted that applying gradual water restriction significantly shortened the vegetative period compared to field capacity water conditions, and that breaking seed dormancy before sowing greatly increased germination rates. Furthermore, they found that gradual water restriction induced water stress in plants, shortening

Table 3. Mean duration (days) of seedling, tillering, stem elongation, and booting growth stages for individual genotypes of barley, bread wheat, and durum wheat under control and speed breeding

Genotype	Seedling				Tillering			Stem Elongation				Booting									
	Cont.	SB	Mean		Cont.	SB	Mean	Cont.	SB	Mean		Cont.	SB	Mean							
H. vulgare	Barış	20.8	15.8	18.3	36.5	27.3	31.9	70.0	35.0	52.5	104.8	a	59.5	d	82.1	b					
	Keçiburcu	22.5	16.8	19.6	35.5	30.5	33.0	69.8	36.3	53.0	96.5	b	51.5	e	74.0	c					
	Kendal	21.8	16.0	18.9	36.5	30.3	33.4	69.8	35.8	52.8	104.0	a	75.0	c	89.5	a					
	ÖNDER	21.8	16.0	18.9	37.5	29.3	33.4	69.8	36.3	53.0	103.3	a	48.0	e	75.6	c					
	TBT16-14	21.8	16.3	19.0	37.5	30.0	33.8	69.8	36.0	52.9	103.3	a	51.5	e	77.4	c					
	Mean	21.7	a	16.15	b	18.9	36.7	a	29.45	b	33.1	69.8	a	35.85	b	52.8	102.35	a	57.10	b	79.7
	CV (%)	5.07	3.96	5.4	8.56	6.42	7.5	0.80	2.90	1.6	2.80	5.51	4.4								
T. aestivum	Ceyhan99	22.8	16.8	19.8	38.0	29.0	33.5	71.5	a	39.8	c	55.6	a	99.5	ab	68.0	cd	83.8	a		
	Dinç	21.8	16.5	19.1	36.3	27.8	32.0	70.5	a	39.0	c	54.8	a	101.5	a	64.0	d	82.8	ab		
	Empire	19.3	16.5	17.9	35.8	28.0	31.9	70.3	a	39.5	c	54.5	a	95.0	b	63.5	d	79.3	b		
	LOK-1	21.0	15.3	18.1	38.0	27.3	32.6	60.3	b	38.8	c	49.9	b	71.0	c	48.0	e	59.5	c		
	Mean	21.2	16.3	18.7	37.0	28.0	32.5	68.1	39.3	53.7	91.8	60.9	76.3								
	CV (%)	12.83	5.37	11.1	6.88	3.03	7.1	0.69	4.40	2.5	3.05	6.26	4.8								
	T. durum	Fırat-93	20.8	16.3	18.5	c	35.5	27.5	31.5	b	70.3	38.8	54.5	b	95.8	50.0	72.9	bc			
Gündaş		22.5	17.3	19.9	ab	34.3	28.5	31.4	b	71.5	41.5	56.5	a	93.3	48.0	70.6	c				
Hasanbey		23.3	17.8	20.5	a	39.0	29.3	34.1	a	71.0	42.0	56.5	a	96.5	56.3	76.4	a				
Hat-300		22.0	15.8	18.9	bc	35.3	28.3	31.8	b	70.8	39.3	55.0	b	94.5	55.5	75.0	ab				
Mean		22.13	a	16.75	b	19.4	36.0	28.4	32.2	70.9	40.4	55.6	95.0	52.4	73.7						
CV (%)		8.28	8.96	6.1	6.41	5.81	5.3	1.20	4.66	2.5	3.88	5.97	4.1								

SB: Speed breeding; Cont: Control; CV: Coefficient of variation.

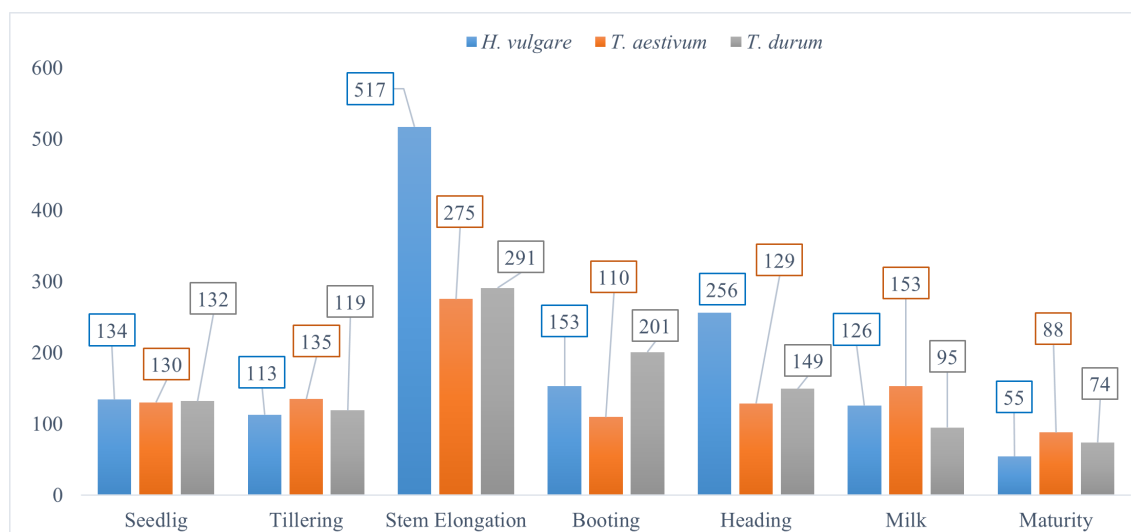


Figure 3. The difference (%) in growth rate of speed breeding compared to control conditions at growth stage.

Table 4. Mean duration (days) of the heading, milk, and maturity growth stages for individual genotypes of barley, bread wheat, and durum wheat under control and speed breeding

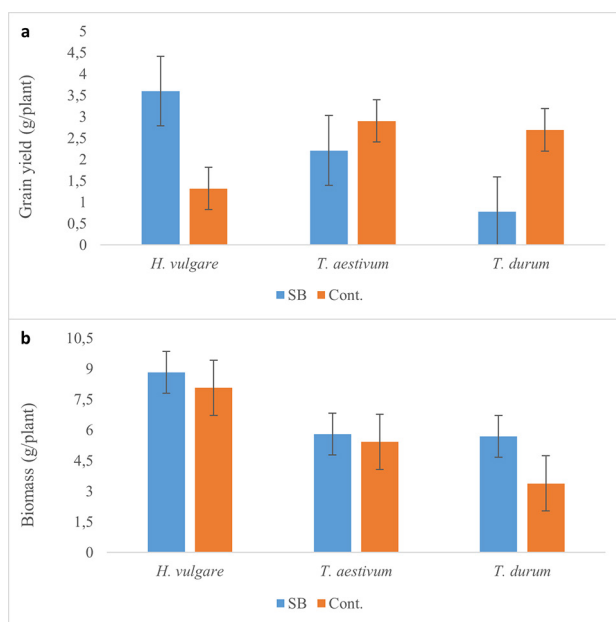
Genotype		Heading				Milk				Maturity			
		Cont.	SB	Mean		Cont.	SB	Mean		Cont.	SB	Mean	
<i>H. vulgare</i>	Bariş	123.8	ab	68.8	d	96.3	b	143.0	ab	87.5	d	115.3	a
	Keçiburcu	122.0	b	59.0	e	90.5	c	143.5	ab	75.3	e	109.4	b
	Kendal	122.3	ab	83.5	c	102.9	a	142.3	ab	94.8	c	118.5	a
	ÖNDER	130.0	a	58.3	e	94.1	bc	147.0	a	72.8	e	109.9	b
	TBT16-14	122.5	ab	58.5	e	90.5	c	142.0	b	75.0	e	108.5	b
	Mean	124.1	a	65.6	b	94.9		143.6	a	81.1	b	112.3	
	CV (%)	5.96		3.78		5.8		2.08		4.40		3.0	
<i>T. aestivum</i>	Ceyhan99	106.8		73.3		90.0	a	129.0		87.5		108.3	a
	Dinç	107.0		73.8		90.4	a	126.8		89.3		108.0	a
	Empire	106.0		71.8		88.9	a	124.0		86.8		105.4	a
	LOK-1	85.0		54.0		69.5	b	111.8		66.0		88.9	b
	Mean	101.2		68.2		84.7		122.9		82.4		102.6	
	CV (%)	2.77		6.55		3.7		4.61		4.74		5.1	
<i>T. durum</i>	Fırat-93	106.0		57.8		81.9		129.8		79.5		104.6	
	Gündaş	103.8		55.8		79.8		125.0		84.0		104.5	
	Hasanbey	104.0		61.3		82.6		129.8		86.3		108.0	
	Hat-300	104.0		60.0		82.0		126.3		83.0		104.6	
	Mean	104.4		58.7		81.6		127.7		83.2		105.4	
	CV (%)	3.57		4.09		3.5		5.94		6.01		6.3	

SB: Speed breeding; Cont: Control; CV: Coefficient of variation.

the generative period. Özer et al. (2019) demonstrated that extending the photoperiod and harvesting seeds earlier can shorten a generation to about 60 days. Özkan et al. (2022) also found the total growing degree days for durum wheat to be 1800.9 °C. In Mitache et al. (2024), six generations per year were achieved with an average generation cycle ranging from 62 to 76 days, demonstrating the effectiveness of speed breeding in reducing generation time.

Under speed breeding conditions, grain yield decreased in both bread and durum wheat, whereas a significant increase was observed in barley. Under these conditions, biomass increased in barley and bread wheat, whereas both biomass and grain yield decreased in durum wheat (Figure 4a and b). Yield loss in durum wheat is attributed to the negative impact of speed breeding on overall productivity. In barley, the reduced grain yield is associated with decreased biomass. When the daily photoperiod is extended, issues such as reduced vegetative growth and poor root development are observed (Watson et al. 2018, Hickey et al. 2019). Since the vegetative period is shortened under speed breeding conditions, plants are unable to absorb nutrients efficiently, which leads to poor growth (Özkan et al. 2025).

Light plays a crucial role in plant life by influencing photomorphogenesis, photosynthesis, and overall growth and development (Avercheva et al. 2009). Solar radiation, especially in the visible range (400–700 nm), affects plants in

**Figure 4.** Mean grain yield and biomass values for speed breeding and control conditions (SB: Speed Breeding; Cont.: Control).

various ways, including root growth, leaf width, and stem length (Zažímalová et al. 2014). Additionally, C3 plants such as wheat may experience reduced yields if exposed to high light intensity. Proper light intensity is essential for optimal wheat yield, and red light promotes wheat heading (Kasajima et al. 2006).

CONCLUSION

This study demonstrated the effectiveness of speed breeding for accelerating the growth and development of wheat and barley genotypes. By manipulating the photoperiod and temperature, a significant reduction in generation time was obtained for all three cereal types, making it a valuable tool for crop improvement programs. This study achieved a reduction in the time required to obtain viable seeds in three cereal species, with an average decrease of 37%. Barley exhibited the fastest growth rate under speed breeding conditions, followed by durum wheat and bread wheat.

The study also found that the growth pattern of all three cereals under speed breeding conditions followed a linear curve, while under control growing conditions, the growth pattern was quadratic. Following the flowering stage, the growth rate slowed compared to earlier stages.

These findings have significant implications for wheat and barley breeding. The ability to shorten the breeding cycle allows quicker accumulation of favorable genes, accelerating the development and release of improved varieties. Speed breeding enhances breeding efficiency by enabling more generations to be grown per year, increasing the rate of genetic gain, and ultimately contributing to food security. In conclusion, speed breeding presents a powerful tool for breeders to overcome temporal constraints, offering a pathway to accelerate crop improvement and more effectively meet the growing global demand for wheat and barley.

DATA AVAILABILITY

The datasets generated and/or analyzed during the current research are available from the corresponding author upon reasonable request.

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