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(RESEARCH ARTICLE)

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Grain yield of bread wheat germplasm under heat and drought stress during the crop season 2023-2024

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Abstract

Forty two advanced bread wheat lines and cultivars Borlaug 100 F2014 and CIANO M2018 were sown on January 15 and 30, 2024, at the Norman E. Borlaug Experimental Station, in the Yaqui Valley, Sonora, Mexico. Plots consisted of 1 bed 2 m long with two rows and 0.80 m apart with two replications, and a seed density of 100 kg ha^{-1} with two complementary irrigations. Average daily temperature (°C), maximum, minimum, relative humidity, rainfall, heat and cold units were recorded from January 15 to May 15, 2024. The average days for heading of the group was 61 for the first sowing date and 56 for the second one, while days for physiological maturity were 98 and 91, respectively. The average plant height of the group for the first date was 77 cm and 74 for the second one; three lines showed the highest average height with 83 cm. The average thousand grain weight was 46.3 g; the line REEDLING-GL5A_1/5/2*SOKOLL/3/PASTOR//HXL7573/2*BAU/4/MEX94.27.1.20/3/SOKOLL//ATTILA/3*BCN showed the highest average TGW with 53.5 g. The average grain yield per plot was 405 g; the line 68.111/RGB-U//WARD/3/AE.SQUARROSA(501)/7/SERI.1B*2/3/KAUZ*2/BOW//KAUZ/4/FRANCOLIN#1/5/MUNAL/6/KACHU#1/KIRITATI//KACHU/8/BORL14 showed the highest average yield with 480 g which corresponded to 6.0 t ha^{-1}, followed by four lines with 470 g (5.88 t ha^{-1}). The average hourly temperature was 18.6 °C with a maximum of 35.8 °C and a minimum of 2.5 °C, the average relative humidity was 61.0 %, there were 8.0 mm of precipitation, and the number of heat and cold units was 231 and 309, respectively.

Keywords: Wheat; *Triticum aestivum*; Grain yield; Drought stress; Heat stress

1. Introduction

In recent decades, increasingly severe heatwaves and drought have affected major wheat-producing regions worldwide, including Australia, Western Europe, Russia, United States, India, and Pakistan [1,2]. Heat stress is defined as an increase in temperature beyond a critical threshold for a sufficient duration to cause irreversible damage to plant growth and development [3,4]. High temperatures affect crops differently depending on their duration, intensity, and timing. In wheat, the reproductive stage is more sensitive to heat stress, as it directly influences grain number, weight, and quality. The degree of damage also varies by genotype [5,6]. A temperature increase of 10 °C during mid-anthesis can reduce grain number per spike by up to 40 % [7], while high temperatures during the grain-filling stage in winter cereal may

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decrease yield by 10 to 15 % [8,9]. Wheat is grown in tropical or subtropical regions [10] where the coolest month exceeds 17.5 °C, covering over 7 million hectares mainly in Southeast Asia, in India and Bangladesh [11], in Sub-Saharan Africa [12], and countries such as Brazil, Thailand, Uganda, Mexico, Sudan, Egypt, Nigeria, and Syria [13]. To meet the global food demand, especially in developing regions, wheat productivity must be improved across both favorable and marginal environments to sustain rising population needs [14]. The wheat plant has morphological, physiological, biochemical, and enzymatic adaptations to withstand heat stress, but further research is needed to enhance it genetic heat tolerance and overall resilience. Wheat consumption and importation by developing countries in the warmer regions are factors that lead to the increase of local wheat production [15]. Drought, caused by inadequate moisture to sustain normal plant growth, is a major stress reducing crop productivity. It leads to low water potential and cell dehydration, which in turn suppress cell division, leaf and stem growth, root development, and stomatal function, ultimately hindering overall plant growth and biomass production [16,17]. The United Nations Development Programme (UNDP) supported the International Maize and Wheat Improvement Center (CIMMYT) breeders by providing resources and institutional backing to expand research on high-yielding, disease-resistant, semi-dwarf wheat cultivars suited to warm, subtropical regions. This partnership accelerated the development and global distribution of improved cultivars, strengthening food security and modernizing wheat production in climate vulnerable areas [18]. The Stress Adaptive Trait Yield Nursery (SATYN) was established, comprising lines tailored for drought and heat-stressed environments, targeting major spring wheat-growing countries including Bangladesh, China, Egypt, India, Iran, Mexico, Nepal, and Pakistan [19]. The objective of this study was to assess the performance of a set of wheat lines from the 13th SATYN under late sowing conditions, which exposed the crop to a warmer, shorter growing season with limited irrigation.

2. Materials and methods

Forty two advanced bread wheat lines from the 13th Stress Adapted Trait Yield Nursery (SATYN), which included eight groups of sister lines (lines 2, 22, and 29; 3, 8, 15, 27, and 32; 4 and 23; 7 and 40; 11 and 25; 26 and 39; 28 and 42; 31 and 35) (Table 1), selected by the International Maize and Wheat Improvement Center´s wheat breeding for their tolerance to stress, were sown on January 15 and 30, 2024, at the Norman E. Borlaug Experimental Station (CENEB) which belongs to the National Institute for Forestry, Agriculture, and Livestock Research, located in block 910 in the Yaqui Valley, Sonora, Mexico (27º22´3.01" N and 109º55´40.22" W) in a clay soil with pH of 7.8. The commercial bread wheat cultivars Borlaug 100 F2014 [20] and CIANO M2018 [21] were used as checks. Cultivar CIANO M2018 showed an average of 1.58 y 6.27 % higher grain yields than Borlaug 100 F2014 under four and two complementary irrigations, respectively, over three cropping seasons at CENEB [21], and yielded 7.19, 3.25, and 4.90 % more under four complementary irrigations in trials conducted in the states of Sonora, Sinaloa, and Baja California, however, a separate study reported that Borlaug 100 F2014 outperformed CIANO M2018 by 1.47 ha^{-1} [22]

Table 1 Advanced bread wheat lines from the 13th Stress Adaptive Trait Yield Nursery from CIMMYT, sown on January 15 and 30, 2024, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico

No	Pedigree and selection history
1	SUP152/BAJ #1/3/KACHU #1/KIRITATI//KACHU/4/BORL14 PTSS19Y00258S-0M-0Y-099M-16Y-0B
2	SOKOLL/3/KACHU/SAUAL//CIRO16 PTSS19Y00313S-0M-0Y-099M-9Y-0B
3	SOKOLL/3/PASTOR//HXL7573/2*BAU/4/MEX94.27.1.20/3/SOKOLL//ATTILA /3*BCN/6/WBLL1*2/BRAMBLING//VORB/FISCAL/3/BECARD/4/MUCUY/5/MUCUY PTSS19Y00179S-0M-0Y-099M-2Y-0B
4	PRL/2*PASTOR//2*CIRO16/3/KUTZ PTSS19Y00198S-0M-0Y-099M-21Y-0B
5	BORLAUG100 F2014 CMSS06Y00605T-099TOPM-099Y-099ZTM-099Y-099M-11WGY-0B-0MEX
6	GARZA/BOY//AE.SQUARROSA(294)/4/2*SUP152/BAJ#1//TRCH/HUIRIVIS #1/3/SUP152/BAJ#1 PTSS20B00077T-099Y-0M-5Y-0B
7	SERI/BAV92//PUB94.15.1.12/WBLL1/3/BORL14

	PTSS19Y00217S-0M-0Y-099B-6Y-0B
8	SOKOLL/3/PASTOR//HXL7573/2*BAU/4/MEX94.27.1.20/3/SOKOLL//ATTILA/3*BCN/6/WBLL1*2/BRAMBLING//VORB/FISCAL/3/BECARD/4/MUCUY/5/MUCUY PTSS19Y00179S-0M-0Y-099M-4Y-0B
9	JNRB.5/PIFED/5/BJY/COC//PRL/BOW/3/SARA/THB//VEE/4/PIFED/6/BORL14 PTSS19Y00239S-0M-0Y-099B-34Y-0B
10	REEDLING-GL5A_1/5/2*SOKOLL/3/PASTOR//HXL7573/2*BAU/4/MEX94.27.1.20 /3/SOKOLL//ATTILA/3*BCN PTSS19B00020T-0Y-099M-15Y-0B
11	COPIO/5/UP2338*2/SHAMA/3/MILAN/KAUZ//CHIL/CHUM18/4/UP2338*2/SHAMA/6/KUTZ PTSS19Y00195S-0M-0Y-099M-3Y-0B
12	SOKOLL CMSS97M00316S-0P20M-0P20Y-43M-010Y
13	68.111/RGB-U//WARD/3/AE.SQUARROSA(501)/7/SERI.1B*2/3/KAUZ*2/BOW// KAUZ/4/FRANCOLIN #1/5/MUNAL/6/KACHU #1/KIRITATI//KACHU/8/BORL14 PTSS19B00030T-0Y-099M-17Y-0B
14	KACHU/SAUAL*2/5/SERI.1B//KAUZ/HEVO/3/AMAD*2/4/KIRITATI/6/SUP152/BAJ #1/3/KACHU #1/KIRITATI//KACHU PTSS19Y00240S-0M-0Y-099M-19Y-0B
15	SOKOLL/3/PASTOR//HXL7573/2*BAU/4/MEX94.27.1.20/3/SOKOLL//ATTILA/ 3*BCN/6/WBLL1*2/BRAMBLING//VORB/FISCAL/3/BECARD/4/MUCUY/5/MUCUY PTSS19Y00179S-0M-0Y-099M-13Y-0B
16	WBLL1//YANGLINGSHAANXI/ESDA/3/ROLF07/6/CETA/AE.SQUARROSA(435) /5/2*UP2338*2/SHAMA/3/MILAN/KAUZ//CHIL/CHUM18/4/UP2338*2/SHAMA PTSS20Y00272S-0B-099Y-099B-4Y-0B
17	PASTOR//HXL7573/2*BAU/3/ATTILA/3*BCN/4/NAVJ07/6/CROC_1/AE. SQUARROSA (205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2/5/CIRO16 PTSS19Y00276S-0M-0Y-099M-3Y-0B
18	CIANO M2018 CMSS12B00828T-099TOPY-099M-0SY-42M-0WGY
19	KACHU/SAUAL/4/VARIS/MISR2/3/FRET2/KUKUNA//FRET2/5/KACHU/SAUAL/6/MEX94.27.1.20/3/SOKOLL//ATTILA/3*BCN/4/PUB94.15.1.12/WBLL1 PTSS19Y00104S-0B-0Y-099M-50Y-0B
20	MEX94.27.1.20/3/SOKOLL//ATTILA/3*BCN/4/PUB94.15.1.12/WBLL1/5/BOKOTA/3/UP2338*2/KKTS*2/ /YANAC PTSS19Y00242S-0M-0Y-099B-39Y-0B
21	YAV79//DACK/RABI/3/SNIPE/4/AE.SQUARROSA(381)/5/2*SUP152/BAJ#1//TRCH/HUIRIVIS #1/3/SUP152/BAJ#1 PTSS20B00087T-099Y-0M-2Y-0B
22	SOKOLL/3/KACHU/SAUAL//CIRO16 PTSS19Y00313S-0M-0Y-099M-17Y-0B
23	PRL/2*PASTOR//2*CIRO16/3/KUTZ PTSS19Y00198S-0M-0Y-0B-16Y-0B
24	MEX94.27.1.20/3/SOKOLL//ATTILA/3*BCN/4/PUB94.15.1.12/WBLL1/5/MUCUY PTSS14Y00328S-0B-099Y-099B-19Y-020Y

25	COPIO/5/UP2338*2/SHAMA/3/MILAN/KAUZ//CHIL/CHUM18/4/UP2338*2/SHAMA/6/KUTZ PTSS19Y00195S-0M-0Y-099M-11Y-0B

26	WBLL4//OAX93.24.35/WBLL1/5/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/
	SARA//TSI/VEE#5/4/FRET2/6/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/
	SARA//TSI/VEE#5/4/FRET2/5/CIRO16
	PTSS19Y00243S-0M-0Y-099M-13Y-0B

27	SOKOLL/3/PASTOR//HXL7573/2*BAU/4/MEX94.27.1.20/3/SOKOLL//ATTILA/3*BCN/6/WBLL1*2/BRAM BLING//VORB/FISCAL/3/BECARD/4/MUCUY/5/MUCUY PTSS19Y00184S-0M-0Y-099M-1Y-0B
28	SOKOLL/WBLL1/4/2*PASTOR//HXL7573/2*BAU/3/WBLL1/5/WBLL4//OAX93.24.35/WBLL1 PTSS20Y00464S-0B-099Y-0B-1Y-0B
29	SOKOLL/3/KACHU/SAUAL//CIRO16 PTSS19Y00313S-0M-0Y-099M-19Y-0B
30	NINGA #1 CMSA11Y00507S-099Y-099M-099NJ-099NJ-19WGY-0B
31	68.111/RGB-U//WARD/3/FGO/4/RABI/5/AE.SQUARROSA(191)/6/2*KACHU/SAUAL//CIRO16 PT19B00003T-0Y-099M-7Y-0B
32	SOKOLL/3/PASTOR//HXL7573/2*BAU/4/MEX94.27.1.20/3/SOKOLL//ATTILA/3*BCN/6/WBLL1*2/BRAM BLING//VORB/FISCAL/3/BECARD/4/MUCUY/5/MUCUY PTSS19Y00184S-0M-0Y-099M-26Y-0B
33	PUB94.15.1.12/FRTL/5/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA// TSI/VEE#5/4/FRET2/6/KUTZ PTSS19Y00202S-0M-0Y-0B-25Y-0B
34	PASTOR//HXL7573/2*BAU/3/WBLL1/6/WBLL4//OAX93.24.35/WBLL1/5/CROC_1/AE.SQUARROSA(205) //BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2 PTSS19Y00106S-0B-0Y-099M-8Y-0B
35	68.111/RGB-U//WARD/3/FGO/4/RABI/5/AE.SQUARROSA(191)/6/2*KACHU/SAUAL//CIRO16 PT19B00003T-0Y-099M-17Y-0B
36	NAINA#1 CMSS11B00910T-099TOPY-099M-099NJ-099NJ-37WGY-0B
37	ALTAR84/AE.SQUARROSA(237)/4/2*KIRITATI/WBLL1//2*BLOUK#1*2/3/KACHU#1/KIRITATI//KACHU PTSS20B00072T-099Y-099M-4Y-0B
38	SOKOLL/3/PASTOR//HXL7573/2*BAU/5/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/ VEE#5/4/FRET2/7/SOKOLL/3/PASTOR//HXL7573/2*BAU*2/6/OASIS/5*BORL95/5/CNDO/R143// ENTE/MEXI75/3/AE.SQ/4/2*OCI PTSS18Y00165S-0M-099Y-099M-32Y-0Y

39	WBLL4//OAX93.24.35/WBLL1/5/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/
	SARA//TSI/VEE#5/4/FRET2/6/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/
	SARA//TSI/VEE#5/4/FRET2/5/CIRO16
	PTSS19Y00243S-0M-0Y-099M-23Y-0B

40	SERI/BAV92//PUB94.15.1.12/WBLL1/3/BORL14 PTSS19Y00217S-0M-0Y-099B-20Y-0B
41	RL6043/4*NAC//2*PASTOR/3/BCN/WBLL1/4/KUTZ PTSS16Y00013S-0B-099Y-099M-1Y-0B-0Y
42	SOKOLL/WBLL1/4/2*PASTOR//HXL7573/2*BAU/3/WBLL1/5/WBLL4//OAX93.24.35/WBLL1

	PTSS20Y00464S-0B-099Y-0B-9Y-0B
43	MEX94.27.1.20/3/SOKOLL//ATTILA/3*BCN/4/PUB94.15.1.12/WBLL1/5/KACHU/SAUAL//CIRO16 PTSS19Y00289S-0M-0Y-099M-6Y-0B
44	CROC_1/AE.SQUARROSA(333)//2*KUTZ PTSS15B00034T-099Y-099M-23Y-0Y-020Y-0B

Plots consisted of 1 bed 2 m long with two rows and 0.80 m apart with two replications, and a seed density of 100 kg ha^{-1}. Weed control was done manually and two complementary irrigations were applied 45 days after the irrigation for seed germination and the second one 30 days later (75 days after the irrigation for seed germination). The agronomic management was based on the technical recommendations by Figueroa-López *et al*. [23]. The daily average temperature (°C), the maximum and minimum, relative humidity, the number of cold and heat units, and precipitation were recorded from January 15 to May 15, 2024 by the weather station CIANO-910, located in block 910 in the Yaqui Valley [24]; this station belongs to the automated weather station network of Sonora [25]. Cold units (CU) were calculated as the temperature > 0.1 °C to < 10 °C that occurs in a given hour and the heat units (HU) as the number of hours with temperature above 30 °C [26]. The variables evaluated were: days to heading, days to physiological maturity, plant height (cm), thousand grain weight (g), and grain weight (g) from a 0.8 m^2 plot, after harvesting with a sickle; threshing was carried out with a Pullman stationary thresher.

3. Results and discussion

The range of the daily average temperature during the period of evaluation was 16.3-23.2 °C (Figure 1), while for the maximum temperature it was 29.7-35.8 °C and 2.5-10.0 °C for the minimum temperature. Maximum temperatures above 30 °C occurred from one to several hours during the following days: January 28 (1 h), 29 (2), 31 (4), March 21 (3), 22 (4), 28 (1), April 3 (2), 10 (6), 11 (5), 14 (7), 15 (4), 16 (3), 17 (6), 18 (7), 19 (8), 20 (8), 21 (7), 22 (8), 23 (7), 24 (7), 25 (6), 28 (3), 29 (7), 30 (6), May 1 (5), 3 (6), 4 (7), 5 (8), 6 (8), 7 (7), 8 (7), 9 (8), 10 (9), 11 (10), 12 (8), 13 (9), 14 (10), 15 (7) (Figure 2). As in crop season 2022-2023 [27], there was more persistence on the occurrence of heat units from April 14 to May 15, although in 2024 heat units occurred on January 28, 29, and 31, and March 21 and 22. Heading dates for the first sowing date occurred from March 13 to 24 and March 23 to from April 1 for the second date. Plants from the first sowing date were exposed to 3 HU on March 21 and to 4 HU on the 22; in contrast, plants from the second date experienced only 1 HU on March 28. As a result, plants from the first date were likely exposed to greater heat stress during flowering [Zadoks stage 65, 28].

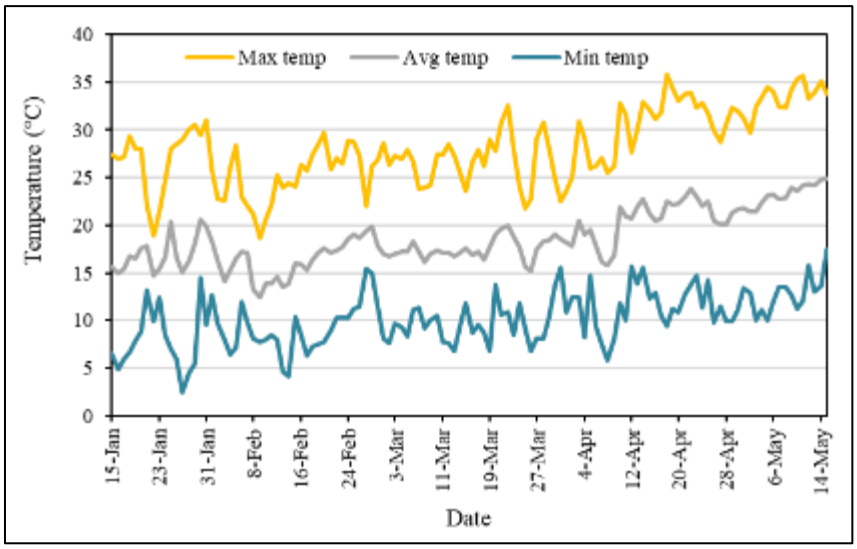

Figure 1 Average daily temperature from January 15 to May 15, 2024, recorded by the weather station CIANO-910, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico, during the crop season 2023-2024

Continuous hours from one to five on 14 different days with temperature above 30 °C occurred between 10:00 and 17:00 pm, while from six to ten on 25 different days between 09:00 am and 18:00 pm. Weeks where the maximum temperature reached more than 30 °C in some days and in some hours were January 28-February 3 (7), March 17-23

(7), March 24-30 (1), March 31-April 6 (2), April 7-13 (11), 14-20 (43), 21-27 (35), April 28-May 4 (34), May 5-11 (57), 12-15 (34).

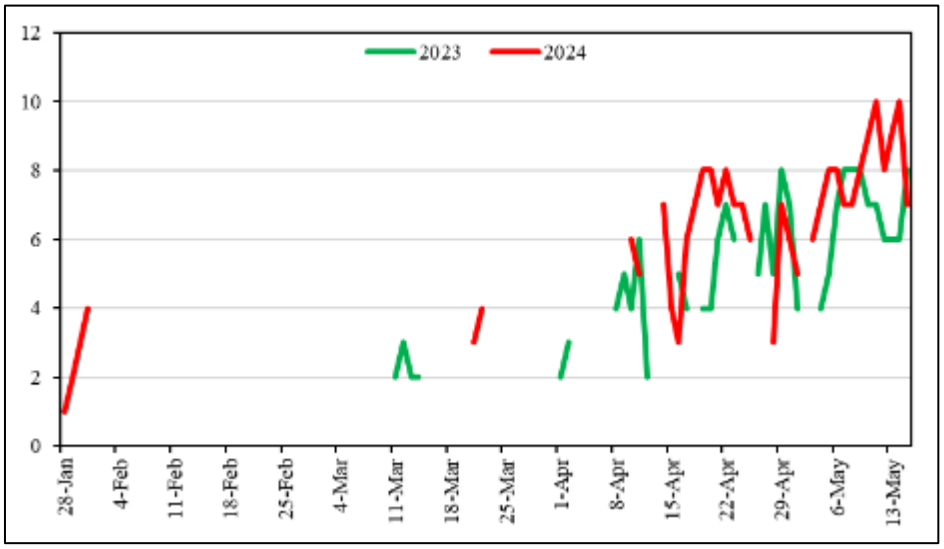

Figure 2 Daily occurrence of heat units from January 15 to May 15, 2024, recorded by the weather station CIANO-910, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico, during the crop seasons 2022-2023 and 2023-2024

The total heat units accumulated during the period of time that covered this work was 231, being a season with a higher number of HU than 2020, 2021 and 2023 [29,30,27], but lower than 2022 [31] (Figure 3). The most contrasting difference in heat units during those years, was 49 units between 2022 and 2023. The accumulation of cold units was recorded from the January 15-20 period to the week of April 28-May 4. The highest accumulation occurred during February 11-17 with 44 CU, January 15-20 with 43, February 4-10 with 37, January 28-February 3 with 28, March 10-16 with 23, and January 21-27, February 18-24, and April 7-13 with 22 CU each (Figure 4). A total of 309 cold units were recorded during the period of the study. All the phenological stages of the wheat plant are sensitive to temperature fluctuation. The temperature is an important environmental factor that influences the expression of developmental responses and flowering time in plants, high temperatures favor a greater metabolic activity of the plant, as well as the speed up of the physiologic processes that determine its growth and development [32,33]. As temperatures drop, plant phenological cycles slow down, leading to greater production yields.

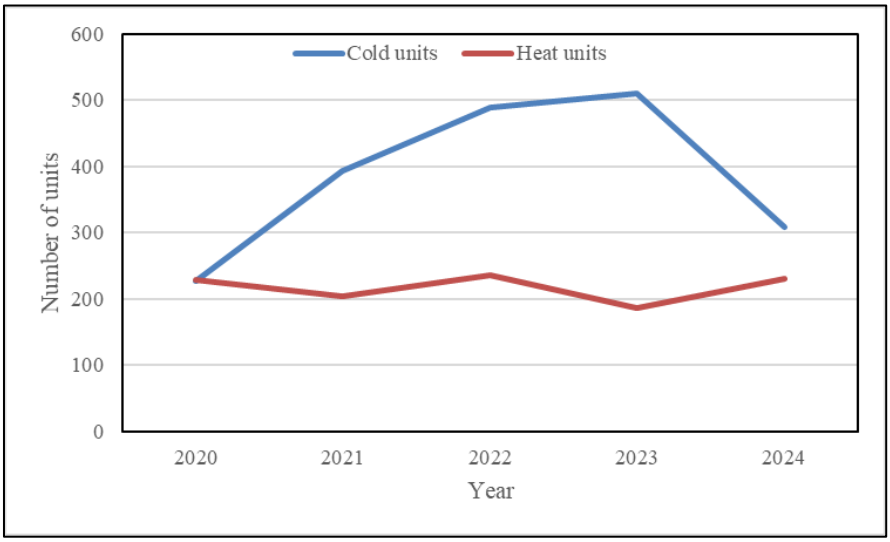

Figure 3 Cold and heat units from January 15 to May 15, recorded by the weather station CIANO-910, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico, during the years 2020 to 2024

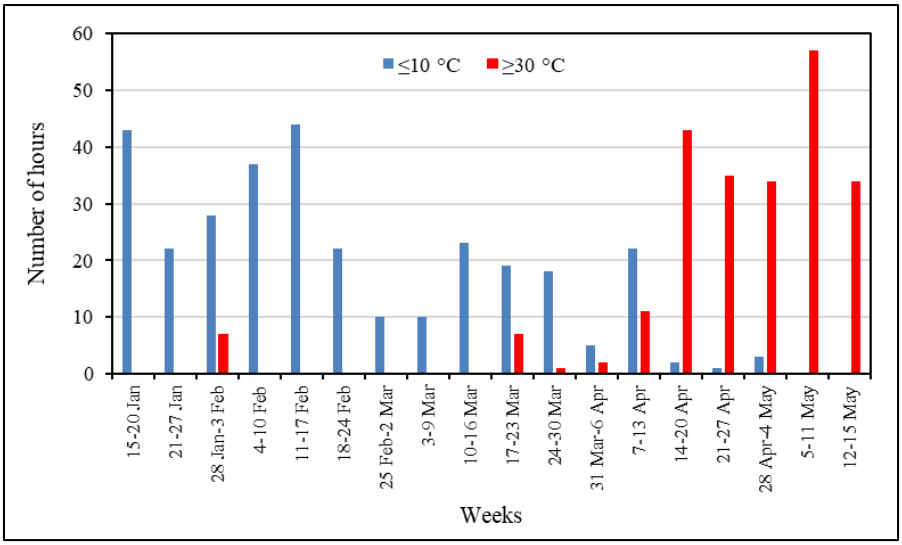

Figure 4 Number of cold and heat units accumulated from January 15 to May 15, 2024, recorded by the weather station CIANO-910, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico, during the crop season 2023-2024

Félix-Valencia *et al*. [26] reported that based on the accumulation of 340 cold units with a grain yield of 4.63 t ha^{-1}, for each increment of 100 cold units, grain yield increases by 330 kg. Although wheat is a cool-season crop whose production is concentrated between latitudes 30-60 °N and 27-40 °S under different climatic areas, it can be grown beyond these limits, with an optimum growth temperature of about 25 °C [34]. The wheat plant needs to accumulate cold units to extend its biological cycle, a process that typically results in higher grain yield [26]. During January the daily low temperature range was 2.5-14.5 °C, in February 4.1-15.4 °C, in March 6.7-15.5 °C, in April 5.9-15.7 °C, and in May 10.0-17.5 °C. In southern Sonora, the recommended wheat sowing period is between November 15 to December 15. Sowing after this window often results in poor tilleting and increased exposure to heat stress [23]. In this study, late sowing combined with reduced irrigation was intentionally applied to the experimental germplasm to induce heat stress conditions. The average days to heading of the group of lines and commercial bread wheat cultivars Borlaug 100 F2014 and CIANO M2018 was 61 for the first sowing date and 56 for the second. In the first sowing date, CIANO M2018 was the second latest entry to reach heading, occurring 68 days after sowing (das), Borlaug 100 F2014 with 64 das, while line No. 29 was the earliest to head with 57 das (Figure 5).

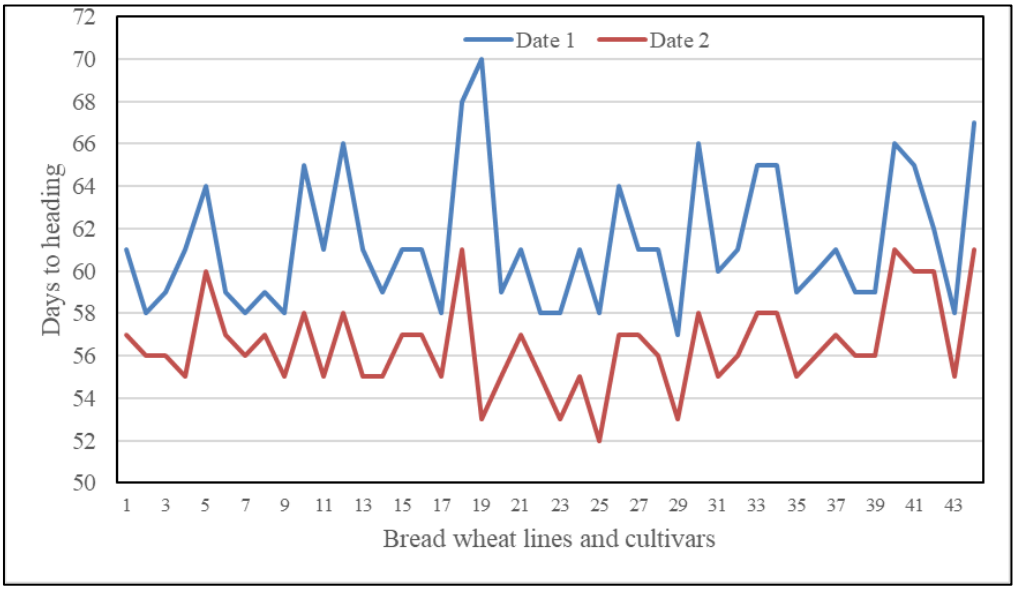

Figure 5 Days to heading of bread wheat cultivars Borlaug 100 F2014 (No. 5) and CIANO M2018 (No. 18), and 42 advanced bread wheat lines adapted to stress, sown late on January 15 and 30, 2024, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico

In the second date, CIANO M2018 was the latest to head with 61 das, while Borlaug 100 F2014 headed in 60 das. Sister line COPIO/5/UP2338*2/SHAMA/3/MILAN/KAUZ//CHIL/CHUM18/4/UP2338*2/SHAMA/6/KUTZ (PTSS19Y00 195S-0M-0Y-099M-11Y-0B, No. 25) was the earliest to head with 52 das. Lines that had a three day difference or less for heading during the first and second dates were No. 2, 3, 6-9, 17, 22, 38, 39, 42, 43; those with a larger difference of four to six days were cultivar Borlaug 100 F2014 and lines No. 1, 4, 11, 13-16, 20, 21, 23-25, 27-29, 31, 32, 35-37, 40, 41, and 44; those with a difference of seven to eight days were cultivar CIANO M2018 and lines No. 10, 12, 26, 30, 33, and 34; while the line KACHU/SAUAL/4/VARIS/MISR2/3/FRET2/KUKUNA//FRET2/5/KACHU/SAUAL/6/ MEX94.27.1.20/3/SOKOLL//ATTILA/3*BCN/4/PUB94.15.1.12/WBLL1 (No. 17) showed the highest difference with 17 days. The average plant height of the group was 77 cm for the first sowing date and 74 cm for the second (Figure 6).

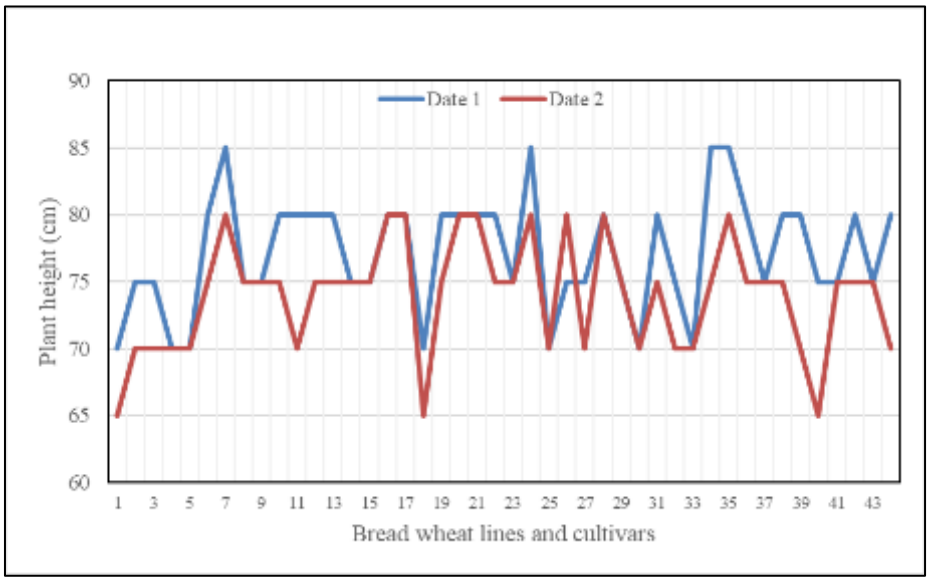

Figure 6 Plant height of bread wheat cultivars Borlaug 100 F2014 (No. 5) and CIANO M2018 (No. 18), and 42 advanced bread wheat lines adapted to stress, sown late on January 15 and 30, 2024, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico

Sister lines SERI/BAV92//PUB94.15.1.12/WBLL1/3/BORL14 (PTSS19Y00217S-0M-0Y-099B-6Y-0B, No. 7) and 68.111/RGB-U//WARD/3/FGO/4/RABI/5/AE.SQUARROSA(191)/6/2*KACHU/SAUAL//CIRO16 (PT19B0000 3T-0Y-099M-17Y-0B, No. 35), and lines MEX94.27.1.20/3/SOKOLL//ATTILA/3*BCN/4/PUB94.15.1.12/ WBLL1/5/MUCUY (No. 24) and PASTOR//HXL7573/2*BAU/3/WBLL1/6/WBLL4//OAX93.24.35/WBLL1/5/CROC_1/AE.SQUARROSA (205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2 (No. 34) were the tallest in the first date with 85 cm, while cultivars CIANO M2018 and Borlaug 100 F2014 and the lines No. 1, 4, 25, and 30 showed the shortest height with 70 cm. In the second date, sister lines No. 7, 26, 28, and 35, and lines No. 16, 17, 20, 21, and 24 were the tallest with 83 cm, while lines No. 1, 40 and cultivar CIANO M2018 were the shortest with 65 cm; cultivar Borlaug 100 F2014 showed a height of 70 cm. With the exception of sister line WBLL4//OAX93.24.35/WBLL1/5/CROC_1/AE.SQUARROSA(205)// BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2/6/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/ VEE#5/4/FRET2/5/CIRO16 (PTSS19Y 00243S-0M-0Y-099M-13Y-0B, No. 26), that was taller in the second date, 18 lines and cultivar Borlaug 100 F2014 did not show any height difference between the first and the second date, but 23 lines and cultivar CIANO M2018 showed differences in height between the first sowing date and the second one, and in all these cases, the first date was taller with a range of 5 to 10 cm. Sister lines No. 11, 39 and 40, and lines No. 34 and 44 showed the greatest difference with 10 cm. Between the 2018-2019 and 2022-2023 crop seasons, the SATYN line groups exhibited an average heading days of 68.8, ranging from 66 to 74 days, and an average plant height of 89 cm, with a range of 83 to 96 cm [27,29,30,31]. In 2023-2024, the group showed an average of 59 days for heading, 10 days below the average of groups in the period indicated, as well as an average of 76 cm in height, 13 cm below the average of groups in the period already indicated (Table 2). Over the same period, cultivar Borlaug 100 F2014 showed an average heading days of 69 with a range of 64 to 74, and an average height of 80.8 cm, ranging from 75 to 86 cm. The average heading days (62) and plant height (70 cm) in crop season 2023-2024 were below the average of the period indicated.

Table 2 Average monthly temperatures recorded by the weather station CIANO B-910, during mid-January to the middle of May in six years in the Yaqui Valley, Sonora, Mexico, days to heading and plant height of selected germplasm with tolerance to drought and heat

Year	Average temperature (°C)					Days to heading (avg)	Plant height (cm)
	January	February	March	April	May		
2019	15.65	15.42	17.84	20.72	22.25	74	92
2020	16.70	16.70	18.00	20.88	24.94	66	83
2021	15.13	15.79	16.99	21.06	24.56	68	96
2022	15.91	15.00	16.82	21.25	24.36	67	89
2023	13.47	14.70	17.50	19.92	22.08	69	85
2024	16.96	16.35	17.52	20.57	23.25	59	76

Average temperatures in 2021 and 2022 were relatively similar, but the average grain weight per plot was higher in 2022 with 350 g [31], compared to 294 g in 2021 [30]. This difference may be due greater heat unit accumulation during the heading-flowering stages in 2021, which likely caused increased stress on the crop compared to 2022.

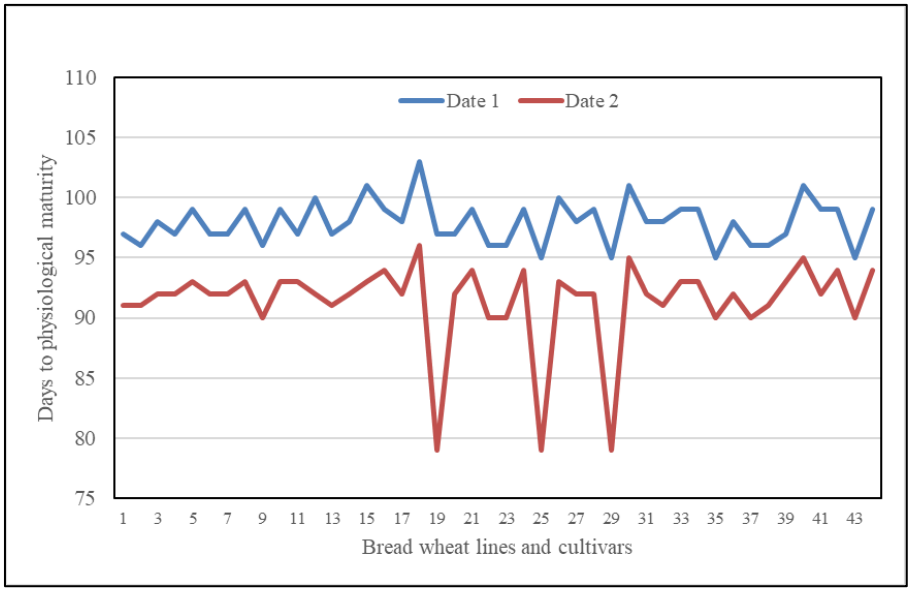

Figure 7 Days to physiological maturity of bread wheat cultivars Borlaug 100 F2014 (No. 5) and CIANO M2018 (No. 18), and 42 advanced bread wheat lines adapted to stress, sown late on January 15 and 30, 2024, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico

It is noteworthy that the average temperature in January (16.96 °C) and February 2024 (16.35 °C) was higher than the compound average of the previous years, since during that period of time, the plant undergoes the early stages of growth and development. The average physiological maturity of the group of lines and cultivars Borlaug 100 F2014 and CIANO M2018 in this study occurred after 98 days for the first sowing date and 91 for the second, with a range of 95 to 103 and 79 to 96, respectively (Figure 7). The average thousand grain weight of the group in the first sowing date was 46.7 g and 45.8 in the second (Figure 8). In the first date, line NAINA #1 (No. 36) showed the highest TGW with 54.43 g, followed by the line REEDLING-GL5A_1/5/2*SOKOLL/3/PASTOR//HXL7573/2*BAU/4/MEX94.27.1.20/3/SOKOLL//ATTILA/3*BCN (No. 10) with 54.41 g, and sister line SOKOLL/WBLL1/4/2*PASTOR//HXL7573/2*BAU/3/WBLL1/5/WBLL4//OAX93.24.35/WBLL1 (PTSS20Y00 464S-0B-099Y-0B-1Y-0B, No. 28) with 52.9 g, while the line SUP152/BAJ #1/3/KACHU #1/KIRITATI//KACHU/4/BORL14 (No. 1), showed the lowest TGW with 38.0 g. In the second date, line No. 10 showed the highest TGW with 52.6 g, followed by line No. 36 with 52.2 g; sister line SERI/BAV92//PUB94.15.1.12/WBLL1/3/ BORL14 (PTSS19Y00217S-0M-0Y-099B-20Y-0B, No. 40) showed the lowest TGW with 39.1 g.

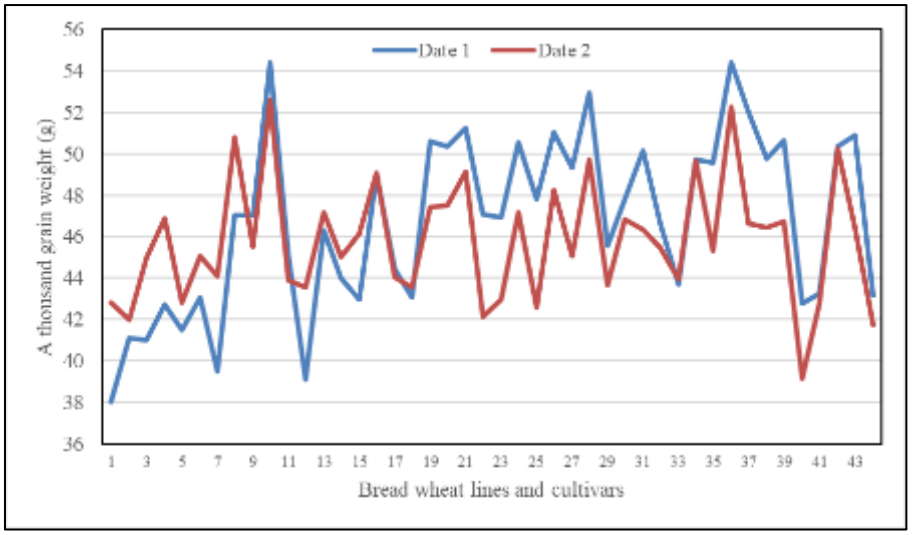

Figure 8 A thousand grain weight of bread wheat cultivars Borlaug 100 F2014 (No. 5) and CIANO M2018 (No. 18), and 42 advanced bread wheat lines adapted to stress, sown late on January 15 and 30, 2024, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico

The average grain weight per plot of the group in the first sowing date was 444 g and 366 in the second (Figure 9). In the first date, line YAV79//DACK/RABI/3/SNIPE/4/AE.SQUARROSA(381)/5/2*SUP152/BAJ#1//TRCH/ HUIRIVIS #1/3/SUP152/BAJ #1 (No. 21) showed the highest weight with 545 g, followed by the line 68.111/RGB-U//WARD/3/AE.SQUARROSA(501)/7/SERI.1B*2/3/KAUZ*2/BOW//KAUZ/4/FRANCOLIN#1/5/MUNAL/6/ KACHU#1/KIRITATI//KACHU/8/BORL14 (No. 13) with 535 g, while lines JNRB.5/PIFED/5/BJY/COC//PRL/ BOW/3/SARA/THB//VEE/4/PIFED/6/BORL14 (No. 9) and ALTAR84/AE.SQUARROSA(237)/4/2*KIRITATI/ WBLL1//2*BLOUK #1*2/3/KACHU #1/KIRITATI//KACHU (No. 37) showed the lowest grain weight with 335 g. In the second date, sister line SOKOLL/3/KACHU/SAUAL//CIRO16 (PTSS19Y00313S-0M-0Y-099M-9Y-0B, No. 2) showed the highest grain weight per plot with 465 g, followed by sister line SERI/BAV92//PUB94.15.1.12/WBLL1/3/BORL14 (PTSS19Y00217S-0M-0Y-099B-6Y-0B, No. 7) with 460 g, and line No. 12 with 445 g. Cultivar Borlaug 100 F2014 (No. 5) showed grain weight (395 g) below the group average in the first date, and above (395 g) the group average in the second one, whilst cultivar CIANO M2018 (18) showed grain weight (445 g) above the group average in the first date, and below (350 g) the group average in the second date.

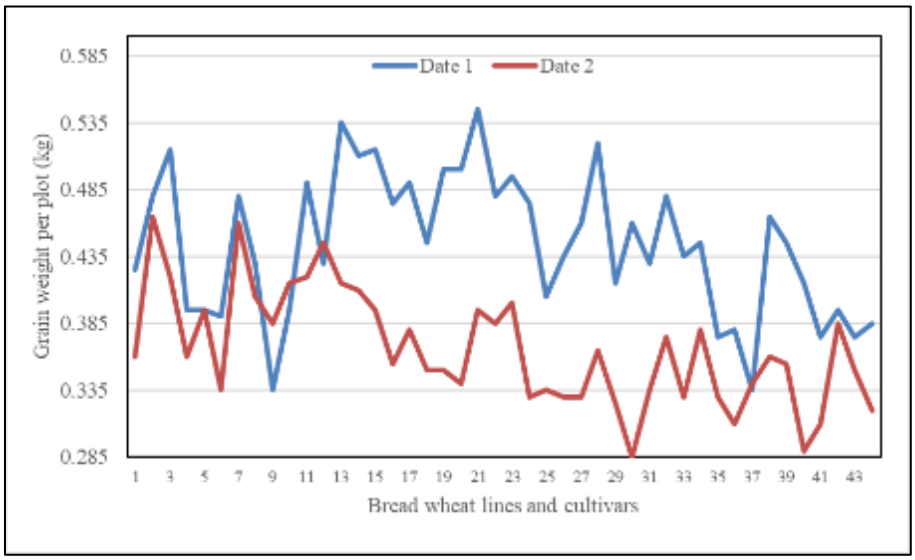

Figure 9 Grain weight per plot of bread wheat cultivars Borlaug 100 F2014 (No. 5) and CIANO M2018 (No. 18), and 42 advanced bread wheat lines adapted to stress, sown late on January 15 and 30, 2024, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico

Although the year 2023, during the crop season 2022-2023, showed the lowest average monthly temperature since 2018-2019, and it accumulated 510 cold units and it only recorded 187 heat units, with an average grain yield per plot of 380 g (4.75 t ha^{-1}), the year 2024 showed greater grain yield per plot with 405 g (5.06 t ha^{-1}), despite the higher average temperature in January (16.96 °C) and February (16.35 °C) than the compound average of the previous years, the accumulated cold units was 309 and the heat units 231 (Figures 3 and 4). The temperature that prevailed in 2023 in partly contributed to an average grain yield per plot of 380 g, equivalent to 4.75 t ha^{-1}, as well as for cultivar Borlaug 100 F2014 with an average grain yield of 376 g (equivalent to 4.70 t ha^{-1}), which surpassed its grain yield of 2022 by 1.4 t ha^{-1}; however, for 2024, the average grain yield per plot was 405 g (5.06 t ha^{-1}), and Borlaug 100 F2014 showed 400 g (5.0 t ha^{-1}). This indicates that the greater number of heat units that occurred during heading-flowering in 2023 than in 2024, might have accounted for the lower grain yield obtained in 2023. Heat stress induces a wide range of physiological and morphological changes in plants. It hampers seed germination and seedling growth, reduces cell turgor and water-use efficiency, and disrupts cellular processes through excessive production of reactive oxygen species (ROS), leading to oxidative stress. Additionally, heat stress accelerates leaf senescence, impairs photosynthesis by inactivating photosynthetic enzymes and damaging chloroplasts, and restricts assimilate translocation. Consequently, both grain growth rate and duration decline, resulting in fewer grains [35]. With the exception of lines JNRB.5/PIFED/5/BJY/COC//PRL/BOW/3/SARA/THB//VEE/4/PIFED/6/BORL14 (No. 9), REEDLING-GL5A_1/5/2*SOKOLL/3/PASTOR//HXL7573/2*BAU/4/MEX94.27.1.20/3/SOKOLL//ATTILA/3*BCN (No. 10), SOKOLL (No. 12), and ALTAR 84/AE.SQUARROSA (237)/4/2*KIRITATI/WBLL1//2*BLOUK#1*2/3/KACHU#1/KIRITATI//KACHU (No. 37) which had greater grain yield per plot in the second date than in the first one, and cultivar Borlaug 100 F2014 which had the same grain weight per plot in both dates, the rest of lines and cultivar CIANO M2018 showed greater grain weight per plot in the first date than in the second one. Seven lines showed a difference lower than 50 g of grain weight per plot between the first and second sowing dates, fifteen lines and cultivar CIANO M2018 between 51 and 100 g, thirteen lines between 101 and 150 g, and three between 151 and 200 g. The greatest difference was shown by NINGA #1 (No. 30) with 175 g, followed by MEX94.27.1.20/3/SOKOLL//ATTILA/3*BCN/4/PUB94.15.1.12/WBLL1/5/BOKOTA/3/UP2338*2/KKTS*2//YANAC (No. 20) with 160 g, and sister line SOKOLL/WBLL1/4/2*PASTOR//HXL7573/2*BAU/3/WBLL1/5/WBLL4//OAX93.24.35/WBLL1 (PTSS20Y00464S-0B-099Y-0B-1Y-0B, No. 28) with 155 g. Lines with the best agronomic type consistent in both dates were: SOKOL (No. 12), and sister line WBLL4//OAX93.24.35/WBLL1/5/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2/6/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2/5/CIRO16 (PTSS19Y00243S-0M-0Y-099M-13Y-0B, No. 26). The temperature that prevailed during this work had an average monthly range of 16.3 to 23.2 °C and an overall average of 18.6 °C. The two complementary irrigations are intended to induce drought stress in the wheat plant impacting all the stages of development, from vegetative and reproductive growth to grain filling and crop maturation [36]. Nitrogen uptake efficiency and utilization in plants are largely reduced under drought conditions due to impaired membrane permeability and disrupted active transport processes. These disruptions lead to decreased transpiration rates and a reduced capacity for root absorption. Furthermore, stomatal closure restricts CO_2 intake, while the accumulation of oxygen within the stomata facilitates the generation of reactive oxygen species (ROS) through partial oxygen reduction. The resulting ROS cause membrane damage and in leakage, adversely affecting respiration, photosynthesis, and overall plant growth. In wheat, the developmental phase from double ridge to anthesis stage is especially sensitive to water deficiency. Drought stress during this critical period negatively affects spikelet and kernel formation, leading to significant yield losses, which may range from 17 to as high as 70 % [36]. The check cultivar used in this study Borlaug 100 F2014, has been the predominant bread wheat cultivar grown in the Yaqui Valley, with a cultivated area ranging from 9,309 to 44,381 ha between the 2018-2019 and 2023-2024 crop seasons [37,38,39,40,41,42]. Under full irrigation (four complementary irrigations), it can achieve a grain yield of 8.797 t ha^{-1} [43]; however, while under reduced irrigation, reported yields decrease to 3.3 t ha^{-1} [31], 4.7 t ha^{-1} [27], or 5.0 t ha^{-1} as observed in the present study. In the case of CIANO M2018 which has occupied from 67.7 ha in 2021-2022 crop season to 4,664.4 ha in 2023-2024 in the Yaqui Valley [40,41,42], it can yield 7.87 t ha^{-1} under three complementary irrigations [31], while 4.43 t ha^{-1} [27] and 5.0 t ha^{-1} as observed in the present study.

4. Conclusion

The average days for heading of forty two advanced bread wheat lines and bread wheat cultivars Borlaug 100 F2014 and CIANO M2018 was 61 days for the first sowing date and 56 for the second one, while days for physiological maturity were 98 and 91, respectively.

The average plant height of the group for the first date was 77 cm and 74 for the second one; two sister lines SERI/BAV92//PUB94.15.1.12/WBLL1/3/BORL14 (PTSS19Y00217S-0M-0Y-099B-6Y-0B) and 68.111/RGB-U//WARD/3/FGO/4/RABI/5/AE.SQUARROSA(191)/6/2*KACHU/SAUAL//CIRO16 (PT19B00003T-0Y-099M-17Y-0B)] and the line MEX94.27.1.20/3/SOKOLL//ATTILA/3*BCN/4/PUB94.15.1.12/WBLL1/5/ MUCUY, showed the highest average height with 83 cm.

The average thousand grain weight was 46.3 g; the line REEDLING-GL5A_1/5/2*SOKOLL/3/PASTOR// HXL7573/2*BAU/4/MEX94.27.1.20/3/SOKOLL//ATTILA/3*BCN showed the highest average TGW with 53.5 g, followed by NAINA #1 with 53.3 g.

The average grain yield per plot was 405 g; the line 68.111/RGB-U//WARD/3/AE.SQUARROSA(501)/7/ SERI.1B*2/3/KAUZ*2/BOW//KAUZ/4/FRANCOLIN#1/5/MUNAL/6/KACHU#1/KIRITATI//KACHU/8/BORL14 showed the highest average yield with 480 g which corresponded to 6.0 t ha^{-1}, followed by four lines with 470 g (5.88 t ha^{-1}). Cultivars Borlaug 100 F2014 and CIANO M2018 showed an average grain yield of 400 g (5 t ha^{-1}).

The average hourly temperature was 18.6 °C with a maximum of 35.8 °C and a minimum of 2.5 °C, the average relative humidity was 61.0 %, there were 8.0 mm of precipitation, and the number of heat and cold units was 231 and 309, respectively.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

The authors declare that No conflict of interest.

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