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Effect of temperature, relative humidity and drip irrigation on productivity of common bean (*Phaseolus vulgaris* L.) in the Yaqui Valley, Sonora, Mexico

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Abstract

In southern Sonora, Mexico, the temperature has maintained a tendency to increase 0.2°C every spring season, which poses a risk for bean production, since high temperatures might occur during the critical periods of flowering and grain-filling that define the final grain yield. The objective was to determine the impact of temperature and relative humidity on bean grain yield and quality in two commercial fields (B-2110 and B-2228) sown in two dates (March 9 and 25, and 3 and 27, respectively) with cultivar Pinto Saltillo, in the Yaqui Valley, Sonora under drip irrigation. The fruiting period was evaluated in relation to temperature, relative humidity and drip irrigation sheets. Meteorological data were obtained from digital sensors installed within the crop, in addition to the meteorological stations closest to each field. The analysis of variance was highly significant for number of pods with grain, number of grains per pod, specific grain weight, and grain yield ha^{-1}. Bean grain yield varied from 1,204 to 3,271 kg ha^{-1}; the highest yield was obtained in field B-2110 on the first date, where a total water sheet of 50.4 cm was applied with a 12.1 day interval between 8 irrigations; while the lowest yield was obtained in B-2228 on the second date where a total water sheet of 59.60 cm was applied with a 5.6 day interval between 14 irrigations. The number of continuous hours and days with temperature greater than 33°C and relative humidity greater than 90% during the fruitful stage of the crop, were related to the greatest number of pods without grain and the lowest grain weight, with a significant reduction in the quality for consumption. The consumption quality of the grain was mainly affected in the late sowing dates, where losses of 32.6 to 48.7% were obtained in fields B-2110 and B-2228, respectively.

Keywords: Extreme temperature; Sowing date; *Phaseolus vulgaris*; Common bean; Irrigation

1. Introduction

Common bean (*Phaseolus vulgaris* L.) has been part of the diet since pre-Hispanic times [1], it is an important crop in many countries since it is a main component in human consumption. World bean production grew at an average annual rate of 1% between 2012 and 2021, except for the years 2018 and 2019 [2]. In 2021, 64.6% of the world production was generated in ten countries, India occupied the first place contributing 21.1%, followed by Brazil (10%), Myanmar (8.6%), United Republic of Tanzania (4.6%), China (4.5%), Mexico (4.4%), the United States (3.5%), Uganda (3%), Argentina (2.6%), and Kenya (2.3%) [2]. In Mexico, it is the second most important crop after maize (*Zea mays* L.) [3,4], and represents not only a tradition of production, but also of consumption, especially in rural areas [5]. The types of beans are classified according to the color and shade of the seed coat and consumption habits vary depending on the region; in the case of northwest Mexico they prefer azufrado types, pintos and bayos are distinguished in the north and northeast, while in central Mexico there is a marked tendency for flor de mayo and in the south black beans are preferred [6]. Currently, beans are grown in the 32 states of the country and are produced in two seasons: spring-summer (SP-S)

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and fall-winter (F-W). Under rainfed conditions, the area grown with beans is smaller during the F-W season, but a higher unit yield is obtained; contrary to the irrigated conditions, where the area sown during the F-W is greater, but the yield is lower than in the SP-S season [7]. In 2022, Mexican bean production was 965,370.65 t, of which only 33.39% were obtained from irrigated areas, the rest of the productivity came from rainfed areas (66.61%); 82% of the production originated from seven states: Zacatecas, Sinaloa, Nayarit, Chihuahua, Chiapas, Durango, and Guanajuato with 307.5, 165.5, 71.1, 69.1, 68.6, 57.5, and 51.8 thousand tons, respectively. The national average grain yield was 0.67 t ha^{-1}, the highest average yields were obtained during the F-W season in the states of Guanajuato, Sonora, and Sinaloa with average grain yields of 2.47, 2.23, and 1.93 t ha^{-1}, respectively. In the state of Sonora, around 5,260 ha were sown in the 2022 agricultural season; 65% of the total area was sown during the F-W, being the most important the irrigation districts in the south of the state (District 038 Navojoa-Mayo Valley and 041 Cajeme-Yaqui Valley) [7]. The most important bean diseases in the state of Sonora are dumping off [*Macrophomina phaseolina* (Tassi) Goid., *Sclerotium rolfsii* Sacc., *Rhizoctonia solani* Kühn, *Fusarium solani* (Mart.) Sacc. and *F. oxysporum* Schlechtend.:Fr. f. sp. *phaseoli* Kendrick and Zinder], white mold [*Sclerotinia sclerotiorum* (Lib.) de Bary], rust [*Uromyces appendiculatus* (Pers.:Pers.) Unger], powdery mildew (*Erysiphe polygoni* DC), halo blight [*Pseudomonas syringae* pv. *phaseolicola* (Burkholder) Young, Dye and Wilkie], common bacterial blight [*Xanthomonas axonopodis* pv. *phaseoli* (Smith) Vauterin, Hoste, Kersters and Swings], Bean common mosaic virus, Bean southern mosaic virus, Bean chlorotic mosaic virus, Bean golden yellow mosaic virus, and Pumpkin leaf curly [8,9,10,11]. In southern Sonora, farmers use various ways for irrigation: flooding, furrow (the most common), drip, center pivot, frontal move, and spray irrigation [12]. In the case of beans which have increased in area in the last few years [13], farmers use primarily furrow irrigation and secondly drip irrigation. The recommended period for the F-W sowing in the Yaqui Valley is from October 1 to 30, and from January 15 to March 15 for SP-S sowing; in the Mayo Valley, the recommended spring date is from January 1 to February 10 [14,15]. Sowing beans during the spring is a feasible option for farmers who sow during the F-W season, because it is a short-season crop, so it can benefit from the residual fertilization, water allocation, and minimum tillage [16]; however, it may have a lower grain yield, since the temperature in that period fluctuates much, promoting the drop in fruiting more than in the F-W sowings. Furthermore, as the temperature increases, the crop cycle is shortened, reducing the period of flower bud formation and flowering [17]. During the last 10 years, in southern Sonora, Mexico, the temperature during the spring bean season has maintained a trend of increasing 0.2°C per season, mainly the month of April has warmed by 1.3°C and the month of May has increased the frequency of hours with temperatures higher than 33°C; in addition to the events of extreme low temperature which have a tendency to increase, and the relative humidity has been unstable [18]. This climatic situation increases the risk in spring bean production, because it is threatened by the high temperatures that occur in the critical period that define the yield, which is flowering and grain filling; but the wide environmental adaptability reported in some types of edible beans indicates that some cultivars can withstand extreme temperatures between 5 and 40ºC [19]. Therefore, it is important to determine the level of risk that beans may have, if sowing is carried out outside the established technical dates recommended for the region [11]. The objective of this work was to assess the impact of temperature and relative humidity on the production and quality of beans in commercial fields under drip irrigation in the Yaqui Valley, Sonora, Mexico.

2. Materials and methods

The productive phase of bean cultivar Pinto Saltillo was analyzed in two commercial fields under drip irrigation with cooperating farmers, located in blocks 2110 (68 ha) (27°08'34.2"N 109°55'42.0"W) and 2228 (300 ha) (27°07'05.9"N 109°44'34.5"W), in the Yaqui Valley, Sonora, México, during the spring 2023. The growth habit of bean cultivar Pinto Saltillo is indeterminate type III postrate with a short terminal guide without climbing ability. Average height of the canopy is 38 cm and the terminal guide length 84. Flowering and physiological maturity take place between 62 and 70, and between 115 and 123 days after sowing, respectively, under irrigated conditions, and between 48 and 59, and between 87 and 100 days, respectively, under rainfed conditions The seed is medium in size with an average weight of 34 g for each of 100 seeds and it is highly resistant to oxidation; the seed is truncate or fastigiate in shape, light cream with light brown spots (Figure 1), and does not darken under storage from 1 to more than 2 years, and therefore, its shelf life is longer than other beans. Average protein content is 21%, and cooking time is 80 min. The average grain yield under irrigation is 2,304 kg ha^{-1} and 1,139 under rainfed conditions. Pinto Saltillo is tolerant to anthracnose [*Colletotrichum lindemuthianum* (Sacc. and Magnus) Lams.-Scrib.], rust, damping off, and bacterial blight [20,21,22,23].

Figure 1 Seed of bean cultivar Pinto Saltillo

In each field, two sowing dates were considered: in B-2110, the first date was March 9 and the second one was March 25, and in B-2228, the first date was March 3 and the second one March 27. Omega digital sensors (OM-EL WIN-USB v7.2.1 data logger software) were placed in each field at the canopy level to record the temperature and relative humidity within the crop; the recording period of the sensors was from March to June and covered the phenological stages of flowering, pod development, and grain filling. Data were also obtained from meteorological stations from the network of automated meteorological stations of the state of Sonora [18] closest to the monitored fields, which were located in: 1) B-2010, 2 km north of the sensor at B-2110, and 2) B-2228, in the same block as the sensor. The irrigation sheets were calculated based on the number of hours, the water expense of the tape, and the frequency of irrigation. The irrigation strip was Stream line 8000 with a capacity of 0.89 liters of water per hour for each dripper, which were separated by 30 cm. Four plant samples of one square meter were collected from each field to quantify the production of pods, pods with grain and without grain, a thousand grain weight, and grain yield. In addition, grain quality was evaluated based on the percentage weight of poorly developed, spotted grain, and healthy grain. The sources of variation were the irrigation sheets and temperature. The analysis of variance was performed with InfoStat [24].

3. Results and discussion

3.1. Temperature and relative humidity and their relationship with the fruiting stage

Sensors located within the fields recorded a higher temperature compared to temperature recorded by the nearest weather station. The B-2228 sensor recorded an average temperature of 31.4°C during the day, during the flowering and grain filling period, which was 3°C higher than the average temperature recorded by the weather station (28.4°C), while the B-2110 sensor recorded 1.8°C higher than the weather station (Table 1). The maximum temperature oscillation was greater at B-2228, with maximum temperature of 37°C recorded by the sensor during the day. Differences were small for maximum temperature oscillation during the night among sensors and weather stations, which had a range of 20.4 to 21.6°C. The average relative humidity during the day in B-2010 recorded by the weather station was higher than that recorded by the sensor within the crop, unlike B-2228, where the sensor recorded a higher relative humidity; on the other hand, the average relative humidity at night recorded at both weather stations was higher than the sensor records with a difference of 4.7 and 3.3%, respectively (Table 1). Oscillation of the maximum relative humidity was higher in both the sensor and the weather station in B-2110 than in B-2228, with an average difference of 6.05% during the day and 3.45% during the night. Overall, the B-2110 field was less warm and more humid than the B-2228 field.

On the first date (March 9) of B-2110, the formation of flower buds began on April 15; on April 28, pod formation began, and on May 12, the first pods began to turn yellow; while on the second date (March 25), the formation of buds began after 34 days (April 28); on May 5 the first pods formed, and on May 19 they began to change color. Harvest to homogenize the drying of pods was at 104 days on the first date, and 88 days for the second date. In relation to the temperature recorded within the field, the sensor recorded low frequencies of temperature above 31 °C after April 9, during flowering. Temperatures higher than 33°C only occurred from June 9, coinciding with the pod drying stage, mainly in the first and second third of the plant on the first date, and with grain-filling in the second third of the plant of the second date, which primarily affected the development and quality of the grain of the third part of the plant. A short period of three continuous hours with temperatures above 33°C was recorded between May 6 and 7, during May 21 to 23, and a long period between June 9 and 21 (Figure 2).

Table 1 Average temperature and relative humidity recorded during flowering and grain filling of common bean, in two commercial fields sown with cultivar Pinto Saltillo, in the Yaqui Valley, Sonora, Mexico, during the spring 2023

Sensors and weather station (WS)	Temperature (°C)		Relative humidity (%)		Maximum temperature oscillation (°C)		Maximum relative humidity oscillation (%)	
	Day	Night	Day	Night	Day	Night	Day	Night
Sensor B-2110	29.1	14.8	50.8	85.2	33.4	20.4	80.9	94.5
WS B-2010	27.3	14.8	55.6	89.9	31.3	21.2	82.3	97.8
Sensor B-2228	31.4	14.3	47.3	78.1	37.0	21.6	74.8	92.3
WS B-2228	28.4	15.0	43.1	81.4	33.8	21.0	76.3	93.1

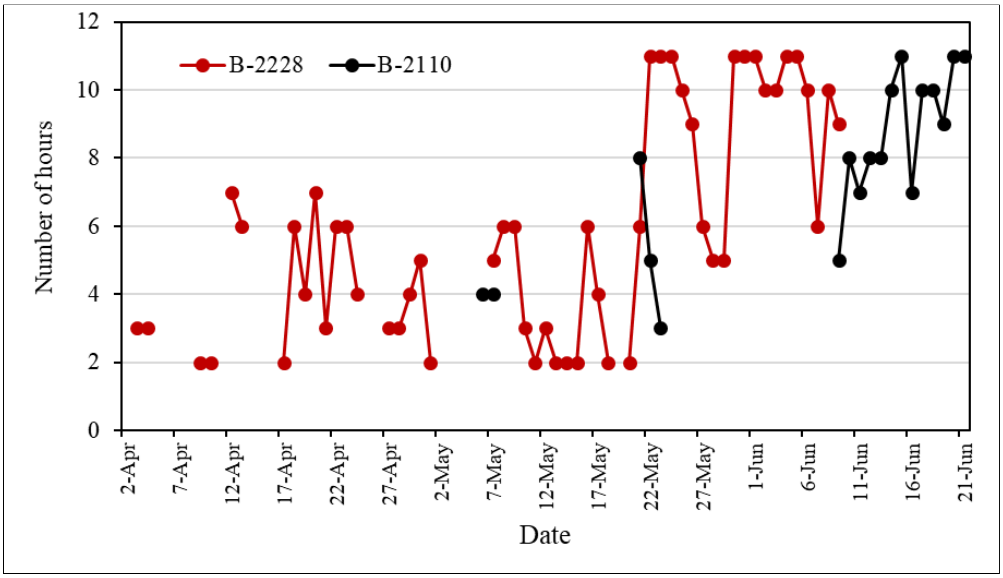

Figure 2 Number of continuous hours and days with temperature greater than 33°C, recorded by sensors installed within the bean canopy, in two commercial fields in the Yaqui Valley, Sonora, Mexico, during the spring season 2023

For relative humidity, there were four periods of three or more continuous days with relative humidity higher than 90% (Figure 3). The first period covered from March 29 to April 2, followed by April 10 to May 11, May 13 to June 12, and June 14 to June 18.

In B-2228, flowering began after 43 days on the first date (March 3), pod formation began seven days later (April 15), and on May 12 the pods began to turn yellow. On the second date (March 27), flowering began after 32 days (April 28), six days later the first pods formed (May 4), and after 15 days, the first yellow pods were observed (May 19). Harvest to homogenize the drying of pods was at 101 days on the first date, and 77 days for the second date. The temperature recorded with the sensor inside the field increased above 31°C starting on April 8, coinciding with the initial of the flowering stage. On April 17, records of extreme temperatures above 33°C began. Four periods were recorded with more than five continuous days of temperature higher than 33°C, ranging from 2 to 11 continuous hours; the first was from April 16 to 23, followed by April 26 to 30, from May 6 to 17 and from May 19 to June 8 (Figure 2). Days with 11 continuous hours with temperatures above 33°C were May 21 to 23, 29 to 31, and Jun 3 and 4. The periods recorded in April coincided with the development of pods and flowers in the second third of the plant, while those recorded in the month of May and June coincided with the development of the grain in the second and third part of the plant. Monterroso and Wien [25] reported that a period of 10 hours at 35°C for two days during the flowering stage caused 82% abscission of pods smaller than 2 cm, and pollen dehydration. Rainey and Griffiths [26] reported that a day/night temperature of 33/30°C caused an average reduction of 83, 63, 47, and 73%, in number of seeds and pods, average weight of seeds, and seeds/pod, respectively, during an evaluation of 24 common bean genotypes. In relation to relative humidity, there were four short periods with records of relative humidity greater than 90%: May 12 to 14, May 17 to 21, May 29 to 31, and June 2 and 3 (Figure 3).

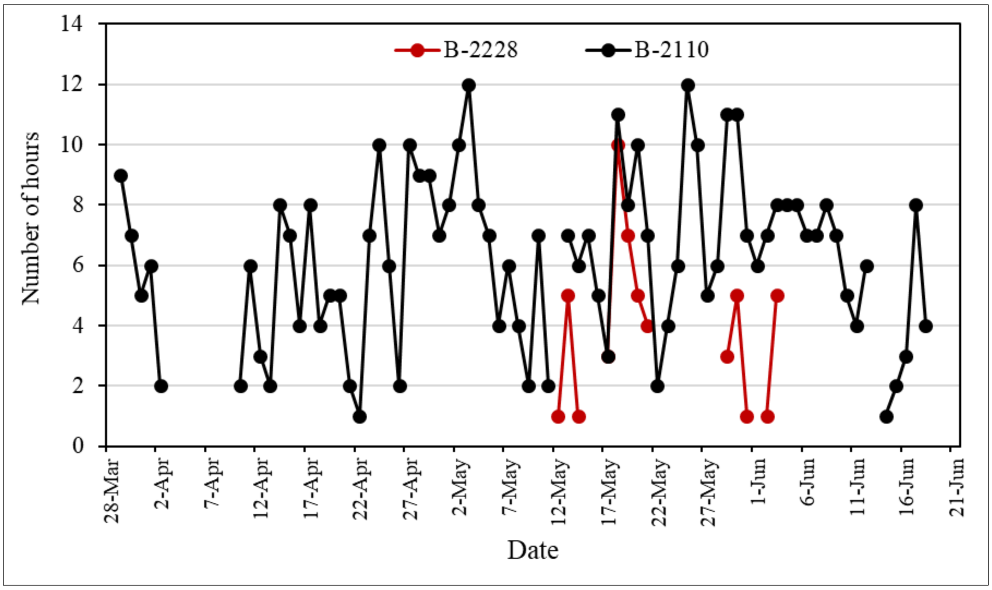

Figure 3 Number of continuous hours and days with relative humidity greater than 90%, recorded by sensors installed within the bean canopy, in two commercial fields in the Yaqui Valley, Sonora, Mexico, during the spring season 2023.

3.2. Irrigation sheet

The total irrigation sheet applied in field B-2110 was 50.4 cm, with an average application frequency of 12.1 days. A total of eight irrigations were applied with an average water sheet of 6.3 cm for each irrigation (Figure 4). On the other hand, the amount of water applied and the number of irrigations were greater in B-2228 than in B-2110, with a total water sheet of 59.6 cm distributed in 14 irrigations (avg 4.3 cm for each irrigation), and a frequency of 5.6 days.

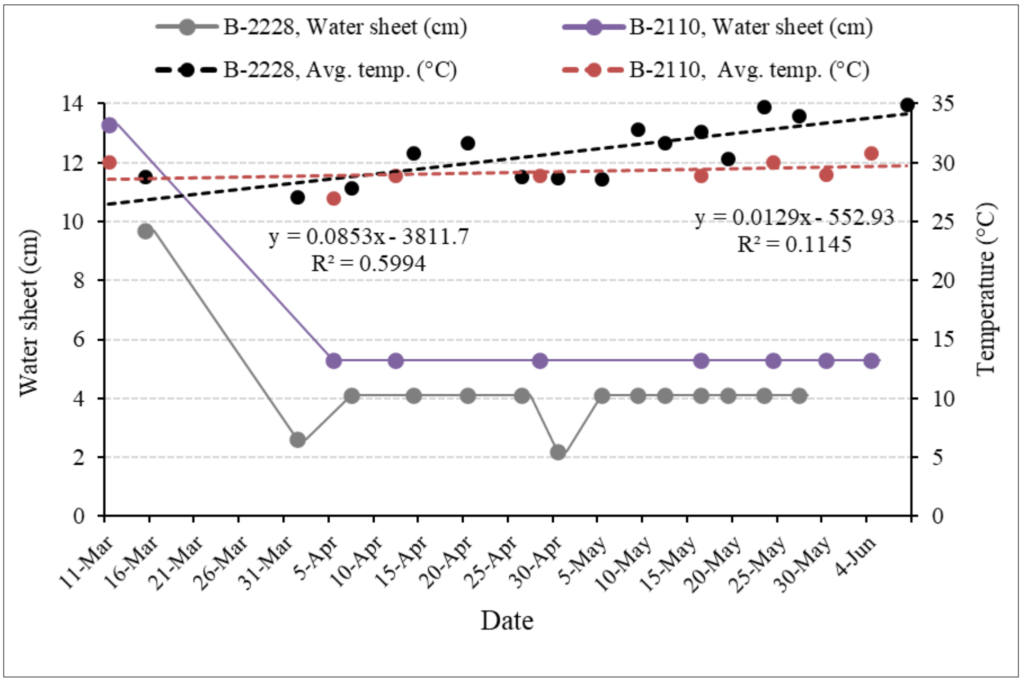

Figure 4 Average temperature between irrigation intervals, recorded by sensors installed within the bean canopy, in two commercial fields in the Yaqui Valley, Sonora, Mexico, during the spring season 2023.

When relating the maximum temperature recorded by sensors during irrigations, it is observed that the temperature was more stable during the irrigation period of the field B-2110 than in B-2228 with a range of 27 to 30.8°C; there was a tendency increase of 0.0129°C per day with the frequency of 12.1 days between irrigations. While in field B-2228, the temperature range was 27.1 to 34.9°C; there was a tendency increase of 0.085°C per day with a frequency of 5.6 days between irrigations. Padilla-Valenzuela *et al*. [11] reported that bean is highly sensitive to water deficit during flowering, because it causes a reduction in the root system due to the death of older roots and the effect is irreversible; they also indicated that for cultivated bean during the fall-winter season in northwest Mexico, it requires around 34 cm and for the spring-summer season around 41 cm. Previous studies indicate that water stress will cause a reduction in the size and number of grains per pod, consequently a reduction in grain yield per area [27,28,29,30,31].

3.3. Analysis of variance

The mean squares of the grain weight, total pods, pods with grain, grains per pod and error obtained from the analysis of variance, as well as the coefficient of variation are presented in Table 2. Highly significant differences were detected between each of the parameters that are related to production and grain quality.

Table 2 Analysis of variance of bean yield components in two commercial fields sown with cultivar Pinto Saltillo, in the Yaqui Valley, Sonora, Mexico, during the spring season 2023

SV	SS	DF	MS	F	p-value
Model	29432894.86	4	7358223.72	208.27	<0.0001
Grain weight	19235407.88	1	19235407.88	544.44	<0.0001
Total pods	8419078.03	1	8419078.03	238.29	<0.0001
Pods with grain	323661.64	1	323661.64	9.16	0.0069
Grains/pod	1454747.31	1	1454747.31	41.18	<0.0001
Error	671282.92	19	35330.68		
Total	30104177.78	23			

CV=38.8 (%).

Additionally, the Hotelling´s test was carried out to more clearly understand the relationship between the performance of grain yield components and the irrigation sheets (Table 3). Statistically significant differences were obtained between fields, being higher the averages of the yield components obtained with the smaller water sheet applied, which was applied in 12.1 day intervals between each irrigation.

Table 3 Hotelling´s test for bean yield components and water sheets applied, in two commercial fields sown with cultivar Pinto Saltillo, in the Yaqui Valley, Sonora, Mexico, during the spring season 2023

Field	Water sheet (cm)	kg ha^{-1}	Total pods	Pods with grain	Grains per pod	($p > 0.05$)
B-2110	50.40	2,968.89	307.53	269.93	3.22	A
B-2228	59.60	1,511.11	275.90	229.36	2.72	B

Despite that during the phenological stages of flowering and grain-filling the average temperature during the day was higher in field B-2228 (Table 1), the average grain yield during the season was significantly higher with higher average recordings of temperature and relative humidity that prevailed in B-2110 (22.2°C, 68.2% RH), B-2228 (21.6°C 63.9% RH). The variability of the data analyzed is attributed to the difference in climatic conditions and the technological management that the farmer provided to each field. Highlighting that B-2110 is located closer to the coastal influence than B-2228. Furthermore, it must be considered that in B-2228 there were more continuous periods of temperatures higher than 33°C than in B-2110, that occurred during the season, which affected flowering and consequently grain yield. Porch and Jahn [32] reported that day temperatures above 30°C and night-time temperatures above 20°C cause abortions of flowers, flower buds and pods, as well as reduced pollen viability and damage in the pollen tube. When high temperature conditions are prolonged and the bean cultivar is susceptible, losses of up to 100% grain yield may occur; even with tolerant materials, yields are seriously reduced [33,34,35,36,37]. In relation to the two sowing dates in each field (Table 4), grain yield varied from 1,204 to 3,271 kg ha^{-1}; both sowing dates in field B-2228 had lower yields than

B-2110; the second date had the lowest yield, but it was statistically similar to the yield in the first date. The highest yield was obtained in the first date of field B-2110 with 3,271.1 kg ha^{-1}, and the second highest yield was obtained in the second date of the same field, and both were statistical similar. The higher water sheet applied to field B-2228 as well as the higher number of water applications, might have had an adverse effect on grain yield.

Table 4 Average grain yield by sowing date in two commercial fields sown with bean cultivar Pinto Saltillo, in the Yaqui Valley, Sonora, Mexico, during the spring season 2023

Field	Sowing date	Grain yield ($kgha^{-1}$)	($p > 0.05$)
B-2110	09-mar	3,271.11	A
B-2110	25-mar	2,666.67	A B
B-2228	03-mar	1,817.78	B C
B-2228	27-mar	1,204.44	C

LSD=1405.5.

Ugalde *et al*. [38] reported that high irrigation levels cause excess humidity, which generates seed rot in the germination stage, plant death due to anaerobiosis, limited plant development due to erosion and soil compaction, emergence and accelerated development of weeds. Also, López and Acosta [39] and Mayek *et al*. [40] agreed that the excess water favors the presence of diseases in the foliage such as rust, angular leaf spot [*Phaeoisariopsis griseola* (Sacc.) Ferraris], and common bacterial blight, as well as root rots which reduce plant population. However, in the present work, it was not evaluated the possible effect of biotic factors that might have had influence in the outcome.

3.4. Grain quality

In bean field B-2110, a loss of 29.8% (grain without consumption quality and undeveloped grain) was obtained on the first sowing date and 32.6% on the second date; in B-2228, the percentage of loss amounted to 36.8% in the first sowing date and 48.7% on the second date (Figure 5). The analysis of the information shows that grain development was mainly affected by the late sowing date.

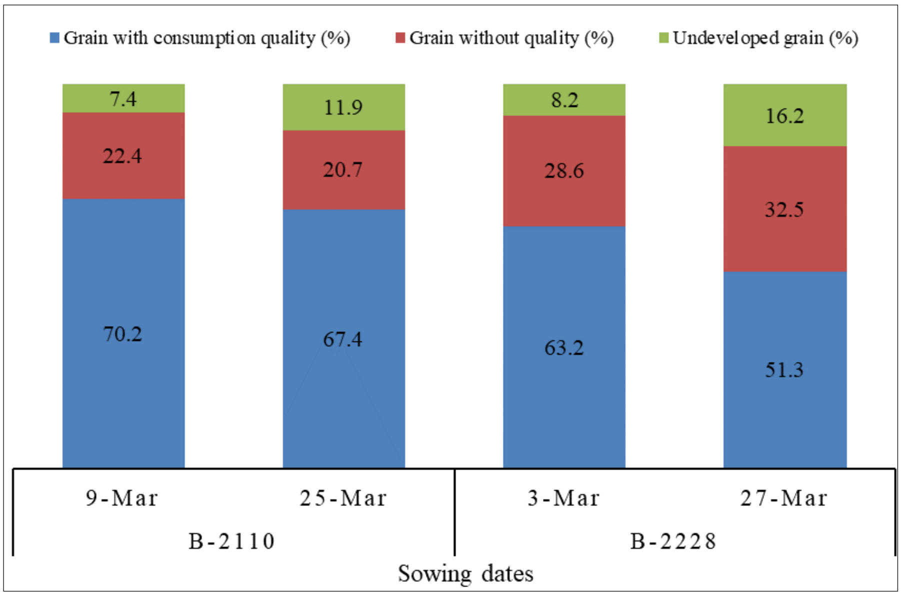

Figure 5 Loss of grain quality for consumption in relation to the sowing date and irrigation management of two commercial fields sown with bean cultivar Pinto Saltillo, in the Yaqui Valley, Sonora, Mexico, during the spring season 2023

Figure 6 A) Bean grains that do not comply with quality for consumption. B) Grains of good quality. C) Pods and grains. D) Pods with grains with good and low quality

The joint effect of irrigation management, temperature and relative humidity, reduced the complete development of the grain and the quality for consumption. The difference in the number of hours and number of continuous periods of temperature greater than 33°C and relative humidity greater than 90% was related to the fruitful stage of the crop. This coincides with the findings of Omae *et al*. [41,42,43], who reported that the effect of the temperature generates a lower water content in the leaf tissue, an increase in photo-inhibition rates, and a lower translocation of assimilates to the reproductive organs, which results in poor bean quality. Therefore, the extreme values of temperature and relative humidity are related in both fields, with a lower number of pods with grain, lower grain weight, and with the high percentage of poor quality grain and undeveloped grain (Figure 6).

Guzmán Tovar *et al*. [44] reported that the cleanliness, uniformity and color of the bean grain, is the first impression that the consumer receives and that well defines their purchase decision.

4. Conclusion

The number of hours and continuous periods of temperature greater than 33°C and relative humidity greater than 90%, during the fruitful stage of the crop, was related to the greatest number of pods without grain and the lowest grain weight, with a significant reduction in the quality for consumption.

Bean grain yield varied from 1,204 to 3,271 kg ha^{-1}; the highest yield was obtained in field B-2110 on the first date (March 9), where a 50.4 cm irrigation sheet was applied with a 12.1 day interval between a total of 8 irrigations; while the lowest yield was obtained in B-2228 on the second date (March 27) where an irrigation sheet of 59.60 cm was applied with a 5.6 day interval between a total of 14 irrigations.

The consumption quality of the grain was mainly affected in the late sowing dates, where losses of 32.6 to 48.7% were obtained in fields B-2110 and B-2228, respectively.

It should be considered that sowing in the spring season in the Yaqui Valley, must be carried out before the risk of high temperature levels increases, and also, areas with high levels of relative humidity should be avoided.

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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