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RECEIVED 04 February 2026
REVISED 24 April 2026
ACCEPTED 04 May 2026
PUBLISHED 26 May 2026

CITATION
Goodspeed I, Jia X, Vishnumolakala SSS
and Hatterman-Valenti H (2026)
Cultivar-specific irrigation responses of
bell pepper (*Capsicum annuum*) in high
tunnel and open-field environments.
Front. Hortic. 5:1804248.
doi: 10.3389/fhort.2026.1804248

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Cultivar-specific irrigation responses of bell pepper (*Capsicum annuum*) in high tunnel and open-field environments

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Introduction: Efficient irrigation management and cultivar selection are critical for improving water productivity and sustaining yield stability in protected vegetable production systems under increasing climatic variability. High tunnel (HT) environments can modify temperature and evapotranspiration dynamics, thereby influencing crop responses to irrigation management. This study aimed to identify bell pepper cultivars with high productivity and stable performance under deficit irrigation strategies in contrasting HT and open field (OF) environments.

Methods: A two-year field study was conducted during the 2022 and 2023 growing seasons to evaluate the performance of Bell pepper cultivars under three irrigation strategies in HT and OF production systems. Irrigation treatments included 10% management allowable depletion (MAD), 30% MAD, and conventional time-based irrigation scheduling. Yield components, marketable and unmarketable yield, fruit number, and fruit size attributes were measured to assess cultivar productivity, irrigation responsiveness, and performance stability across environments.

Results: The HT environment moderated diurnal temperature fluctuations while maintaining consistently higher minimum temperatures than the OF environment, with seasonal increases ranging from 1.1 to 5.2 °C and maximum temperatures occasionally reaching 40.7 °C. Significant cultivar × irrigation interactions were observed under HT conditions for total yield, marketable yield, and fruit number, indicating differential cultivar responses to soil moisture management. Cultivars such as Early Sunsation and King Arthur produced greater yields under MAD-based irrigation treatments, demonstrating strong responsiveness to optimized soil water depletion and improved production efficiency under deficit irrigation. Conversely, cultivars including Ninja and X3R Red Knight maintained relatively stable yields across irrigation treatments, suggesting greater physiological stability and adaptability to reduced irrigation inputs. Under OF conditions, irrigation treatments did not significantly influence yield parameters, likely because rainfall and lower evaporative demand minimized

differences in soil water availability among treatments. However, cultivar effects significantly influenced unmarketable yield, primarily due to physiological disorders such as sunscald and blossom-end rot. Fruit size characteristics remained relatively stable across irrigation treatments and were predominantly determined by genetic factors.

Discussion: The results demonstrated substantial genotypic variation in irrigation responsiveness and water-use efficiency among bell pepper cultivars under protected cultivation. Deficit irrigation strategies based on MAD thresholds improved irrigation efficiency without compromising productivity in adapted cultivars, particularly under HT conditions where elevated thermal demand increased the importance of precise soil moisture management. Cultivars exhibiting both high productivity and stable performance under reduced irrigation represent promising genetic resources for sustainable protected vegetable production. Integrating cultivar selection with precision irrigation management may therefore enhance yield stability, resource-use efficiency, and climate resilience in HT bell pepper production systems.

KEYWORDS

bell pepper cultivars, high tunnel, Irrigation scheduling, management allowable depletion (MAD), season extension, water deficit irrigation

1 Introduction

Although the function of a high tunnel (HT) is based on the function of a greenhouse, HTs are distinct due to passive heating and cooling and flexible plastic covering (Lamont, 2005; Wien, 2009). In HTs, plants are typically grown directly in the soil, whereas in greenhouses, they are often cultivated in containers on benches. These tunnel-like structures are increasingly used to protect crops from unfavorable weather and extend the growing season by creating a more favorable microclimate (Lamont, 2009; Zhao and Carey, 2009). Such environments can extend production by 1 to 4 weeks in spring and 2 to 8 weeks in fall (Wells and Loy, 1993). Tomato (*Solanum lycopersicum*) and bell pepper (*Capsicum annuum*) are among the most economically important crops grown in HTs (Lamont, 2009).

Bell pepper originated in South and Central America and is now cultivated worldwide as a high-value vegetable crop (Hernández-Pérez et al., 2020). Its fruits are consumed in various forms, including fresh, processed, and dried products (Hernández-Pérez et al., 2020). Similar to tomato, bell pepper is sensitive to water stress (Wahid et al., 2007; Steduto et al., 2012), particularly during flowering and fruit development stages, while also being adversely affected by excessive soil moisture and poor aeration (Mačkić et al., 2023). Research has also shown that a moderate deficit irrigation can enhance water use efficiency (WUE) without compromising productivity (Kabir et al., 2021).

Drip irrigation has been widely adopted as an efficient water management strategy in vegetable production systems, including tomato, cucumber (*Cucumis sativus*), and muskmelon (*Cucumis melo*) (Du et al., 2017; Wang et al., 2018, 2019). This system

minimizes water losses and improves application efficiency (Cassel Sharmasarkar et al., 2001; Sun et al., 2013) and crop yield responses can be effectively managed through regulated water and nutrient supply strategies, including fertigation and differential irrigation scheduling (Kumar et al., 2020). However, effective drip irrigation management remains challenging due to system complexity and associated costs (Yang et al., 2023). Consequently, precise irrigation scheduling is essential for optimizing water use in high-value cropping systems (Dukes, 2020).

Sensor-based irrigation scheduling has emerged as a promising approach for improving water management by integrating soil moisture monitoring and crop water demand (Shortridge and Porter, 2021). In this context, management allowable depletion (MAD) thresholds are used to guide irrigation timing by defining the level of soil water depletion at which irrigation should be initiated. Soil matric potential provides a direct measure of plant-available water and root-zone hydraulic conditions, making it particularly suitable for irrigation control (Hanson and Peters, 2000; Thompson et al., 2007).

The selection of soil matric potential thresholds of -10 and -20 kPa (10% and 30% MAD) is supported by both soil physical principles and plant physiological responses. Soil water potentials near -10 kPa are generally associated with conditions close to field capacity in coarse- to medium-textured soils, where hydraulic conductivity remains high and plant water uptake is not limited (Campbell and Norman, 1998; Smajstrla and Locascio, 1996). Under these conditions, stomatal conductance and transpiration rates are typically maximized. In contrast, -20 kPa represents the onset of mild soil water deficit, where water remains readily available but requires greater root effort for extraction, often leading to partial stomatal regulation and improved WUE (Jones, 2004; Wang et al., 2007). Empirical studies in vegetable crops further support this range, showing that maintaining soil matric potential between -10 and -20 kPa sustains yield while enhancing WUE

Abbreviations: HT, high tunnel; OF, open field; MAD, management allowable depletion; NDAWN, North Dakota agricultural weather network; Max, maximum; Min, minimum; Avg, average.

relative to wetter conditions (Shock et al., 1998; Wang et al., 2007). Collectively, this range represents a critical transition between non-limiting and moderately deficit soil moisture conditions, making it well suited for irrigation strategy evaluation in intensive vegetable systems.

Despite advances in irrigation technologies, a clear gap remains in understanding how physiologically based soil moisture thresholds influence crop performance under contrasting production environments such as HT and open field (OF) systems. The interaction between irrigation scheduling and the modified microclimate of HTs, which are characterized by higher temperatures, reduced rainfall, and increased evapotranspiration, remains insufficiently quantified for bell pepper production.

We hypothesize that moderate deficit irrigation (30% MAD) will maintain comparable yield and fruit quality to well-watered conditions (10% MAD), while improving WUE, particularly under HT conditions. Additionally, we expect that sensor-based irrigation scheduling will outperform time-based irrigation by more effectively matching water application with crop demand. Accordingly, the objective of this study was to evaluate bell pepper cultivar growth and yield responses to soil moisture-based drip irrigation scheduling at 10% MAD and 30% MAD, compared with conventional time-based irrigation under HT and OF conditions.

2 Materials and methods

2.1 Experimental location and design

Field experiments were conducted during the 2022 and 2023 growing seasons under HT and OF conditions at the North Dakota State University (NDSU) Horticulture Research Farm in Cass County, near Absaraka, ND (46°59'28.2" N 97°21'19.9" W, elevation of 1,070 m). The region has a continental climate with an annual precipitation of 380–760 mm and minimum winter temperatures averaging −34 °C (hardiness zone 4a) (Tollerud et al., 2018). The soil is classified as a Warsing series (fine-loamy over sandy or sandy-skeletal, mixed, superactive, cold oxyaquic hapludolls) with well-drained loam over sand and gravel (USNRCS, 1983).

Plots were prepared using standard tillage, and raised beds (4.6 m × 0.69 m) were formed with 1.83 m row spacing. The experiment followed a split-plot design with irrigation as the main plot and cultivar as the subplot, arranged in three replications. Irrigation treatments included the standard time-based irrigation (three times weekly for 24 min at 09:00 h) and two soil moisture-based irrigation at −10 and −20 kPa thresholds (corresponding to 10% and 30% MAD, respectively). Eight bell pepper F1 hybrid cultivars ("Olympus", "Ninja", "X3R Red Knight", "Classic", "King Arthur", "Early Sunsation", "Intruder", and "Orange Blaze") were evaluated. Weather data, air temperature, and relative humidity were recorded using a nearby North Dakota Agricultural Weather Network (NDAWN) station located near Prosper, ND. Relative humidity and temperature sensors from the NDAWN station were

installed 1.5 m above the soil surface. To monitor indoor and outdoor air temperature, one EM50 data logger (Decagon Devices, Inc., Pullman, WA) was implemented at the experimental site. Data loggers were set up to be identical to the NDAWN stations regarding air temperature measurements.

2.2 High tunnel and environmental monitoring

The HT was a gothic-style HT (Northpoint, Rimol Greenhouse Systems, Inc., Hooksett, NH) covered with a double-layer air-inflated 4 year-rated 0.6 mm clear polyethylene greenhouse film treated with anti-condensate and ultraviolet features with 1.18 mm steel framework for support. The length of the HT was oriented north to south with dimensions 29 m long, 9 m wide, and 5 m tall. Ventilation was accomplished by thermostatically controlled electric roll-up sidewalls running the length of both sides set to open at 24 °C and motorized shutter vents in each gable end wall set to open at 25 °C. Additional air circulation during the hot days was provided by manually opening the two large end wall doors.

2.3 Plant establishment and crop management

Seeds were sown into the standard insert 800 series (T.O. Plastics, Clearwater, MN) containing a peat-based growing media (PRO-MIX BX, Premier Tech, Quebec, Canada) 6 weeks before their intended transplant date (HT: 5 May 2022 and 1 May 2023; OF: 1 June 2022 and 12 June 2023) at the NDSU greenhouse Fargo, ND (23.9 °C, 16:8 L:D, RH = 40%–65%). After 3 weeks, seedlings were transplanted into 152-cm³ plastic pots (SVD-450, T.O. Plastics, Clearwater, MN) filled with the same growing media. Seedlings were fertigated weekly using a fertilizer injector (Dosatron International, Clearwater, FL) and a 20-20-20 general-purpose water-soluble fertilizer (JR Peters Inc., Allentown, PA) at 100 mg L^{−1} N. Seedlings for the OF trials were acclimated at a protected outdoor location 1 week prior to transplanting. Two lines of 1.5-mm drip tape with 20.3-cm spacing between emitters (Toro® Aqua-Traxx, DripWorks, Willits, CA) and a 1.89 L min^{−1} flow rate per 30.5-m drip length at a pressure range of 69–103 kPa were installed underneath the 0.025-mm black plastic mulch that was placed over each raised bed to conserve soil moisture and suppress weed seed germination.

Irrigation control boards were installed, both inside and outside the HT, to host various instruments and sensors for irrigation scheduling. One soil potential sensor was connected to a Soil-Click (Hunter Industries, Inc., San Marcos, CA), with the Soil-Click connected to a controller (Hunter PRO C, Hunter Industries, Inc., San Marcos, CA) for each irrigation treatment. A solenoid valve was utilized to trigger each irrigation. A flowmeter (Midwest Instruments and Controls, Rice Lake, WI) and data logger (Onset, HOBO Inc., Bourne, MA) were utilized to record the water amount used for irrigation. Two more flowmeters were mounted at the headline to measure the total flow amount inside and outside the HT. Based on the soil water retention curve generated using the

HYPROP and WP4 systems (Roy et al., 2018), a matric potential of -10 kPa was selected for the 10% MAD threshold, whereas -20 kPa was selected for the 30% MAD threshold. Crop management practices, such as weeding, were done by hand, while pest control was carried out when necessary, according to extension recommendations (El Chami et al., 2023). Calcium nitrate (15.5-0-19 Ca) at the rate of 0.12 kg ha $^{-1}$ was also applied during the growing season as a split application to boost calcium level as the fruits began to form and expand. Fertigation was applied as three splits during the entire growing season to attain a total of 134.5:134.5:134.5 (NPK) kg ha $^{-1}$.

2.4 Data collection and analysis

Fruit were harvested twice per week followed by fruit diameter and height measurements using a digital Vernier caliper. Marketable and culled fruit from each plant were counted and weighed. Culled fruits were determined unmarketable due to blossom end rot (BER) or sunscald symptoms.

Data were analyzed by linear mixed model using SAS PROC MIXED version 9.4 (SAS Institute, Cary, NC). Where applicable, means were separated using Fisher's LSD test at $p < 0.05$. Year and replications were considered random variables, while irrigation and cultivar were fixed variables. Data were combined across years after confirming homogeneity of variances.

3 Results

3.1 Weather data in high tunnel and open field 2022

In June, the OF had a maximum temperature of 38.5 °C, a daily average of 21.2 °C, and a minimum of 3.4 °C (Table 1). The HT temperatures were higher by 1.9 °C for maximum, 1.1 °C for daily average, and 4 °C for minimum compared to the OF. By July, the OF maximum air temperature was 36.6 °C, with a daily average of 22.8 °C and a minimum of 10.6 °C, while the HT remained warmer, exceeding the OF temperatures by 2.3 °C, 1.9 °C, and 2.9 °C, respectively. The highest temperature recorded was 39.6 °C in the HT in June, while the lowest was 3.4 °C in the OF that same month.

TABLE 1 Mean maximum (Max.), daily average (Avg.), and minimum (Min.) air temperature (°C) for the open field and high tunnel at the Horticulture Research Farm near Absaraka, ND, during 2022.

Month	High tunnel ¹			Open field ²		
	Avg (°C)	Max (°C)	Min (°C)	Avg (°C)	Max (°C)	Min (°C)
May	18.2	32.2	3.6	–	–	–
June	23.1	39.6	7.4	21.2	38.5	3.4
July	25.1	38.5	13.5	22.8	36.6	10.6
August	23.2	38.6	12.1	20.8	35.9	8.3

¹High tunnel data are from 11 May to 26 August.

²Open field data represent data from 1 June to 25 August.

3.2 Weather data in high tunnel and open field 2023

In June, the OF temperatures reached a maximum of 35.9 °C, a daily average of 21.8 °C and a minimum of 9.6 °C, while HT temperatures were higher by 2.6 °C, 2.3 °C, and 5.2 °C, respectively (Table 2). In July, the OF temperatures reached a maximum of 36.4 °C, a daily average of 20.6 °C, and a low of 7.1 °C, with temperatures in the HT warmer by 3.1 °C, 4.3 °C, and 4.5 °C respectively. The warmest 2023 temperature of 40.7 °C was in July in the HT, while the lowest temperature of -4.6 °C was in October in the HT.

3.3 High tunnel total yield

The main effects of irrigation and cultivar as well as the irrigation by cultivar interaction were significant for total yield per plant; therefore, only the interaction will be discussed. "Classic", "Intruder", "Ninja", "Orange Blaze", and "X3R Red Knight" had similar total yields across all irrigation treatments (Table 3). "Early Sunsation" and "King Arthur" had greater total yields when plants were irrigated at 10% or 30% MAD compared to time-based irrigation, while "Olympus" had greater total yields when plants were irrigated at 10% MAD or time-based compared to 30% MAD.

3.4 High tunnel marketable yield

The main effects of irrigation and cultivar as well as the irrigation by cultivar interaction were significant for bell pepper marketable yield. When examining the cultivar response to irrigation interaction, "Classic", "Intruder", "Ninja", and "Orange Blaze" were not influenced by irrigation, producing similar marketable yields per plant across all irrigation treatments (Table 4). Similar to total yield, "Early Sunsation" and "King Arthur" had greater marketable yield under the two MAD irrigation treatments compared to the time-based treatment. The same was true for "X3R Red Knight" except that marketable yield under 10% MAD and time-based irrigation was similar.

TABLE 2 Mean maximum (Max.), daily average (Avg.), and minimum (Min.) air temperature (°C) for the open field and high tunnel at the Horticulture Research Farm near Absaraka, ND during 2023.

Month	High tunnel ¹			Open field ²		
	Avg (°C)	Max (°C)	Min (°C)	Avg (°C)	Max (°C)	Min (°C)
June	24.4	38.2	14.8	21.8	35.9	9.6
July	23.7	40.7	11.6	20.6	36.4	7.1
August	23.3	38.1	13.7	20.9	34.6	9.8
September	19.8	37.4	7.8	17.5	35.6	3.7
October	12.4	34.6	-4.6	10.0	34.1	-3.8
November	3.9	20.6	-2.1	–	–	–

¹High tunnel data represent data from 15 June to 2 November.

²Open field data represents data from 15 June to 27 October.

TABLE 3 Influence of irrigation and cultivar on bell pepper total yield per plant (kg) in the high tunnel at the Horticulture Research Farm near Absaraka, ND, combined over 2022 and 2023.

Cultivar	Total yield (kg plant ⁻¹)		
	10% MAD	30% MAD	Time-based
Classic	4.81 a ¹	4.89 a	3.72 a
Early Sunsation	5.45 a	5.40 a	3.62 b
Intruder	4.38 a	4.48 a	4.01 a
King Arthur	6.23 a	5.44 a	3.95 b
Ninja	5.74 a	4.56 a	4.67 a
Olympus	5.02 a	3.01 b	5.12 a
Orange Blaze	3.12 a	3.26 a	2.60 a
X3R Red Knight	5.02 a	5.48 a	4.18 a

¹Means followed by the same letter within a row are not significantly different using Fisher's protected least significant difference (LSD) test at $p < 0.05$.

TABLE 5 Influence of irrigation and cultivar on bell pepper marketable fruit number per plant in the high tunnel at the Horticulture Research Farm near Absaraka, ND, combined over 2022 and 2023.

Cultivar	Marketable fruit number per plant		
	10% MAD	30% MAD	Time based
Classic	39.17 a 1	39.17 a	29.67 a
Early Sunsation	41.17 a	41.00 a	25.33 b
Intruder	33.33 a	34.00 a	30.67 a
King Arthur	48.83 a	45.33 a	29.67 b
Ninja	44.67 a	39.83 a	38.67 a
Olympus	36.17 a	22.67 b	37.00 a
Orange Blaze	44.67 ab	52.33 a	41.67 b
X3R Red Knight	40.83 a	47.00 a	32.33 a

¹Means followed by the same letter within a row are not significantly different using Fisher's protected least significant difference (LSD) test at $p < 0.05$.

3.5 High tunnel marketable fruit number

The main effects of irrigation and cultivar as well as the irrigation by cultivar interaction were significant for marketable number of fruits per plant; thus, analysis focused on the interaction. Cultivars Classic, Intruder, Ninja, and X3R Red Knight produced similar marketable fruit numbers per plant across all irrigation treatments (Table 5). Like total and marketable yield, cultivars Early Sunsation and King Arthur produced more marketable fruit when irrigated by 10% or 30% MAD compared to the number of marketable fruit produced when plants were irrigated under the time-based treatment. The same was true for "Orange Blaze" except that marketable fruit number under 10% MAD and time-based irrigation was similar.

3.6 High tunnel fruit size

Average fruit diameter differed significantly among cultivars, whereas fruit length showed a moderate but significant effect (Table 6). "Intruder" produced the longest fruits (7.91 cm), followed

by "Olympus" (7.79 cm), although these were not significantly different from most cultivars except "King Arthur" (7.62 cm) and "X3R Red Knight" (7.42 cm), which had shorter fruit lengths. Cultivar X3R Red Knight exhibited the shortest fruits overall. Fruit diameter was greatest in "King Arthur" (7.85 cm), although it did not differ significantly from "Intruder" (7.71 cm). "Early Sunsation" (7.67 cm) and "Ninja" (7.61 cm) were intermediate and not significantly different from each other. In contrast, "Classic" (7.24 cm) and especially "Orange Blaze" (5.24 cm) produced significantly smaller fruit diameters compared to other cultivars. Distinct differences in fruit morphology were also observed. "Intruder", "Ninja", "Early Sunsation", "King Arthur", and "X3R Red Knight" produced typical blocky bell-shaped fruits, whereas "Classic" and "Olympus" exhibited more elongated forms. "Orange Blaze" differed markedly from other cultivars, producing elongated, tapered fruits characteristic of non-bell pepper types.

TABLE 4 Influence of irrigation and cultivar on bell pepper marketable yield per plant (kg) in the high tunnel at the Horticulture Research Farm near Absaraka, ND, combined over 2022 and 2023.

Cultivar	Marketable yield (kg plant ⁻¹)		
	10% MAD	30% MAD	Time based
Classic	4.69 a ¹	4.77 a	3.66 a
Early Sunsation	5.43 a	5.24 a	3.40 b
Intruder	4.30 a	4.45 a	3.94 a
King Arthur	6.19 a	5.37 a	3.73 b
Ninja	5.57 a	4.43 a	4.50 a
Olympus	4.97 a	2.94 b	4.80 a
Orange Blaze	3.09 a	3.21 a	2.52 a
X3R Red Knight	4.92 ab	5.38 a	3.91 b

¹Means followed by the same letter within a row are not significantly different using Fisher's protected least significant difference (LSD) test at $p < 0.05$.

TABLE 6 Average bell pepper fruit length, diameter, and shape (length: diameter ratio) in the high tunnel at the Horticulture Research Farm near Absaraka, ND, combined over 2022 and 2023.

Cultivar	Length (cm)	Diameter (cm)	Fruit shape ²
X3R Red Knight	7.42 c ¹	7.65 b	0.97
Classic	7.69 ab	7.24 d	1.06
Intruder	7.91 a	7.71 ab	1.03
Ninja	7.66 abc	7.61 bc	1.01
King Arthur	7.62 bc	7.85 a	0.97
Olympus	7.79 ab	7.45 c	1.05
Orange Blaze	7.75 ab	5.24 e	1.48
Early Sunsation	7.67 abc	7.67 b	1.00

¹Means followed by the same letter within a column are not significantly different using Fisher's protected least significant difference (LSD) test at $p < 0.05$.

²Length-to-diameter ratio; ≤ 0.95 : very blocky, flattened shape; 1.00: blocky, length equal to diameter; ≥ 1.05 : elongated shape with length greater than diameter. Variable was not subjected to statistical analysis.

TABLE 7 Influence of irrigation and cultivar on bell pepper marketable no. of fruits, marketable yield, and total yield in the open field at the Horticulture Research Farm near Absaraka, ND, combined over 2022 and 2023.

Cultivar	Marketable fruit (no. plant ⁻¹)			Total yield (kg plant ⁻¹)			Marketable yield (kg plant ⁻¹)		
	10% MAD	30% MAD	Time based	10% MAD	30% MAD	Time based	10% MAD	30% MAD	Time based
Orange Blaze	21.4	24.5	27.7	1.5	1.6	1.9	1.5	1.6	1.9
Classic	14.3	24.5	14.0	1.9	3.1	1.8	1.9	3.0	1.7
X3R Red Knight	24.2	22.7	12.5	2.9	2.8	1.8	2.9	2.7	1.7
Intruder	17.1	13.7	19.3	2.3	1.9	2.4	2.3	1.8	2.3
Olympus	13.2	7.8	15.5	1.9	1.1	2.3	1.8	1.1	2.0
Ninja	14.4	14.3	11.8	2.1	1.8	1.9	1.8	1.6	1.6
King Arthur	14.0	12.0	12.8	2.1	1.6	1.8	2.1	1.6	1.8
Early Sunsation	12.5	11.3	13.7	1.8	1.5	1.8	1.7	1.3	1.8
Significance ¹	NS	NS	NS	NS	NS	NS	NS	NS	NS

¹Means separated within columns and treatment group using Fisher’s protected least significant difference test ($p < 0.05$). NS = not significant at $p < 0.05$.

3.7 Open field marketable yield

There were no significant differences for total yield, marketable yields, and marketable number of fruits produced in the open field (Table 7). However, marketable fruit numbers ranged from 11 to 27 fruits plant⁻¹ with “Orange Blaze” as the top producer under time-based irrigation. For the total yields, “X3R Red Knight” was the top producer under 10% MAD while “Classic” and “X3R Red Knight” produced the highest weights under 30% MAD.

3.8 Open field unmarketable fruit number

Cultivar had a significant effect on both the number and weight of unmarketable fruit (Table 8).

The incidence of unmarketable fruit varied significantly among cultivars, with most defects attributed to sunscald and BER, although these disorders were not separated analytically (data not

shown). “Ninja” produced the highest number of unmarketable fruits (2.74 fruit plant⁻¹), corresponding to the greatest unmarketable yield (0.29 kg plant⁻¹). In contrast, “Olympus” produced 1.19 unmarketable fruits per plant, which was not significantly different from most cultivars but remained lower than “Ninja”. “Orange Blaze” exhibited the lowest unmarketable yield (0.03 kg plant⁻¹), which was significantly lower than “Ninja” but not statistically different from the remaining cultivars.

3.9 Open field fruit size

The average fruit diameter was highly significant while the average length of the fruit was significant as shown on (Table 9) “King Arthur” measured the widest with a diameter of 7.64 cm but was not significantly wider when compared to “X3R Red Knight”, “Intruder”, and “Ninja” at 7.51, 7.44, and 7.5 cm, respectively. “Classic” measured 6.99 cm but wasn’t significantly wider than

TABLE 8 Effect of cultivar on unmarketable fruit number and unmarketable weight in the open field trial at the Horticulture Research Farm near Absaraka, ND, combined over 2022 and 2023.

Cultivar	Unmarketable fruit number	Unmarketable weight (kg plant ⁻¹)
Classic	0.61 b ¹	0.06 b
Early Sunsation	0.86 b	0.06 b
Intruder	0.88 b	0.12 b
King Arthur	0.22 b	0.03 b
Ninja	2.74 a	0.29 a
Olympus	1.19 b	0.11 b
Orange Blaze	0.63 b	0.03 b
X3R Red Knight	1.06 b	0.11 b

¹Means followed by the same letter within a column are not significantly different using Fisher’s protected least significant difference (LSD) test at $p < 0.05$.

TABLE 9 Average bell pepper fruit length and diameter in the open field at the Horticulture Research Farm near Absaraka, ND, combined over 2022 and 2023.

Cultivar	Length (cm)	Diameter (cm)	Fruit shape ¹
X3R Red Knight	7.83 ab ²	7.51 ab	1.04
Classic	7.67 ab	6.99 c	1.10
Intruder	7.85 ab	7.44 ab	1.06
Ninja	7.76 ab	7.5 ab	1.03
King Arthur	7.94 a	7.64 a	1.04
Olympus	6.82 c	6.87 c	0.99
Orange Blaze	7.64 ab	5.21 d	1.47
Early Sunsation	7.40 b	7.35 b	1.01

¹Length-to-diameter ratio; ≤ 0.95 : very blocky, flattened shape; 1.00: blocky, length equal to diameter; ≥ 1.05 : elongated shape with length greater than diameter. Variable was not subjected to statistical analysis.

²Means followed by the same letter are not significantly different on least significant difference (LSD) test at $p < 0.05$.

“Olympus” at 6.87 cm. “Orange Blaze” had the least diameter of 5.21 cm and was significantly different from the rest of all the cultivars. Cultivars X3R Red Knight, Ninja, King Arthur, Early Sunstation, and Olympus had a blocky shape with their lengths being equal to their diameters while Classic and Intruder had elongated shapes; lengths were greater than the diameter. “Orange Blaze” was much longer than any of the bell peppers tested since it is generally a tapered type of pepper.

4 Discussion

The differential responses observed between HT and OF environments highlight the central role of soil–plant–atmosphere interactions in mediating the effects of irrigation thresholds and cultivar performance. In the HT, significant cultivar $\times$ irrigation interactions for total and marketable yield indicate that crop response was strongly influenced by the combination of elevated temperature, increased vapor pressure deficit (VPD), and controlled soil water availability (Flexas, 2002). In contrast, the absence of such interactions in the OF suggests that environmental buffering by rainfall and lower evaporative demand minimized treatment effects, resulting in more uniform plant water status across irrigation regimes.

HT conditions typically elevate air and soil temperatures while reducing wind and excluding rainfall, thereby increasing atmospheric demand and accelerating soil water depletion (Lamont, 2005). Under these conditions, irrigation thresholds based on soil matric potential (10% MAD vs. 30% MAD) imposed distinct physiological regimes. At 10% MAD, soil water content remains near field capacity, maintaining high hydraulic conductivity and facilitating unrestricted root water uptake, stomatal conductance, and photosynthesis (Campbell and Norman, 1998; Hillel, 1998). Conversely, the 30% MAD threshold represents the onset of mild water deficit, where declining soil water potential reduces hydraulic conductivity and induces partial stomatal closure. This limits transpiration more than carbon assimilation, thereby improving intrinsic WUE (Feres and Soriano, 2007; Wang et al., 2007; Flexas et al., 2004). Under the elevated VPD conditions typical of HTs, this distinction becomes critical, as transpiration demand is amplified and small differences in soil water potential can lead to pronounced differences in plant water status and growth (Allen et al., 2001; Steduto et al., 2012). The importance of precise irrigation control under HT conditions is further supported by findings from Vishnumolakala et al. (2025), who reported that sensor-based drip irrigation improved WUE in both tomato and pepper, particularly within HT systems.

The observed cultivar-specific responses under HT conditions reflect inherent differences in drought adaptation mechanisms. Genotypic variation in traits such as stomatal regulation, osmotic adjustment, root system architecture, and hydraulic conductance can strongly influence plant performance under moderate water deficits (Chavez et al., 2003; Blum, 2010, 2011; Tardieu, 2012). Cultivars that maintained yield under 30% MAD likely exhibited more conservative water use strategies or greater capacity for

maintaining turgor under declining soil water potential. In contrast, more sensitive cultivars may have required near-field-capacity conditions (-10 kPa) to sustain fruit set and growth, particularly under the combined effects of high temperature and VPD. Similar nonlinear responses to deficit irrigation have been reported in pepper and other vegetable crops, where moderate stress can maintain productivity while more severe deficits reduce yield (Feres and Soriano, 2007; Du et al., 2017; Agyemang Duah et al., 2021).

In contrast, under OF conditions, no significant effects of irrigation or cultivar $\times$ irrigation interactions were detected for yield components. This can be attributed to periodic rainfall events that likely maintained soil matric potential above critical thresholds, thereby reducing the distinction between 10% MAD and 30% MAD treatments. Additionally, lower temperatures and reduced VPD would have decreased transpiration demand, further stabilizing plant water status across treatments (Allen et al., 2001; Steduto et al., 2012). These findings are consistent with previous reports indicating that bell pepper can tolerate a range of soil moisture conditions without yield reduction when environmental stress is limited (Dorji and Zegbe-Domínguez, 2005). Collectively, this suggests that the effectiveness of soil moisture-based irrigation scheduling is highly environment-dependent, with greater benefits realized under controlled or high-demand conditions such as HT systems.

While yield responses were relatively stable under OF conditions, cultivar significantly influenced unmarketable fruit number and weight, indicating that fruit quality is more sensitive to genotypic traits than to irrigation under moderate environmental conditions. The majority of unmarketable fruit were affected by sunscald and BER, disorders closely linked to fruit microclimate and calcium transport dynamics rather than total soil water availability (Taylor and Locascio, 2004; Saure, 2001). The BER is associated with inadequate calcium delivery to rapidly expanding fruit tissues, a process governed by transpiration-driven xylem flow and its partitioning among plant organs (Ho and White, 2005). Fluctuations in plant water status, even under adequate soil moisture, can disrupt calcium transport and increase BER incidence (de Freitas et al., 2011; Saure, 2014).

The persistence of these disorders across irrigation treatments suggests that cultivar-specific traits such as canopy architecture, fruit exposure, and calcium use efficiency were primary determinants of fruit quality. For example, cultivars with more open canopies may be more susceptible to sunscald due to increased radiation exposure, while differences in transpiration patterns and vascular development can influence calcium allocation to fruit tissues (Ho and White, 2005; de Freitas et al., 2011). In this study, “Ninja” exhibited the highest incidence of unmarketable fruit, indicating lower adaptability to OF conditions, whereas “King Arthur” and “Orange Blaze” showed greater stability, producing fewer defective fruits. Similar genotype-dependent variation in physiological disorder susceptibility has been reported in pepper (Nahida et al., 2024).

Differences in fruit size and morphology were largely governed by genetic factors and remained relatively stable across environments,

consistent with previous findings that fruit shape and size in pepper are highly heritable traits (Marame et al., 2010). Although water availability can influence fruit expansion, particularly during cell enlargement phases (Marcelis, 1996), the observed variation in fruit diameter and shape among cultivars primarily reflects inherent genetic differences rather than irrigation effects.

Overall, these results demonstrate that the interaction between irrigation thresholds and environmental conditions determines both yield and WUE outcomes, with HT systems amplifying the importance of precise irrigation management due to higher evaporative demand. Moderate soil water deficits (30% MAD) can improve WUE without substantial yield penalties in tolerant cultivars, whereas well-watered conditions (10% MAD) may be required for maximum productivity in more sensitive genotypes. In contrast, under OF conditions, rainfall and reduced atmospheric demand diminish the impact of irrigation treatments, shifting the primary determinant of performance toward cultivar-specific traits. These findings underscore the importance of integrating physiologically based irrigation scheduling with cultivar selection to optimize both productivity and resource use efficiency in diverse production environments.

5 Conclusions

Environmental conditions differed consistently between HT and OF systems, with HTs characterized by elevated temperatures and greater atmospheric demand, which intensified soil moisture depletion and plant water use. These conditions increased the sensitivity of crop performance to irrigation management and highlighted the importance of physiologically based irrigation thresholds.

Under HT conditions, cultivar-specific responses to soil water potential thresholds (10% MAD and 30% MAD) demonstrated that irrigation effects are mediated by genotype-dependent physiological traits. Certain cultivars (e.g., Early Sunset and King Arthur) exhibited enhanced yield under MAD-based irrigation, while others (e.g., Ninja and X3R Red Knight) maintained stable productivity across irrigation regimes, indicating greater tolerance to moderate soil water deficits. These results suggest that moderate deficit irrigation (30% MAD) can improve WUE without substantial yield penalties in adapted cultivars, whereas near-field-capacity conditions (10% MAD) may be required to maximize productivity in more sensitive genotypes.

In contrast, OF production showed minimal response to irrigation treatments, likely due to rainfall inputs and lower evaporative demand maintaining soil water availability above critical thresholds. This indicates that, under field conditions, environmental variability can override irrigation effects, reducing the relative benefit of soil moisture-based scheduling.

Unmarketable yield was primarily influenced by cultivar susceptibility to physiological disorders, particularly sunscald and blossom-end rot, underscoring the role of genotype in regulating

fruit quality through traits related to canopy structure and calcium transport. Fruit size and morphology were largely genetically determined and remained stable across irrigation treatments.

Overall, these findings demonstrate that the effectiveness of deficit irrigation strategies is environment-dependent, with the greatest benefits realized under HT conditions where water availability can be precisely controlled. Integrating cultivar selection with soil moisture-based irrigation thresholds provide a practical framework for optimizing yield, improving WUE, and enhancing sustainability in protected vegetable production systems.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

IG: Data curation, Methodology, Writing – review & editing, Investigation, Validation, Writing – original draft, Formal analysis. SV: Investigation, Methodology, Validation, Writing – review & editing. XJ: Methodology, Validation, Conceptualization, Writing – review & editing. HH-V: Conceptualization, Methodology, Writing – review & editing, Data curation, Funding acquisition, Project administration, Software, Supervision, Visualization.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This project was supported by the North Dakota Department of Agriculture Specialty Crop Block Grant (#21-346).

Acknowledgments

The authors would like to thank all those who contributed to the successful completion of the research, including Mr. Colin Auwarter and Dr. Dongqing Lin.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

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