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RESEARCH ARTICLE

Tapered deficit irrigation strategies can reduce water use in processing tomatoes

Tapered deficit irrigation improved water use efficiency in processing tomatoes without reducing yield or Brix across three field seasons.

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Abstract

California processing tomato growers must adapt their irrigation management practices to cope with frequent droughts and increasingly limited groundwater supplies. Processing tomatoes' water stress tolerance provides a water savings opportunity through deficit irrigation. However, it is important to initiate deficit irrigation at key growth stages to maintain yields. We conducted a deficit irrigation experiment over three years using a randomized block design with four treatments in three commercially operated fields in Fresno County. A tapered deficit treatment was applied, where the amount of water deficit was increased partway through the deficit period to ease the crop into higher water stress while further reducing irrigation. In all three seasons, there were no differences between treatments in yield, with some seasons having an improvement in Brix with the higher deficit treatments. This was achieved with up to a 29% reduction in irrigation compared to the grower's standard practice. The results of this study suggest that tapered deficit irrigation can be a viable option for optimizing water savings in processing tomato systems.

Processing tomatoes (*Solanum lycopersicum*) are the primary ingredient in a diverse array of food products such as sauce, ketchup, and tomato paste and play a pivotal role in California agriculture. California is a major global producer of processing tomatoes, producing 12.8 million tons (11.6 million tonnes) annually and accounting for 96% of the United States' production, and bringing in an average annual revenue of $960 million (USDA NASS 2024). Most of the 230.6 thousand acres (93.4 thousand hectares [ha]) planted in 2022 were located in Fresno, Yolo, and Kings counties (52.9, 34.1, and 29.9 thousand acres or 21.4, 13.8, and 12.1 thousand ha, respectively) (USDA 2022). Processing tomatoes in California receive an average of 25 inches (in) (635 millimeters [mm]) of irrigation throughout the course of their season (Miyao et al. 2013). The annual average water use of processing tomatoes totals 156 billion gallons (593 million cubic meters) in the state of California (Miyao et al. 2013; USDA 2022).

Tomato beds. The authors' research shows that using a tapering strategy is a commercially viable option for processing tomato growers with limited freshwater allocations and access to groundwater. *Photo:* Logan Ebert.

The Central Valley of California, particularly Fresno County, faces ongoing challenges with agricultural water shortages due to frequent drought. Over the past decade, many growers in the region have not received their expected surface water allocations, highlighting the persistent issue of water scarcity (Fresno County 2022). This creates a difficult situation with high annual uncertainty, causing growers to use saline groundwater or fallow their fields. The low recharge, reduced leaching, and high agricultural groundwater use in Fresno County leads to challenges with salt accumulation and groundwater depletion, reducing the viability of supplementing surface water allocations with groundwater in future dry years (Kang and Jackson 2016). To comply with Sustainable Groundwater Management Act (SGMA) goals to reduce groundwater overuse and make the best of allocated water, growers are in need of water-saving irrigation strategies.

Deficit irrigation has been a long-studied water saving management strategy in processing tomatoes (Carucci et al. 2023; Mitchell et al. 1991; Patanè et al. 2011; Sepaskhah and Ghahraman 2004). The deficit irrigation treatments in these previous studies were based on either a percentage of potential crop evapotranspiration (ET_c) or a maximum allowable depletion of available water content in the soil. These previous studies demonstrate a consensus that deficit irrigation performs best after the fruit has set (Johnstone et al. 2005; Kuşçu et al. 2014; Lovelli et al. 2017; Lu et al. 2019; Patanè and Cosentino 2010; Patanè et al. 2011; Valcárcel et al. 2020; Wang et al. 2015).

Cultivar also plays a significant role in the success of deficit irrigation, with some cultivars being more tolerant of water stress (Beaulieu and Swett 2022; Bogale et al. 2016; Giuliani et al. 2017; Ripoll et al. 2016). Across cultivars, most studies found that irrigating at a rate >50% ET_c after fruit set had a negligible impact on yield with mixed impacts on fruit quality (Kuşçu et al. 2014; Lovelli et al. 2017; Patanè and Cosentino 2010; Patanè et al. 2011; Valcárcel et al. 2020). However, studies have also found that irrigating at rates <50% ET_c after fruit set resulted in yield reductions. A few studies have used a tapering strategy in which the percentage of ET_c irrigated is ramped down over the remaining part of the season after fruit set to ease the plants into harsher deficits (Kuşçu et al. 2014; Patanè et al. 2011). Additionally, in some cultivars, deficit irrigation has been found to improve certain marketable quality parameters, including degrees Brix (°Bx) (Johnstone et al. 2005; Patanè et al. 2011; Takács et al. 2020; Valcárcel et al. 2020). While these studies show promise for deficit irrigation in processing tomatoes, growers need more information about how much deficit to apply and the effectiveness of different tapering strategies.

The aim of this research was to evaluate the impact of tapered deficit irrigation on processing tomato yield, fruit quality, and water savings. We hypothesized that yield and fruit quality would either improve or stay the same under tapered deficit irrigation.

Site description and irrigation treatment

Our study took place on a commercial farm in Fresno County, conducted on three different fields for each of the 2020, 2021, and 2022 growing seasons to account for crop rotations. Summer daily mean temperatures ranged from 52.7°F to 92.84°F (11.5°C to 33.8°C) for the three growing seasons, with daily reference evapotranspiration (ET_o) ranging from 0.05 to 0.40 in (1.23 to 9.96 mm). Air temperature and ET_o values came from the California Irrigation Management Information System (CIMIS) meteorological station located in Five Points, California.

Each field within the farm was managed similarly by the same grower. Irrigation was supplied via subsurface drip buried at 10 in (25 centimeters [cm]) with an emitter spacing of 12 in (30 cm). The bed width was 5.6 feet (1.7 meters [m]) and these fields were single planted with a spacing of 13.8 in (35 cm). Web Soil Survey classified the three fields as Colfax clay loams from 0 to 12 in (0 to 30 cm) (USDA NRCS 2023). Cultivars were selected for each year of the study (H5508, SVTM9023, and SVTM9016 for 2020–2022, respectively) because of similar marketable yield, quality parameters, and planting/harvest dates.

We designed the deficit irrigation experimental schedule using ET_c values for processing tomatoes in California. These were estimated using weekly CIMIS reference ET values multiplied by processing tomato crop coefficients (Dong et al. 1992; Doorenbos and Pruitt 1977). Four irrigation treatments were used for this study: control, low stress, high stress, and tapered (table 1). Treatments followed a randomized block design with three replicates. Replicates were 2.0, 1.3, and 3.3 acres (0.8, 0.5, and 1.3 ha) for the 2020–2022 seasons, respectively. Growers in Fresno County have expressed interest in deficit irrigation (CTRI 2021) and some, including our grower collaborator, have already opted to apply a standard deficit of 75% ET_c after the fruit has set. Following this practice, we implemented a 75% ET_c deficit after the fruit set as the control. We did not include any 0% ET_c treatments following fruit set; current research indicates that such treatments cause significant yield reductions (Bogale et al. 2016; Lovelli et al. 2017; Patanè et al. 2011; Takács et al. 2020). Irrigation amounts between treatments were consistent until fruit set, after which the deficit irrigation treatments began. The control and the tapered deficit treatment both employed a tapering strategy where halfway between the start of the deficit initiation and dry down, the amount of deficit irrigation was increased to full deficit. Finally, a dry down period was applied where irrigation was completely cut off to prompt ripening (table 1). We imposed four different irrigation management periods across treatments: full irrigation, initial deficit, full deficit, and dry down (table 1). Important management dates can be found in table 2.

Assessing marketable value and yield

We conducted harvest assessments within the week of harvest for each year. For 2020, a 3.3-foot (1 m) transect was taken from each of the replicates where all the marketable fruit (excluding green, rotten, or damaged fruit) were weighed per transect (sampling was not as robust for the 2020 season, as the team had fewer members during the COVID-19 pandemic). For 2021 and 2022, three 6.6-foot (2 m) transects were taken from each of the replicates where all the marketable fruit were weighed per transect. The yield from the transects were scaled up to hectares by using the transect length and the bed width. For all three years, three composite samples were collected from each replicate and were taken to a Processing Tomato Advisory Board grading facility (Los Gatos Tomato Products, Huron, Calif.) to be tested for Brix. A one-way ANOVA was conducted for yield and Brix between the different deficit treatments.

There were no significant yield differences among treatments in any of the three seasons, with mean values of 45.8, 55.7, and 63.1 tons acre^{-1} (102.7, 124.8, and 141.4 tonnes ha^{-1}), for the 2020–2022 seasons, respectively (table 3). In Fresno County, yield across all cultivars was 57.3, 49.8, and 47.3 tons acre^{-1} (128.5, 111.7, and 106.0 tonnes ha^{-1}) for the 2020–2022 seasons, respectively (USDA 2020; USDA 2021; USDA 2022).

There were significant differences in °Bx across treatments in both the 2020 and 2022 seasons (table 3). In 2020, the low stress (6.03 °Bx) and high stress (6.20 °Bx) treatments had significantly higher °Bx than the control (5.61 °Bx), but the tapered (5.77 °Bx) treatment was not found to be significantly different from any of the other treatments. In 2022, the tapered (5.40 °Bx) and high stress (5.31 °Bx) treatments were significantly higher than the control (4.99 °Bx), but the low stress (5.13 °Bx) treatment was not significantly different from any of the other treatments. There were no significant differences across treatments in the 2021 season and the mean °Bx across all treatments was 5.21 °Bx (table 3). In Fresno County, each season's respective cultivar had a mean of 4.78, 5.64, and 5.36 °Bx for the 2020–2022 seasons, respectively (PTAB 2019; PTAB 2021; PTAB 2022).

The harvest assessment was consistent with previous studies where a deficit applied after fruit set had no negative effects on yield and Brix (Kuşçu et al. 2014; Mitchell et al. 1991; Patanè and Cosentino 2010; Patanè et al. 2011; Valcárcel et al. 2020).

Measuring water use reduction

Total irrigation was highest in the 2020 season with 28.3, 25.9, 24.2, and 25.4 in (719, 657, 614, and 646 mm) applied to the control, low stress, high stress, and tapered treatments, respectively (table 4). Total irrigation in the 2021 season applied 27.2, 26.0, 24.6, and 25.2 in (690, 661, 625, and 640 mm) to the control, low stress, high stress, and tapered treatments, respectively (table 4). Total irrigation was the lowest in the 2022 season with 26.3, 23.7, 21.5, and 22.8 in (667, 602, 580, and 546 mm) applied to the control, low stress, high stress, and tapered treatments, respectively (table 4). Differences in total irrigation of the three years are expected because the duration of full irrigation, from transplanting to deficit initiation, was 85, 75, and 70 days for 2020–2022, respectively.

Comparing the amount of irrigation used for each treatment relative to control, we calculated the water

TABLE 1. Deficit irrigation treatment schedules using California Irrigation Management Information System potential crop evapotranspiration estimates for processing tomato (ET_c)

Treatment	Full irrigation	Deficit initiation	Full deficit	Dry down
Control	100% ET_c	75% ET_c	50% ET_c	0% ET_c
Low stress	100% ET_c	50% ET_c	50% ET_c	0% ET_c
High stress	100% ET_c	37% ET_c	37% ET_c	0% ET_c
Tapered	100% ET_c	50% ET_c	37% ET_c	0% ET_c

TABLE 2. Important dates for the three field seasons

Year	Full irrigation (transplant date)	Deficit initiation	Full deficit	Dry down	Harvest
2020	May 21	August 19	September 02	September 17	October 08
	(0)*	(85)	(105)	(120)	(140)
2021	May 20	August 17	September 01	September 11	September 27
	(0)	(75)	(105)	(115)	(129)
2022	May 01	July 11	August 05	August 23	September 09
	(0)	(70)	(95)	(114)	(131)

* Days since transplanting are in parentheses.

Deficit initiation occurred at fruit set. The full deficit started around halfway between deficit initiation and the anticipated dry down period.

savings (%) for each season. In 2020, there was a water savings of 8.6%, 14.6%, and 10.1% for the low stress, high stress, and tapered treatments, respectively. There was a water savings in 2021 of 4.3%, 9.5%, and 7.3% for the low stress, high stress, and tapered treatments, respectively. In 2022, there was a water savings of 17.2%, 29.1%, and 20.1% for the low stress, high stress, and tapered treatments, respectively. The variability in water savings and water use efficiency across the three seasons was in part because deficit irrigation was initiated at a different time each year relative to transplanting dates (table 2). The time it took for the fruit to set each year varied, changing the amount of time each season was under the different deficit treatments. For example, 2022 had the greatest difference in water use between treatments due to having the earliest fruit set (70 days after transplanting). Additionally, differences in evaporative demand also changed the irrigation requirements during the different seasons' deficit periods.

We calculated irrigation water use efficiency (IWUE) for each treatment as the ratio of the fresh weight of marketable yield to the water applied as irrigation expressed as pounds of tomatoes per cubic feet of water applied (lb ft^{-3}) (Cerasola et al. 2022). IWUE averaged 0.99, 1.17, and 1.48 lb ft^{-3} (15.8, 19.1, and 23.8 kilograms of tomatoes per cubic meter of water applied [kg m^{-3}]) across all treatments for the 2020–2022 fields, respectively (table 4). The 2022 season was the only one where there were significant differences among treatments in IWUE. The high stress (1.58 lb ft^{-3} [25.3 kg m^{-3}]) and tapered (1.56 lb ft^{-3} [25.0 kg m^{-3}]) treatments had higher IWUE than the control (1.32 lb ft^{-3} [21.1 kg m^{-3}]), but the low stress (1.47 lb ft^{-3} [23.6 kg m^{-3}]) treatment was not significantly different in IWUE from the other treatments (table 4).

Tapered deficit irrigation in practice

Processing tomato cultivars change rapidly each season in response to shifting goals and parameters for processing and agronomic management. We selected the three cultivars in this study (H5508, SVTM9023, and SVTM9016 for 2020–2022, respectively) because they were late season (high irrigation demand). In terms of marketable quality parameters, all three of these cultivars performed well when a deficit was applied after fruit set.

We observed either a significant increase or no significant reduction in yield and Brix with our deficit treatments, but this is not the case for every cultivar (Bogale et al. 2016; Takács et al. 2020). Cultivars differ in responses to stress, with some varieties showing signs of stress with no reduction in performance (Giuliani et al. 2017). However, more research is needed on how changes in irrigation under deficit strategies influence disease dynamics, as shifts in canopy microclimate and soil moisture can affect pathogen pressure and crop susceptibility (Swett 2020).

Our high stress treatment also had the highest IWUE across the board and the highest Brix in 2020 and 2022.

The tapered strategy offers a balanced approach, maintaining strong performance in both yield and Brix while gradually increasing water stress to conserve more water toward the end of the season.

TABLE 3. Marketable quality parameters from harvest assessment across the different deficit treatments

	Year	Control	Low stress	High stress	Tapered
Yield tons/acre (tonnes/hectare)	2020	46.1 ± 5.4 (103.4 ± 12.0)	45.8 ± 6.5 (102.7 ± 14.6)	46.3 ± 7.5 (103.7 ± 16.9)	45.1 ± 8.6 (101.0 ± 19.3)
	2021	58.7 ± 10.0 (131.6 ± 22.5)	51.6 ± 10.0 (115.6 ± 22.5)	58.7 ± 11.8 (131.6 ± 26.4)	53.7 ± 6.2 (120.3 ± 13.9)
	2022	62.6 ± 7.0 (140.4 ± 15.8)	63.4 ± 12.4 (142.2 ± 27.7)	61.6 ± 9.8 (138.1 ± 22.0)	64.7 ± 8.0 (145.0 ± 18.0)
°Brix	2020	5.61 ± 0.20[b]	6.03 ± 0.30[a]	6.20 ± 0.36[a]	5.77 ± 0.48[ab]
	2021	4.98 ± 0.19	5.36 ± 0.48	5.19 ± 0.50	5.30 ± 0.44
	2022	4.99 ± 0.27[b]	5.13 ± 0.27[ab]	5.31 ± 0.30[a]	5.40 ± 0.30[a]

Standard deviation is shown as a plus or minus of the mean values.
Statistical significance for °Brix is shown within a given year between the different treatments.

TABLE 4. Total irrigation and irrigation water use efficiency (marketable yield over total irrigation volume) for each field season and deficit treatment

	Year	Control	Low stress	High stress	Tapered
Irrigation inches (mm)	2020	28.3 (719)	25.9 (657)	24.2 (614)	25.4 (646)
	2021	27.2 (690)	26.0 (660)	24.6 (624)	25.2 (640)
	2022	26.3 (667)	23.7 (602)	21.5 (546)	22.8 (580)
IWUE lb ft^{-3} (kg m^{-3})	2020	0.94 (15.1)	0.97 (15.6)	1.06 (16.9)	0.97 (15.6)
	2021	1.19 (19.1)	1.09 (17.5)	1.32 (21.1)	1.17 (18.8)
	2022	1.32 (21.1)[b]	1.47 (23.6)[ab]	1.58 (25.3)[a]	1.56 (25.0)[ab]

Statistical significance for irrigation water use efficiency (IWUE) is shown within a given year between the different treatments.

However, imposing an abrupt 37% ET_c deficit after fruit set may be too extreme for certain cultivars (Johnstone et al. 2005; Kuşçu et al. 2014; Patanè et al. 2011). The tapered strategy offers a balanced approach, maintaining strong performance in both yield and Brix while gradually increasing water stress to conserve more water toward the end of the season. The optimal deficit irrigation strategy may vary by cultivar, depending on factors such as the timing of fruit set, water stress response, disease resistance, and yield potential. Since we had no reduction in marketable yield or Brix, our data support the hypothesis that these parameters and water savings would improve or stay the same with the tested deficit irrigation strategies. Given increasing water scarcity in California, our findings demonstrate that deficit irrigation using a tapering strategy is a commercially viable option for processing tomato growers with limited freshwater allocations and access to groundwater. CA

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