Watermelon Production under Protected Culture in Missouri, USA, to Reach the Local Fourth of July Market

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KEYWORDS. *Citrullus lanatus*, high tunnel, low tunnel, marginal analysis, temperature, yield

ABSTRACT. Eating watermelon (*Citrullus lanatus*) is a traditional part of the Fourth of July holidays in the United States; however, growing watermelon in Missouri, USA for the local Fourth of July market requires an early growing season start (beginning of April) under protected culture because of low temperatures and the risk of freezing. Therefore, 'Yellow Doll' watermelon production was investigated under low tunnel (LT) and caterpillar high tunnel [HT (walk-in movable two-row tunnel)], and the economic feasibility was assessed by marginal analysis for both protected cultures. Planting in early April allowed harvest to start 1 to 2 weeks before the target market date. In addition, yield increased under HT in comparison with LT and open field (Op). Marginal analysis under the conditions of this study and prices obtained from local farmers' markets showed a positive marginal rate of return for HT in comparison with the control Op. The marginal rate of return sensitivity study suggests that differences in marketable yield of 300–400 and 200–250 lb/1200 ft^2 are necessary under HT and LT, respectively, for the protected culture to be economically feasible with watermelon prices above \$0.75/lb and/or \$1.00/lb as obtained in local farmers' markets. Therefore, it is possible and there is potential to produce watermelon under protected culture for the local Fourth of July market. A gain in market share with potential premium prices for watermelon may increase the sustainability of small and medium-size specialty crop farmers in Missouri. To accomplish this, it is necessary to use early cultivars (70 to 80 days to maturity), plant in early April with transplants grown in greenhouses, and make sure to manage tunnels properly to maintain favorable growing conditions, protect against freezing temperatures and ensuring good pollination.

It is difficult for specialty crop farmers in Missouri, USA, to grow watermelon (*Citrullus lanatus*) early enough in the growing season (beginning of April) to reach the local Fourth of July holiday market (Independence Day in the United States) due to cold temperatures and the risk of freezing. Watermelon and melon (*Cucumis melo*) production under low tunnels (LT) covered with spun-bonded row-cover has been developed for growing season extension and early production (Arancibia and Motsenbocker 2008; Rubatzky and Yamaguchi 1997; Soltani et al. 1995; Wells and Loy 1985, 1993). Similarly, growing watermelon under high tunnels (HT) for early production in Missouri was described previously (Jett 2006), but there was no information on harvest before the Fourth of July market and no comparison with LT. The advantage of LT and caterpillar HT (walk-in, movable two-row tunnel) is that they are more affordable in the short term and easy to relocate, avoiding repeated crops in the same soil. This study focused on early watermelon production under protected culture (LT and caterpillar HT) in Missouri to reach the local Fourth of July market window expecting premium prices in direct sales markets. Securing a share of the Fourth of July market may increase the sustainability of small and medium-size specialty crop farmers in Missouri.

Watermelon is a relatively important specialty crop in Missouri with 3000 acres valued at \$8.445 million in 2017 [US Department of Agriculture (USDA), Economics, Statistics and Market Information System 2022], but down from more than 5000 acres in the mid-1990s and early 2000s (Roach et al. 2017). Furthermore, of the 352 watermelon farms in 2017, 12 farms managed 100 acres or more for a total of 2111 acres, but 313 farms managed less than 5 acres for a total of 209 acres (USDA, National Agricultural Statistics Service 2019). Therefore, increasing watermelon production and gaining market share early in the season may not only revitalize and improve the economic sustainability of the industry but also improve the well-being of small and medium-sized farmers.

Watermelon is a warm season crop, and therefore, day and night temperatures of 86 and 68 °F, respectively, are optimal for growth and production (Rubatzky and Yamaguchi 1997). In addition, there are cultivars with a wide range of fruit sizes from very small/personal type watermelon (5 to 7 lb) to large ones (30 to 50 lb or more). Early maturing cultivars usually have small fruit and require shorter growing period (between planting and harvest) than cultivars with medium to large fruit. The growing period of early maturing cultivars including some icebox type ranges from 70 to 85 d to maturity, but medium to large fruit cultivars may take 100 to 150 d to maturity and harvest. Therefore, Missourian farmers would have to grow early maturing cultivars planted in early April under

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
0.3048	ft	m	3.2808
0.0929	ft^2	m^2	10.7639
2.54	inch(es)	cm	0.3937
0.4536	lb	kg	2.2046
1.1209	lb/acre	kg·ha^{-1}	0.8922
0.0254	mil(s)	mm	39.3701
33.9057	oz/yard^2	g·m^{-2}	0.0295
(°F − 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

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protected culture to harvest 1 to 2 weeks before the Fourth of July market.

April temperatures in Missouri vary depending on the area. Based on 30-year data, average temperature is warmer in the southeast (56 to 64 °F) and cooler in central and north Missouri (48 to 56 °F) (University of Missouri 2020a). Average minimum temperature in April ranges between 36 and 42 °F in north Missouri and 48 to 54 °F in southeast Missouri. In addition, freezing events are common in April. The median spring date with 50% probability of freezing temperature (≤32 °F) is 31 Mar and 27 Apr in southeastern and northern Missouri, respectively (University of Missouri 2020b). Therefore, the use of protected culture is necessary when planting in early April for early production.

Protected culture such as LT and HT can modify the plant environment by increasing mean and maximum temperature, stopping wind, and reducing solar radiation and evapotranspiration (Acharya et al. 2019; Arancibia and Motsenbocker 2008; Jett 2006; Wells and Loy 1985, 1993). Careful management of tunnels; however, is necessary to increase minimum temperature and protect against mild freezes. The increase in temperature inside the tunnels compared with the outside makes protected culture useful to enhance growth and extend the production season. However, the difference in minimum air temperatures under the LT during a freeze event varies depending on several factors such as wind, relative humidity, cover type (plastic film or spunbonded polypropylene fabric) and thickness of the rowcover, soil temperature, for example (Wells and Loy 1985). The heavier the spunbonded rowcover fabric, the larger the difference in temperature.

For lightweight rowcovers, temperature differences of 3 to 4 °F can be expected (Wells and Loy 1993); however, a temperature difference of 7.2 °F was recorded in a near freezing event with 0.9 oz/yard^2 rowcover in Louisiana, USA (Arancibia and Motsenbocker 2008). Temperature differences in HT during freezing events also depend on several factors. Because HT are covered with polyethylene film, most heat retention and frost protection are due to condensation of moisture on the inside surface of the film as the temperature falls during the night and the dew point is reached inside the tunnel (Wells and Loy 1985). Water is opaque to long wave radiation (infrared), so the condensation serves as a heat barrier. However, under certain conditions, minimum air temperature inside a single-layer plastic HT may not differ much from the outside temperature (Both et al. 2007). In fact, positive and negative differences have been reported (Hunter et al. 2012; Ogden and van Iersel 2009). Therefore, LT inside the HT has been used to improve protection against freezing events. Temperature differences under the LT inside the HT to outside ambient temperature may vary from 7 to 27 °F depending on the environmental conditions as reported in northern New Mexico, USA (Uchanski et al. 2020).

The economic benefit of a new technology is information that growers need to make informed decisions when adopting that technology. A commodity budget that includes the costs of growing under protected culture is helpful to determine whether growing that crop is profitable (Ernst 2020). When the crop is already profitable without the new technology, a marginal analysis is appropriate to assess the marginal rate of return of the additional investment due to the new adopted technology (Arancibia and Motsenbocker 2008; Centro Internacional de Mejoramiento de Maíz y Trigo 1988). Marginal analysis compares the additional income and costs that vary due to the adopted technology to the crop without the technology. Therefore, time of harvest, yield, prices, and costs that vary when producing under protected culture influence the marginal rate of return.

The hypothesis of this study was that it is feasible to produce watermelon for the Fourth of July market in Missouri using protected culture. Therefore, the objective was to demonstrate that early watermelon cultivars can be planted and grown under LT and HT in Missouri early enough (early April) to reach the local Fourth of July market.

Methods

This study was conducted at the Horticulture and Agroforestry Research Center in New Franklin, MO, USA (lat. 39.021381°N, long. 92.759935°W). Soil at the experiment site was Sibley silt loam down to 18 inches and silty clay loam from 18 to 72 inches deep (USDA Natural Resources Conservation Service 2023). Fertilization was based on the soil test, which recommended 80 lb/acre nitrogen (N), 77 lb/acre phosphorus (P), and 29 lb/acre potassium (K). Half of the N and all the P and K were added before laying black plastic mulch and drip irrigation both years. The rest of the N was added through the drip irrigation at the time of rowcover removal. Drip-irrigation was weekly for 30 min initially. The frequency and time increased as plant size increased to 4 h three times per week when the foliage had fully covered the surface area. Pest management followed recommendations of Egel (2020).

The field layout followed a completely randomized block design with three replications. We compared three production methods (treatments): 1) growing watermelon under caterpillar HT (12 × 30 ft) covered with greenhouse plastic film (4 mil) in 2021 and under low LT inside the HT in 2022; 2) growing watermelon under LT made of wire hoops and covered with spunbonded polypropylene rowcover [1 oz/yard^2 (DeWitt, Sikeston, MO, USA)]; and 3) uncovered open (Op) control. The experimental unit (plot) consisted of two rows 6 ft apart (center to center) and 30 ft long (360 ft^2) with 3-ft in-row planting distance. An alley of 5 ft was left between plots along the rows and a 6-ft-wide skip row between side-by-side plots. Each plot had one datalogger station (three replications) with shield (WatchDog A125; Spectrum Technologies, Inc., Aurora, IL, USA) to record air and soil temperatures hourly. Air temperature was at canopy level (12 inches aboveground), and soil temperature was 2 inches deep below the plastic mulch. Vines that extended outside the edge of the 12-ft-wide, 30-ft-long plot were turned back toward the plots area. The record area for harvest was the 6-ft-wide, 24-ft-long center between the row middles.

'Yellow Doll' watermelon, an early (70 to 75 d to maturity) and small seeded fruit (5 to 7 lb) diploid cultivar was used for early harvest. Transplants were grown in the greenhouse during February and March with minimum and maximum temperatures of 65 and 85 °F, respectively. Seeds were planted the first week of February in 50-cell trays filled with soilless media (Pro-Mix HP; Premier Horticulture Inc., Quakertown, PA, USA) and irrigated daily. Transplants had two to four true leaves at the time of field planting. The goal was to plant in the tunnels the first week of April, but planting was delayed in 2021 to 23 Apr to avoid freezing events that would have affected the Op. This planting postponement delayed harvesting time beyond the target Fourth of July market in 2021. Therefore, in 2022, the HT and LT were planted on 12 Apr to subject them to freezing events and determine the level of protection. The Op was planted 27 Apr after the last freeze event and plants under the LT that did not survive were replaced.

The field was monitored weekly, and ripe fruit was identified and harvested based on both the brown/dry tendril and the creamy color of the ground spot. Each watermelon was weighed to separate them into three categories based on fruit size for the cultivar: Small (3 to <5 lb), medium (5 to 7 lb), and large (>7 lb). Marketable yield included medium and large fruit. Weekly harvests before and after the Fourth of July were summarized to determine percent harvested fruit before the target market date. Total marketable yield was subjected to analysis of variance and mean separation using the MIXED procedure of SAS statistical software (ver. 9.4; SAS Institute Inc., Cary, NC, USA).

A marginal analysis (Centro Internacional de Mejoramiento de Maíz y Trigo 1988) was conducted to determine the "marginal rate of return" to the additional investment in protected culture (LT and HT) in comparison with the conventional production without protection (Op). "Gross income" was estimated by multiplying the price per fruit by the number of marketable fruit in each category. Prices ($7 and $4 per >7-lb and 5 to 7-lb fruit, respectively) were obtained from local farmers' markets (Nevada and Clinton, MO, USA) during the target date. The fruit number in a 1200-ft^2 production area, which is a common size of a caterpillar HT (12 ft ×100 ft) used by many small growers in Missouri, was estimated from the 2021 data because there was no Op data in 2022 due to wildlife incursion. The "additional income" was estimated by the difference in "gross income" between the protected culture (LT and HT) and the control Op. "Costs that vary" correspond to those additional costs incurred when adopting the technology and were determined for a 1200-ft^2 production area according to the caterpillar HT used. The costs of the materials for the LT and caterpillar HT were obtained from the purchases for this study and were prorated by crops per year and years of use. Other costs that varied were labor costs of laying and removing the tunnels, and additional harvest labor due to an increase in fruit number compared with the control without protection. The cost of rowcover was based on 2 years or crops use, wire hoops were based on 5 years use, HT structure was based on 15 years use with two crops per year, plastic film was prorated over 4 years use with two crops per year, and cord to hold the plastic was prorated over 2 years. The estimated costs that varied for 1200-ft^2 LT and HT were $157 and $266, respectively, compared with Op. The "marginal (additional) gain" of adopting LT or HT was estimated by the difference between the "marginal (additional) income" and the "costs that vary." Then, "marginal rate of return" was estimated by the ratio between "marginal gain" and the "costs that vary."

A price sensitivity analysis based on the "marginal rate of return" was conducted to determine the conditions (additional yield and price) at which adopting protected culture would be economically feasible in Missouri. This "marginal rate of return" was obtained by "marginal analysis" of 'Yellow Doll' watermelon production under HT and LT over Op with data from 2021, and it was based on a 1200-ft^2 production area. The price ranged from $0.5/lb to $1.0/lb based on what growers obtained in local farmers' markets at the target date.

Results and discussion

The tunnels were kept open and/or closed depending on type and weather conditions. The HTs stayed open in 2021 since there was no risk of freezing events after planting. The LTs were covered for 28 d until 21 May 2021 and rowcover was removed for pollination. In contrast, HTs were kept closed for 9 d until 21 Apr 2022 during the cold weather (expected minimum temperature <40 °F) and risk of freezing events and then kept open because weather was warmer and there was no chance of freezing in the forecast. However, LTs inside the HT and outside were kept covered until 23 May 2022 when rowcover was removed for pollination and fruit set. Daily maximum temperature in the HT and LT reached more than 110 °F on two and seven occasions in 2021 and 2022, respectively, because of sunny warm days (Fig. 1); however, vegetative growth appeared to have not been affected. This apparent lack of detrimental effect with daily maximum temperature above 100 °F was reported previously in a 2-year study in Louisiana, USA, where the 3-week average maximum temperatures under LT were 116.7 and 105.1 °F, respectively (Arancibia and Motsenbocker 2008).

Average daily maximum air temperature in 2021 was higher ($P < 0.001$)

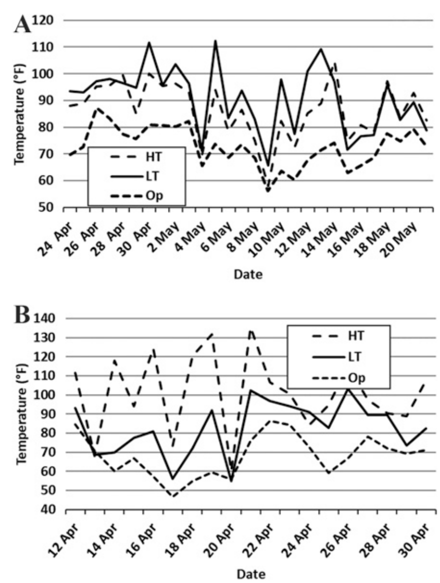

Fig. 1. Daily maximum temperature after watermelon transplanting in caterpillar high tunnel [HT (walk-in movable two-row tunnel)], low tunnel (LT), and control open field (Op) plots in 2021 (A) and 2022 (B) at the Horticulture and Agroforestry Research Center in New Franklin, MO, USA. HT [(12 ft (3.66 m) wide] were covered with one layer of plastic film. LT were covered with spunbonded rowcover [0.9 oz/yard^2 (30.52 g·m^{-2})], which was removed when female flowers appeared. In 2021, HT were kept open because there was no risk of freezing. In 2022, plants inside the HT were under LT also and HT were kept closed the first 9 d after planting during cold weather; (°F – 32) ÷ 1.8 = °C.

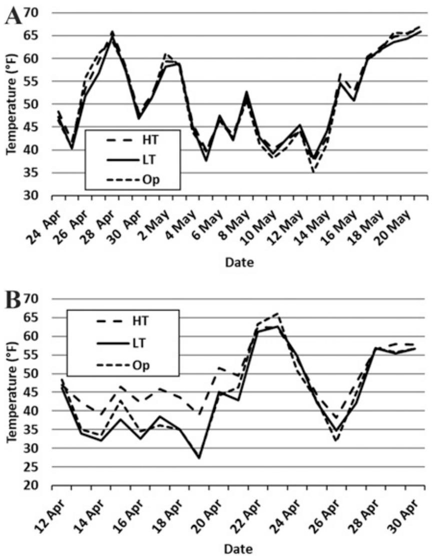

Fig. 2. Daily minimum temperature after watermelon transplanting in caterpillar high tunnel [HT (walk-in movable two-row tunnel)], low tunnel (LT), and control open field (Op) plots in 2021 (A) and 2022 (B) at the Horticulture and Agroforestry Research Center in New Franklin, MO, USA. HT [(12 ft (3.66 m) wide] were covered with one layer of plastic film. LT were covered with spunbonded rowcover [0.9 oz/yard^2 (30.52 g·m^{-2})], which was removed when female flowers appeared. In 2021, HT were kept open since there was no risk of freezing. In 2022, plants inside the HT were under LT also and HT were kept closed the first 9 d after planting during cold weather; (°F – 32) ÷ 1.8 = °C.

under the LT (90.8 °F) than HT (86.5 °F) and Op (72.6 °F). Average daily maximum temperature in the HT was also higher than the Op. Average daily maximum temperature in the HT did not increase as much as under the LT because it was kept open. In contrast, average daily maximum temperature under the LT inside the HT (101.2 °F) in the first 18 d of the study in 2022 was higher ($P < 0.001$) than the LT outside (82.6 °F) and Op (68 °F). This temperature increase in the double tunnel system compared with LT in 2022, especially when the HT was closed and to a lesser extent when it was open (Fig. 1), suggests an improved system to grow warm season crops early in the season. Average daily maximum temperature in the LT was also higher than Op. Consequently, the warmer air temperatures under the tunnels promoted vegetative growth and plants were larger at the time of rowcover removal in comparison with Op in both years. Furthermore, female flowers were already present when the rowcover was removed in 2022, which suggests that removal could have been done a few days earlier. These results support previous reports indicating enhanced vegetative growth due to more favorable conditions (temperature, wind, solar radiation, and evapotranspiration) under the tunnels even in the absence of freezing temperatures or during the summer (Acharya et al. 2019, 2020; Arancibia 2019; Arancibia and Motsenbocker 2008; Jett 2006; Wells and Loy 1985).

Since HTs were kept open in 2021, daily minimum air temperatures among production methods during the initial growth period of the crop were similar in 2021 with few days where there were slight differences (Fig. 2A). The average daily minimum temperatures for HT (51.9 °F), LT (51.1 °F), and Op (51.2 °F) were not different ($P = 0.075$). In 2022, however, average daily minimum temperatures under the LT inside the HT (44.6 °F) were higher ($P < 0.001$) than LT outside (37.1 °F) and Op (38.4 °F) in the first 9 d after planting while the HT was closed. When the HT was open between 10 and 18 d after planting, average daily minimum temperatures were the same among production methods (Fig. 2B). This increased daily minimum temperature in the double tunnel system while the HT was closed supports the finding in New Mexico, USA and indicate an improved system to protect against freezing events (Uchanski et al. 2020). Average daily minimum temperatures were the same between LT and Op; however, there were nights in which daily minimum temperatures were slightly lower under the LT than Op in both years. These negative differences support previous reports indicating that under certain conditions the tunnels may not protect against freezing temperatures (Both et al. 2007; Hunter et al. 2012; Ogden and van Iersel 2009; Wells and Loy 1985). The lack of protection is likely due to low humidity and therefore, minimal or no water condensation in the tunnels allowing fast heat loss through the plastic film and/or rowcover. It is worth noting that tunnels block the wind and therefore may provide a degree of protection against the cooling effect of dry cold wind in a freezing or near freezing event (wind chill) because most of the plants under the LT survived the freeze on 19 Apr 2022 (Fig. 2B).

Furthermore, average daily maximum soil temperature at a depth of 2 inches in 2021 was higher ($P < 0.001$) under the HT (86.2 °F) than LT (77.5 °F) and Op (72.1 °F). Average daily maximum soil temperature under the LT was also higher than Op. In 2022, average daily maximum soil temperature under the LT inside the HT (72.1 °F) was also higher ($P < 0.001$) than in the LT outside (67.1 °F) in the first 9 d after planting while the HT was closed. There are no Op data in this period for 2022 because the soil temperature sensors were set later when Op was planted. Average daily minimum soil temperature in 2021 was lower ($P = 0.019$) in Op (52 °F) than under HT (55.7 °F) and LT (54.3 °F), but minimum soil temperature under the HT and LT were the same. In 2022, however, average daily minimum soil temperature under the LT inside the HT (56 °F) was higher ($P < 0.001$) than in the LT outside (51.4 °F) in the first 9 d after planting while the HT was closed. Higher soil temperatures under LT have been reported previously and may have contributed to the enhanced vegetative growth and early flowering seen in HT and LT compared with Op (Arancibia and Motsenbocker 2008).

Harvest started the week after 4 Jul in 2021 (Fig. 3A). Only 4% of the marketable fruit (≥5 lb) were harvested from the HT. In contrast, 8% and 21% of the marketable fruit from the HTs were harvested 2 weeks and 1 week, respectively, before the target market date in 2022 (Fig. 3B). Only 15% of the marketable fruit was harvested from the LT treatment 1 week before the target market date. The rest was harvested 1 and 2 weeks after the target market date. There is no Op data in 2022 due to wildlife incursion. The earlier planting and warmer temperatures under the tunnels in 2022 enhanced vegetative growth earlier in the season, which was conducive to an earlier harvest before the target date. Simultaneously, two farmers successfully produced 'Sugar Baby' watermelon (icebox type of 10 to 12-lb fruit and 75 to 80 d to maturity) under LT and HT in Henry and Vernon Counties, MO, respectively. They started harvesting more than 1 week before

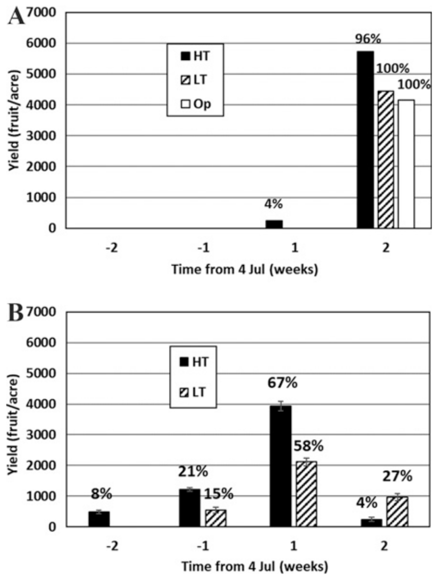

Fig. 3. Weekly harvest percent of marketable 'Yellow Doll' watermelon [≥5 lb (2.27 kg)] before and after the target Fourth of July market from plants grown in caterpillar high tunnel [HT (walk-in movable two-row tunnel)], low tunnel (LT), and control open field (Op) plots in 2021 (A) and 2022 (B) at the Horticulture and Agroforestry Research Center in New Franklin, MO, USA. HT [(12 ft (3.66 m) wide] were covered with one layer of plastic film. LT were covered with spunbonded rowcover [0.9 oz/yard^2 (30.52 g·m^{-2})], which was removed when female flowers appeared. In 2021, HT were kept open because there was no risk of freezing. In 2022, plants inside the HT were under LT also and HT were kept closed the first 9 d after planting during cold weather; 1 fruit/acre = 2.4711 fruit/ha.

the target Fourth of July market and were able to get \$10 to \$12 per fruit at their farm store and at the farmers' market up to 2 weeks after the Fourth of July. Furthermore, growers planted 'Sweet Gem' watermelon in 2023 (12-lb seedless triploid cultivar with 83 d to maturity) and were able to start harvesting 2 weeks before the Fourth of July. Therefore, these results indicate that it is possible to grow seeded and/or seedless watermelon early in the season under protected culture to reach the local Fourth of July market in Missouri. These results support similar studies indicating that LT covered with spunbonded rowcover allow earlier watermelon planting and harvest than open field (Arancibia and Motsenbocker 2008; Marr et al. 1991; Soltani et al. 1995). Specifically, the study in Louisiana, USA, reported that 'Sangria' (seeded) and 'Crimson Jewel' (seedless) watermelon planted at the end of March and beginning of April and grown under LT were harvested 1 to 2 weeks before the Fourth of July (Arancibia and Motsenbocker 2008). Using the double tunnel system (LT inside the HT) appears to provide better growing conditions for warm season crops early in the season and improve protection against freezing. Early cultivars with smaller personal size fruit have a better chance to ripen before the Fourth of July market in Missouri because plants need a shorter period to accumulate the necessary degree days to maturity.

Watermelon grown under HT had the largest total (≥3 lb) and marketable (≥5 lb) yields in 2021 (Table 1). Marketable yield under HT increased by 38% and 76% over LT and Op, respectively, in 2021, and 55% over LT in 2022. Total and marketable yields from LT were the same as Op. Similarly, the number of total and marketable fruit in the HT were larger than LT and Op in 2021, but total fruit from Op was larger than LT. In 2022, marketable yield and marketable fruit were larger under HT than LT (Table 1), and the difference was larger in the initial 3 harvest weeks because percent marketable fruit from LT was larger in the last harvest (Fig. 3B). However, the variability in total yield and total fruit reduced the significance of the difference between treatments likely due to the large number of small fruit set later/further in the vine that usually are smaller. The larger marketable yield under HT in both years supports the general notion that production under protected culture increases yield (Wells and Loy 1985 1993). In contrast, there was no significant total and marketable yield increase under LT in comparison with Op in 2021, which disagrees with most reports indicating an increase in watermelon marketable yield under LT (Arancibia and Motsenbocker 2008; Baker et al. 1998; Marr et al. 1991; Soltani et al. 1995). The yields in this study; however, were below the reported yield range for watermelon, suggesting that potential for larger yield with other cultivars is possible.

Yield and number of medium size fruit (5 and <7 lb; $P = 0.310$ and $P = 0.278$, respectively), and large size fruit (≥7 lb) for this cultivar ($P = 0.124$ and $P = 0.175$, respectively) were no different among production method in 2021 (data not presented). In 2022, yield and fruit number ≥7 lb were larger under the HT than LT ($P < 0.001$ and $P = 0.002$, respectively), but there were no differences in yield and number of medium size fruit ($P = 0.272$ and $P = 0.229$, respectively) between HT and LT (data not presented). In a previous study in Louisiana, 'Sangria' (seeded) and 'Crimson Jewel' (seedless) watermelon yield and fruit number increased under LT in comparison with OP, but in detriment of fruit size, which decreased under LT (Arancibia and Motsenbocker 2008). In another study in Louisiana, planting

Table 1. Yield of 'Yellow Doll' watermelon grown under caterpillar high tunnel [HT (walk-in movable two-row tunnel)], low tunnel (LT) covered with spunbonded rowcover [0.9 oz/yard^2 (30.52 g·m^{-2})] until flowering, and control open field (Op) to reach the Fourth of July market in Missouri, USA.

Protection method[i]	Total yield (lb/acre)[ii]	Marketable yield (lb/acre)[ii]	Total fruit (no./acre)[ii]	Marketable fruit (no./acre)[ii]
		2021		
HT	52,411 a[iii]	40,760 a	8,914 a	5,969 a
LT	39,144 b	29,540 b	6,857 c	4,437 b
Op	41,112 b	26,268 b	7,905 b	4,154 b
P value	0.009	0.036	0.003	0.037
		2022[iv]		
HT	42,340	35,413	7,805	5,869
LT	28,488	20,022	5,808	3,449
P value	0.061	0.024	0.160	0.031

[i] HT were 12 ft (3.66 m) wide.

[ii] Total yield and total fruit includes fruit ≥3 lb (1.36 kg); marketable yield and marketable fruit includes fruit ≥5 lb (2.27 kg); 1 lb/acre = 1.1209 kg·ha^{-1}, 1 fruit/acre = 2.4711 fruit/ha.

[iii] Means within a column followed by different letters are significantly different from each other by Fisher's least significant difference at $P \leq 0.05$.

[iv] In 2022, plants inside the HT were under LT also and Op production was lost to wildlife.

Table 2. Marginal analyses of adopting low tunnel (LT) and caterpillar high tunnel [HT (walk-in movable two-row tunnel)] compared with control open field (Op) for spring production of 'Yellow Doll' watermelon to reach the Fourth of July market in Missouri, USA.

Protection method[i]	Gross income[ii]	Costs that vary[iii]	Additional income[iv]	Marginal gain[v]	Marginal rate of return ($/$)[vii]
	($/1200 ft^2)[vi]				
Op	544				
LT	609	157	64	−92	−0.59
HT	831	266	287	21	0.08

[i] HT were 12 ft (3.66 m) wide.
[ii] Gross income = yield × price ($7 and $4 per fruit >7 lb and 5 to 7 lb, respectively); 1 lb = 0.4536 kg.
[iii] Costs that vary (additional investment): LT = hoops (prorated over 5 years) + rowcover (prorated over two crops) + labor (laying + removing) + additional harvest labor; HT = bows (prorated over two crops per year and 15 years) + HT film (prorated over two crops per year and 4 years) + cord (prorated over 2 years) + labor assemble disassemble (prorated over two crops per year) + labor for additional harvest.
[iv] Additional income = gross income (HT or LT) – Op gross income, based on 2021 yield data and prices at farmers' markets.
[v] Marginal gain (loss) = additional income – costs that vary (positive = net additional gain; negative = net loss to the additional investment).
[vi] $1/1200 ft^2 (111.5 m^2) = $36.3000/acre = $89.6993/ha.
[vii] Marginal rate of return = marginal gain (loss)/costs that vary (positive = gain per additional dollar invested in the technology over the control open; negative = loss per additional dollar invested).

distance influenced fruit size and yield of watermelon (Motsenbocker and Arancibia 2002). These results suggest that cultural practices and cultivar selection can optimize yield of marketable fruit for the desire size demanded by the market.

Marginal analyses based on the yields from 2021 in this study and watermelon prices estimated based on local farmers' market data showed negative marginal rate of return for LT and positive for HT in comparison with the control Op (Table 2). The analyses were based on the additional cost (costs that vary) of $157 and $266 per 1200 ft^2 of LT and HT, respectively, which prorated the costs of the materials for several years and crops per year as described in methods above. The costs that varied was not estimated for the double tunnel system (LT inside HT) because only the data from 2021 were used, but it should be larger. The marginal rates of return indicated a loss of $0.59 and a gain of $0.08 per additional $1.00 invested in LT and HT, respectively. This means that even though there was an increase in marketable yields and additional incomes due to the protected culture, it was not enough to cover the additional cost for LT, but there was a marginal gain per dollar invested in HT. In contrast, a study in Louisiana, USA, with 'Sangria' and 'Crimson Jewel' watermelon grown under LT estimated a rate of return of 0.22 and 0.29, respectively, with prices from direct sale markets (Arancibia and Motsenbocker 2008). Yields in this study were below those from other reports including in the neighbor state of Kansas, USA, which suggest that potentially larger yield differences could increase the additional income and marginal rate of return (Arancibia and Motsenbocker 2008; Baker et al. 1998; Marr et al. 1991; Soltani et al. 1995).

The price sensitivity analysis (Table 3) shows the marginal rate of return at several combination of yield increase under protected culture in comparison with the control Op at specific estimated prices and the additional cost. Highest estimated price was based on that obtained at farmers' markets during the harvest period by growers in the area for ice box type watermelon: $10 per 10 to 12-lb fruit. For simplicity, these estimates do not consider possible price changes before and after the Fourth of July market or with seedless cultivars. Positive marginal rate of return indicates a gain in dollars per additional dollar invested in the protected culture for each price-yield difference combination. These results suggest that yield increases of 300–400 and 200–250 lb/1200 ft^2 are necessary under HT and LT, respectively, for the protected culture to be economically feasible with watermelon prices above $0.75/lb and $1.00/lb.

In summary, it is possible and there is potential to produce watermelon under protected culture, in particular HT, for the Fourth of July market in Missouri. To accomplish this, it is necessary to use early cultivars (70 to 80 d to maturity), plant in early April with transplants grown in greenhouses, and make sure to manage the tunnels properly to protect against cold/freezing temperatures as well as ensuring good pollination and high yields necessary to cover the additional costs and still get a marginal gain to the additional investment.

Table 3. Marginal rate of return to the additional investment of producing 'Yellow Doll' watermelon under caterpillar high tunnel [HT (walk-in movable two-row tunnel)] and low tunnel with rowcover (LT) to reach the Fourth of July market in Missouri, USA, compared with control open field conditions.

Protection method[i]	Additional harvest (lb/1200 ft^2)[ii]	Marginal rate of return ($/$)[iii]		
		Watermelon price ($/lb)[iv]		
		0.5	0.75	1.00
HT	200	−0.62	−0.44	−0.25
	300	−0.44	−0.15	**0.13**
	400	−0.25	**0.13**	**0.50**
	500	−0.06	**0.41**	**0.88**
LT	150	−0.52	−0.28	−0.04
	200	−0.36	−0.04	**0.28**
	250	−0.20	**0.20**	**0.60**
	300	−0.04	**0.44**	**0.91**

[i] HT were 12 ft (3.66 m) wide.
[ii] Additional harvest: due to the adoption of the protected culture compared with control open field; 1 lb/1200 ft^2 (111.5 m^2) = 36.3000 lb/acre = 40.6869 kg·ha^{-1}.
[iii] Marginal rate of return: additional dollar in net return per additional dollar invested in the new practice (HT or LT) over the control open. Positive rate = gain to the additional investment. Negative rate = loss to the additional investment.
[iv] Watermelon price obtained from Farmers' Markets and on-farm produce store; $1/lb = $2.2046/kg.

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