Active Versus Passive Winter Row Cover Management: Impacts on Strawberry Yields and Pests Inside High Tunnels

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ABSTRACT. Growing fall-planted strawberries on plastic mulch in high tunnels is a promising strategy for strawberry production in Indiana. Despite previous success, the system faces challenges, including increased populations of soft-bodied insects such as twospotted spider mites (TSSMs) and aphids. Although using row covers for winter protection is a common practice in open-field plasticulture strawberry production in the region, the optimal use of row covers in the winter inside high tunnels remains unclear. To address this, three row cover management strategies—no cover (NC), active cover with hoops (AH), and passive cover with hoops (PH)—were applied during the winters of the 2021–22 and 2022–23 strawberry seasons in high tunnels in Vincennes, IN, USA. This study assessed strawberry yield and the population dynamics of TSSMs and aphids throughout the seasons. Although the row cover treatments created varying environmental conditions during the winter, no significant differences in strawberry yield were observed among the treatments in either season. Row covers increased temperatures, which facilitated the overwintering of TSSMs and created more favorable conditions for aphid reproduction, potentially leading to higher pest pressure and greater management challenges in the spring. Although the findings suggest that winter use of row covers did not provide significant benefits under the strawberry production system during the experimental years, they remain a valuable insurance measure during extremely cold conditions.

Strawberries (*Fragaria* × *ananassa*) are a popular fruit in the United States, and their per capita consumption increased from 4.86 pounds in 2000 to 8.5 pounds in 2020 (Lewers et al. 2020; Shahbandeh 2023). Although nearly 99% of the country's strawberry production is concentrated in California and Florida (US Department of Agriculture 2024), strawberries are grown in almost every state for local direct-to-consumer sales. Consumer preference for locally produced strawberries (Darby et al. 2006) has led to increased interest in growing strawberries in Indiana.

Although strawberries are primarily grown in open fields in the United States, cultivating them in protected structures ranging from advanced high-tech greenhouses to simpler high tunnel systems is a widely adopted practice. In countries such as Spain, Japan, and China, over 90% of strawberry production occurs under protected structures (Becerril et al. 2008; Oda et al. 2012; Zhang et al. 2016). Growing strawberry under protected structures protects the crop against adverse weather, reduces foliar disease pressures, and generally improves fruit quality (Gu et al. 2017; Gude et al. 2018).

High tunnels have become one of the fastest growing sectors in agricultural production in the United States, largely because of their lower initial cost compared with that of greenhouses and the availability of financial support through the NRCS EQIP program, which reimburses farmers for building high tunnels. Unlike greenhouses, however, high tunnels do not have active heating and cooling systems, thus limiting their ability to control the environmental conditions to the natural weather conditions of a specific location (Bruce et al. 2021).

In Indiana, high tunnels are most commonly used to extend the growing season for warm-season crops such as tomatoes (*Solanum lycopersicum*) and cultivate leafy greens such as lettuce (*Lactuca sativa*) and spinach (*Spinacia oleracea*) in fall, winter, and spring. As the number of high tunnels in the region continues to grow, there is an increasing need to explore crop diversification to enhance the system's production and economic sustainability.

In a previous study, we demonstrated success growing fall-planted strawberries on plastic mulch-covered beds inside high tunnels in US Department of Agriculture Hardiness Zone 6 (Guan et al. 2022). The high tunnel increased growing degree days in the fall compared with those in open-field conditions. This allowed strawberry plants to develop an adequate number of branch crowns in the fall and winter, resulting in exceptional yields the following spring. Additionally, using row covers inside the high tunnels during the spring effectively mitigated the risk of frost damage, offering a clear advantage over plasticulture systems in open-field production in the region.

Despite these promising results, the system presents challenges. One notable issue is the increased soft-body insects, especially twospotted spider mites (*Tetranychus urticae*) (TSSMs) and various aphid species (Aphidoidea), compared with those in open field production. Because a substantial portion of high tunnel farmers use organic approaches for pest management (Bruce et al. 2021), we are particularly interested in exploring strategies to modify environmental conditions within high tunnels to suppress pest populations.

To ensure the success of cultivating strawberries in high tunnels, we need to establish a production system that optimally adapts to the high tunnel environment of local conditions.

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A topic that is currently lacking knowledge is the use of row covers during the winter months in this system.

Row covers are fabric-type materials available in various weights. Lightweight row covers protect plants from insect pests. Medium-weight covers provide light freeze protection and promote plant growth. Heavy-weight materials are most effective for protecting plants from severe cold injury (Jadrnicek 2016). Row covers are used alone or in combination with high tunnels to extend the production season (Grubinger and Northeast 2016).

In regions of North Carolina, where winter temperatures can drop below 10 °F, heavy-weight row covers (1.5 oz per yd^2) are recommended for open-field strawberry production. These covers are typically installed from late November to early December and removed in early March (Poling et al. 2005). A similar row cover management approach has been adopted for open-field plasticulture strawberry production in southern Indiana (US Department of Agriculture Hardiness Zone 6), where winter minimum temperatures are comparable to those in the upper mountain areas of North Carolina.

However, for strawberry production in high tunnels in southern Indiana, the necessity of using row covers during the winter remains unclear. Additionally, the optimal management strategy for row covers inside high tunnels is not well-defined. Key questions include whether row covers should be used at all, and, if they should be used, whether they should be actively managed—by covering and uncovering overwintered plants in response to temperature fluctuations—or left in place throughout the winter as part of a passive management approach.

These management approaches involve a clear tradeoff of labor and material inputs. However, their impacts on plant growth, yield, and the prevalence of invertebrate pests and diseases are unclear. To address the knowledge gap, we conducted this study to evaluate winter row cover management strategies in high tunnel strawberry production systems. The study aimed to compare environmental conditions under different management approaches and assess their effects on strawberry yield and pest populations during the winter and spring.

Materials and methods

Planting and high tunnel management

The experiment was conducted in gothic-style high tunnels (Rimol Greenhouse Systems, Hooksett, NH, USA) at the Southwest Purdue Agricultural Center located in Vincennes, IN, USA, during the 2021–22 and 2022–23 seasons. The high tunnels (width, 30 ft; length, 96 ft) had 6-ft-high side walls and 15-ft-high centers. The soil type was a fine sandy loam with 0.9% organic matter. Six beds were made inside the high tunnels (width, 20 inches; height, 3 inches) with 4-ft center-to-center bed spacing. The beds were covered with 3-ft wide and 1-mil-thick black plastic mulch. One drip tape with 8-inch emitter spacing and 0.67 gal/min per 100 ft (Trickle-EEZ Irrigation Inc., St. Joseph, MI, USA) was placed in the middle of each bed. Row middles were covered with a 3.2-oz woven white groundcover on the top (Dewitt Co., Sikeston, MO, USA) and 1-oz black weed barrier (Dewitt Co.) on the bottom. The high tunnels were equipped with roll-up sidewalls that automatically opened when inside temperatures were above 70 °F. During the blooming periods in spring, sidewalls were opened or partially opened when inside temperatures were above 50 °F to encourage wind flow for pollination.

Strawberry plugs sourced from McNitt Growers (Carbondale, IL, USA) were planted on 7 Sep 2021 and 8 Sep 2022, in two rows staggered 10 inches apart on each bed; in-row spacing was 14 inches. In 2021–22, cultivars Chandler and Sensation were used. In 2022–23, seven cultivars, Chandler, Sweet Charlie, Merced, Sensation, Ruby June, San Andreas, and Monterey, were tested. Each experimental unit had eight strawberry plants.

Row cover treatments

Row covers of 1.5 oz/yd^2 (Agribon AG-50) were used in the winter and spring of the production seasons. Three treatments were applied in the winter that included no cover (NC), active cover with hoops (AH), and passive cover with hoops (PH); row covers were placed on approximately 1.5-ft-high wire hoops in the center.

For the actively managed treatment (AH), plants were covered when the forecasted outside ambient temperature was below 32 °F. Covers were removed the following morning if the temperature inside the high tunnel reached 50 to 55 °F. Row covers were not removed if temperatures stayed low inside the high tunnels or during the weekends and holidays. During the 2021–22 season, AH management began on 22 Nov 2021, and it continued until 28 Feb 2022; 35 covering and uncovering events were involved. In the 2022–23 season, AH management started on 11 Nov 2022, and it lasted until 13 Feb 2023, with a total of 28 covering and uncovering events.

For the passively managed treatment (PH), row covers were applied when the forecasted outside ambient temperature dropped below 20 °F. For the 2021–22 season, row covers were applied on 3 Jan 2022 and removed on 28 Feb 2022. In the 2022–23 season, covers were applied on 25 Dec 2022 and removed on 13 Feb 2023. Row covers were removed when the daily average temperature had reached 50°F and no nighttime temperatures below 20°F were forecasted in the near term.

Crop management

The plants were fertigated in the fall and spring using fertilizer 4N–0P–8K (Brandt 4-0-8; Brandt Consolidated, Inc., Springfield, IL, USA); a total of 100 lb/acre N was applied throughout each season. Plant runners were hand-removed in the fall. At the end of February, following the termination of row cover treatments, fully expanded overwintered leaves were removed, leaving the crown and newly emerged leaves. In the spring, regardless of row cover treatments in the winter, row covers were applied for frost protection when needed to all the plants during the blooming period.

To manage TSSMs, a single release of the predatory mite *Neoseiulus fallacis* (Garman) (BioTactics, Menifee, CA, USA) was conducted on 4 Nov 2022. Approximately 2000 individuals were released into the high tunnel by evenly spreading the product among the strawberry plants.

Data collection

Fully ripe strawberry fruit was harvested twice per week in spring of both years. The fruit was graded as marketable or nonmarketable (severely misshapen or damaged by diseases or insects), and the total fruit weight and the number of fruits per experimental unit were recorded and reported as averages per plant.

In the 2022–23 season, we regularly collected leaf samples and scouted the plants for insects to determine pest presence. Strawberry leaflets were collected once in Oct 2022 and twice per month from Nov 2022 to Jun 2023. One trifoliate leaf from each of the seven cultivars nested within the covering treatment was collected and pooled together. Leaflets were processed using a mite brushing machine to dislodge pests onto a soapy plate that was scanned under a dissecting microscope. We focused on aphids, TSSMs, and predatory mites to determine covering impacts on pests, predator retention, and biocontrol efficacy.

ENVIRONMENTAL MEASUREMENTS. In the 2021–22 season, air and soil temperatures were measured every 30 min using HOBO external temperature data loggers. In the 2022–23 season, temperature and relative humidity were measured in the crop canopy using a temperature/relative humidity smart sensor (S-THC-M002; ONSET, Bourne, MA, USA). The sensors were placed at the plant canopy height between two plants. Photosynthetic active radiation (*PAR*) was measured approximately 3 inches above the canopy using a photosynthetic light sensor (Onset S-LIA-M003; ONSET). Data were recorded every 30 min and stored in the HOBO USB Micro Station Data Logger (ONSET). Soil temperature was measured at a 4-inch depth using HOBO external temperature data loggers (U23 Pro v2; ONSET). The environmental data were measured in two replications for each cover treatment. Because similar trends were observed in both datasets, environmental data from only one location are presented in this manuscript.

Experiment design and statistical analyses

A split-block design with three replications was used in both years of the experiment. The row cover treatment was assigned as the main plot factor, and cultivar was assigned as the subplot factor. Yield data were analyzed separately by year. For insect data collection, leaves from different cultivars within the same row cover treatment were pooled. Insect data were analyzed separately for each sampling date. All data were subjected to analysis of variance using JMP (JMP Pro 16; SAS Institute, Cary, NC, USA). Treatment means were compared using Fisher's protected least significant difference test at $\alpha = 0.05$.

Results and discussion

Plant response to environmental changes under row cover treatments

PLANT GROWTH AND YIELD. Regardless of row cover treatments, plants recovered from winter and resumed growth by late February. Harvest began in mid-April and lasted until mid-May in 2022 and early June in 2023. The observed growth patterns and harvest duration were consistent with previous findings (Guan et al. 2022).

Unmarketable fruit losses were consistently below 10% and showed no significant variation across the row cover treatments. In the 2021–22 season, plants exhibited stunted growth, resulting in lower yields compared with other years. The similar plant decline was observed on 'Sensation' in the 2022–23 season. A crown disease caused by *Neopestalotiopsis* sp. was suspected to have affected 'Chandler' and 'Sensation' in 2021 and 'Sensation' in 2022.

No significant interactions between cultivar × row cover treatments were observed for either marketable or total yields. All evaluated cultivars performed similarly across the different row cover treatments despite the variable environmental conditions created by the covers during the winter (Table 1). Among the seven cultivars evaluated during the 2022–23 season, significant differences were found in both marketable and total yields (Table 2). 'Monterey' produced the highest marketable yield, which was significantly higher compared with that of 'Merced', 'Chandler', 'Ruby June', 'Sweet Charlie', and 'Sensation'. Sweet Charlie and Sensation cultivars had the lowest marketable yields among the cultivars tested.

Table 1. Marketable and total yield (lb/plant) across strawberry cultivars during the 2021–22 and 2022–23 seasons.

	2021–22 Season		2022–23 Season	
Treatment	Marketable yield (lb/plant)	Total yield (lb/plant)	Marketable yield (lb/plant)	Total yield (lb/plant)
NC	0.73	0.73	1.48	1.63
AH	0.61	0.65	1.57	1.73
PH	0.68	0.69	1.44	1.55
P value	0.3502	0.5963	0.1621	0.0736

AH = active cover with hoops; NC = no cover; PH = passive cover with hoops.

Table 2. Marketable and total yield (lb/plant) of evaluated cultivars across row cover treatments during the 2021–22 and 2022–23 seasons.

Cultivars	Marketable yield (lb/plant)	Total yield (lb/plant)
	2021–22 Season	
Chandler	0.73	0.74
Sensation	0.61	0.65
P value	0.0866	0.2238
	2022–23 Season	
Monterey	1.98 a[i]	2.13 a
San Andreas	1.89 ab	2.01 ab
Merced	1.77 b	1.87 b
Chandler	1.75 b	1.92 ab
Ruby June	1.03 c	1.15 c
Sweet Charlie	0.96 c	1.11 c
Sensation	0.94 c	1.05 c
P value	<0.0001	<0.0001

[i] Means labeled by the same letters are not significantly different at $P \leq 0.05$ according to Fisher's protected least significant difference.

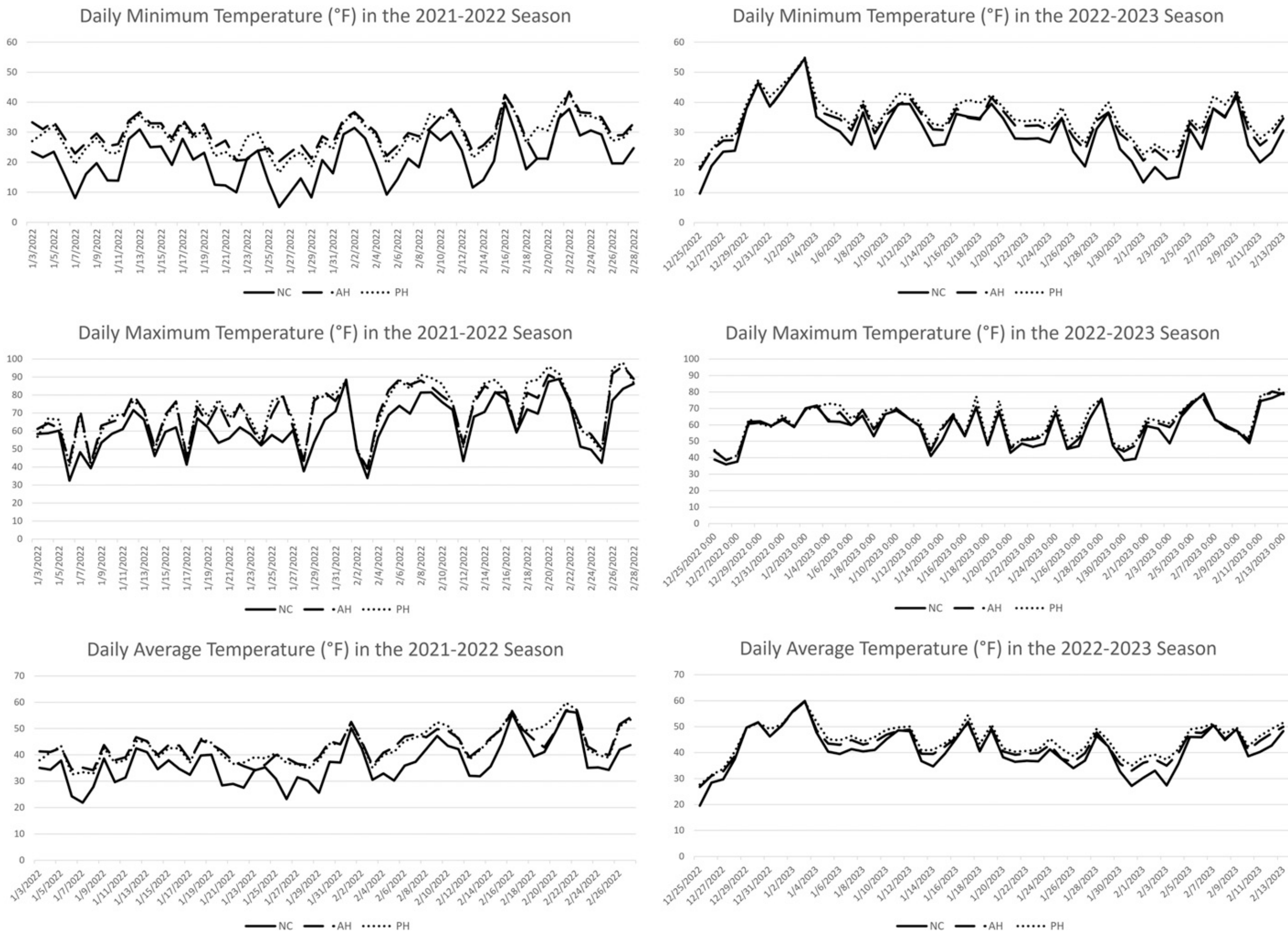


Fig. 1. Daily minimum, maximum and average temperatures (°F) recorded during the row cover treatment periods of the 2021–22 and 2022–23 strawberry seasons inside a high tunnel at Southwest Purdue Agricultural Center in Vincennes, IN, USA. Treatments included no row cover used during the period (NC), actively managed row cover during the treatment period (AH), and passively managed row cover and continuously covered strawberry plants throughout the treatment period (PH).

Minimum temperature. Strawberries are susceptible to cold injury, which can result in browning of crown tissues, abnormal leaf growth, and reduced blossom numbers, ultimately lowering yields in the following spring. Hardened strawberry plants of certain genotypes may tolerate temperatures as low as 10 °F at crown levels (Harris 1973). However, prolonged exposure to such temperatures can be detrimental. Marini and Boyce (1979) reported that exposing strawberry plants to 10 °F at the crown level for 1 month resulted in 50% plant mortality and significantly reduced blossom numbers in surviving plants.

In the current experiment, the NC treatment recorded a minimum air temperature of 5.0 °F on 26 Jan 2022 (Fig. 1). Air temperatures below 10 °F persisted for approximately 6 h and recovered to 53 °F during the daytime. Additional nights in the 2021–22 winter also had recorded minimum temperatures at or below 10 °F, with durations ranging from 1 to 5 h for the NC treatment. During the 2022–23 winter treatment period, the lowest air temperature for the NC treatment was 9.7 °F recorded on 25 Dec 2022, and it lasted for 2 h. Although crown temperatures at the soil surface were not directly measured, they were likely higher than the recorded air temperatures at the canopy level. Moreover, soil temperatures at a 4-inch depth for the NC treatment remained above 32 °F throughout winter. These conditions suggest that cold temperatures detrimental to overwintered strawberry plants were either not reached or occurred only briefly, thus preventing cold injury, even in the absence of row cover protection during the winter.

Both active (AH) and passive (PH) row cover treatments increased the daily minimum temperatures compared with the NC treatment. The minimum temperatures remained above 16 °F for all the cover treatments in both seasons.

The temperature differences between PH and NC treatments were negatively correlated with the minimum temperatures recorded for the NC treatment (2021–22: $r = -0.89$, $P < 0.0001$; 2022–23 season: $r = -0.93$, $P < 0.0001$) (Fig. 2). When the minimum temperature in the NC treatment dropped to 10 °F, the row covers used in this experiment increased the minimum temperature to approximately 20 °F. When the minimum temperature in the NC treatment approached 50 °F, the row covers had minimal effect on temperature enhancement at night.

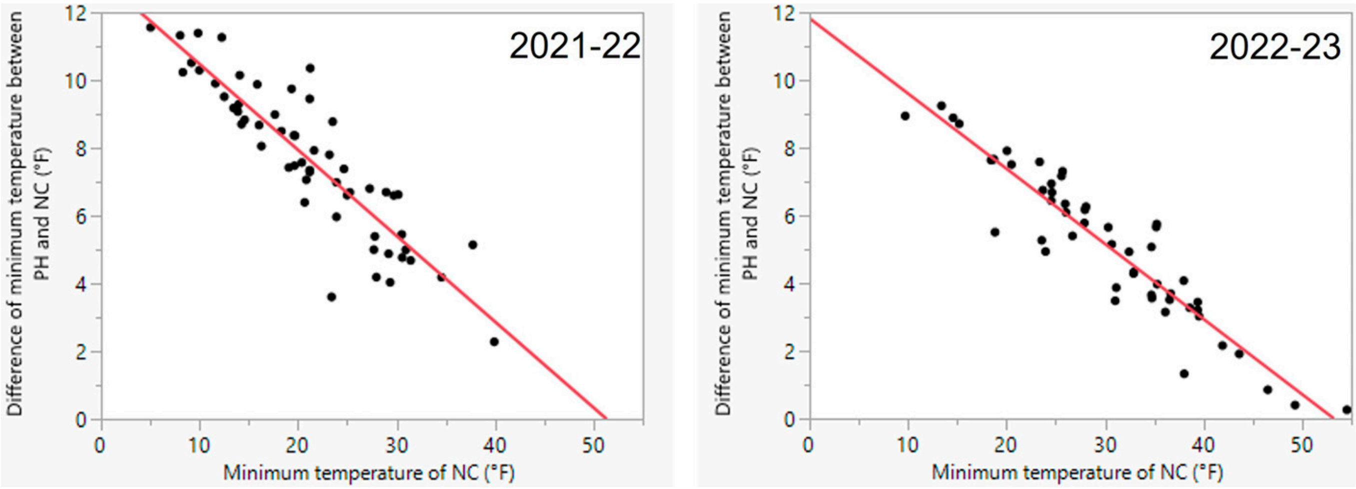


Fig. 2. Relationship between temperature differences of passive row cover (PH) and no cover (NC) treatments and minimum temperatures recorded for the NC treatment in the 2021–22 season (left) and 2022–23 season (right). The line represents a fitted linear regression.

Maximum temperature. When row covers were used passively, the risk of daily maximum temperatures reaching critical levels became a concern. For strawberries, 86 °F is considered a critical threshold (Ullah et al. 2024), especially during the reproductive stage. Elevated temperatures during this phase can disrupt pollen development and growth, ultimately affecting fruit set (Ledesma and Sugiyama 2005).

During the winter of the 2021–22 season, daily maximum temperatures in the PH treatment exceeded 86 °F during 14 d and surpassed 90 °F during 5 d. While peak strawberry blooming for the high tunnel system usually occurs in March, plants in the PH treatment bloomed earlier. These early blooms are unlikely to produce marketable fruit because of limited air movement within the high tunnel during winter, which is further restricted by the use of row covers. Additionally, excessively high temperatures observed in the PH treatment may have contributed to poor pollination. Together, these factors could have led to failed fruit set or the development of unmarketable fruit.

Grow degree days. A base temperature of 50 °F is commonly used to calculate growing degree days (GDDs) for strawberries (Hoffmann et al. 2022). During the winter treatment period of the 2021–22 season, the NC, AH, and PH treatments accumulated 58, 169, and 192 GDDs, respectively. In the 2022–23 season, accumulated GDDs were 81 for NC, 109 for AH, and 143 for PH. Although the covering treatments generally resulted in more GDDs during the winter, the absence of effects on yield suggests that the GDDs accumulated during this period had minimal impact on yield potential compared with the more than 1000 GDDs accumulated in the fall.

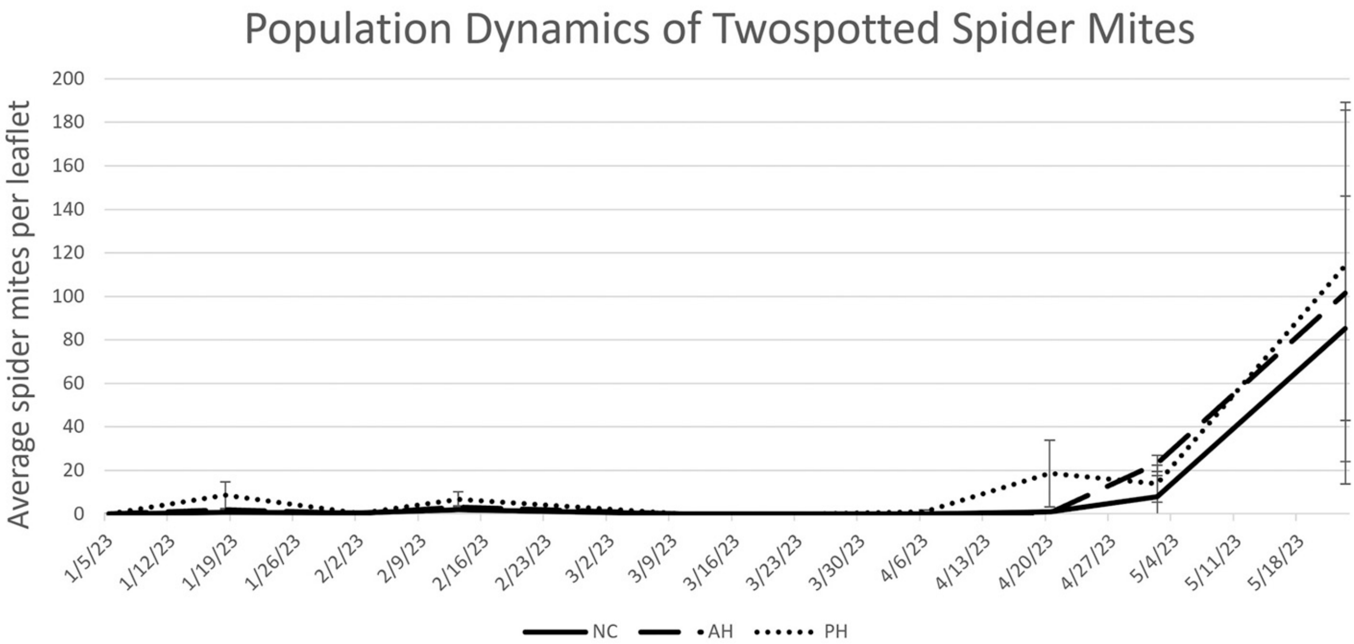
Light intensity. During the winter treatment period of the 2022–23 season, the daily average *PAR* remained below 100 μmol/m^2/s for the PH treatment, but it occasionally exceeded 100 μmol/m^2/s for the NC and AH treatments. Optimal light levels for strawberry growth reportedly range from 100 to 300 μmol/m^2/s (Yoshida et al. 2016). Although light levels during the winter months were lower than optimal, even for the NC treatment, previous studies have found that light intensities below 90 μmol/m^2/s are adequate to support root growth (Zheng et al. 2019). Because average soil temperatures were close to 45 °F across treatments, it is likely that plants continued root growth during the winter months.

Invertebrate pest response to temperature variations under row cover

Spider mites and predatory mites. Predatory mites *Neoseiulus fallacis* were released in early November, before the application of row cover treatments. At the time of release, the TSSM population had reached an average of 6.7 mites per leaflet across the high tunnel. The TSSM population was at a minimal level after the release of *Neoseiulus fallacis* in November and December. During the treatment period in the winter and after termination of the treatments in the spring, the average number of TSSMs per strawberry leaflet varied greatly (Fig. 3).

During the treatment period of the data collected on 18 Jan, plants grown under PH had numerically higher TSSM density (8.59 per leaflet), and NC treatment had lower TSSM density (0.67 per leaflet). However, differences among covering treatments were not statistically significant, likely because of substantial variations in mite populations across plants. After the termination of cover treatments, TSSM population densities across the high tunnel remained at low levels. We hypothesized that this is the result of heavy plant pruning that removed overwintered leaves (and mites), further reducing the population, because mites at this time are often found colonizing the older leaves on the plants (Butcher et al. 1987).

The TSSM population densities increased in April. On 20 Apr, plants that received the PH treatment during the winter had significantly higher TSSM populations compared with those that received the NC or AH treatments in the winter. By mid-May, TSSM densities reached high levels (>80 per leaflet) across all winter cover treatments.



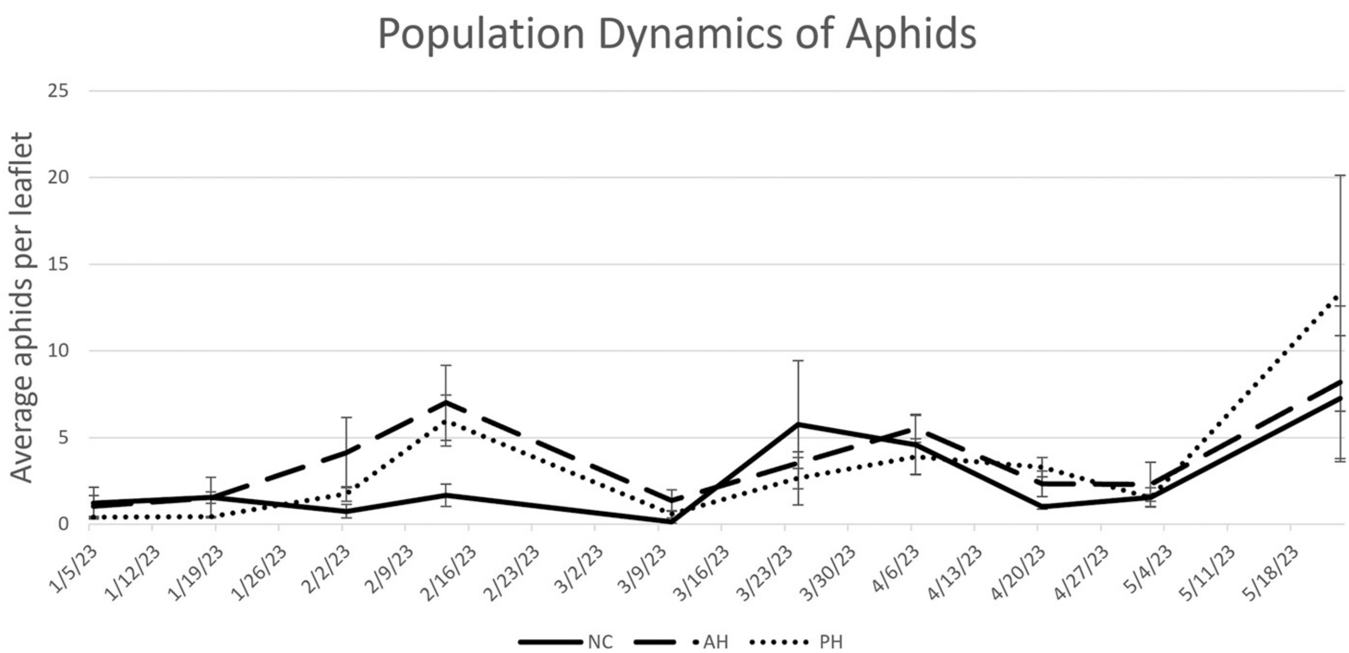


Fig. 3. Population dynamics of twospotted spider mites and aphids in the winter and spring of the 2022–23 strawberry season inside a high tunnel at Southwest Purdue Agricultural Center in Vincennes, IN, USA. Treatments included no row cover used during the period (NH), actively managed row cover during the treatment period (AH), and passively managed row cover and continuously covered strawberry plants throughout the treatment period (PH). The treatments were applied on 25 Dec 2022 and removed on 13 Feb 2023 in the 2022–23 season.

The TSSMs enter a diapausing stage during the winter to enhance their overwintering survival. Diapausing TSSMs were observed in this study. During this diapausing state, physiology and reproduction are reduced and/or halted. The lethal temperatures that cause 50% population mortality in diapausing female TSSMs is −3 °F, compared with 8 °F for nondiapausing female TSSMs (Khodayari et al. 2012). The results of this experiment indicate that TSSMs can successfully overwinter under high tunnel conditions in the region, even in the absence of row covers. However, further research is needed to understand how varying environmental conditions influence the diapause state of TSSMs.

Predatory mites *N. fallacis* were occasionally observed in the spring on plants that received a cover treatment in the winter. However, their populations remained less than one per leaflet until the end of May. *N. fallacis* is a naturally occurring predatory mite capable of overwintering in temperate climates, such as New York (Willden et al. 2022). The current study confirmed their ability to overwinter within the high tunnel system in southern Indiana. However, their population recovery was slower compared with that of TSSMs. To effectively suppress the spring buildup of TSSM populations, supplemental releases of predatory mites are necessary under the current production system.

Aphids. Few aphids were observed from Oct to Dec 2022. However, populations gradually increased on plants under the PH and AH treatments in the winter. Toward the end of the row cover treatment, on 13 Feb, PH and AH treatments had six or seven aphids per leaflet, which was significantly higher compared with that of NC treatment, which had an average of two aphids per leaflet.

Similar to trends observed with TSSM, the aphid densities declined following the removal of overwintered strawberry leaves. However, the aphid population rebounded in March.

Aphids are tolerant of low temperatures, with minimal mortality observed in green peach aphids (*Myzus persicae*) even at temperatures as low as 5 °F (McLeod 1987). They can survive in winter high tunnel environments and also reproduce. Studies have shown that both green peach aphid and potato aphid (*Macrosiphum euphorbiae*) can successfully reproduce at temperatures as low as 40 °F (Barlow 1962). Because of their ability to survive and reproduce under low temperatures, aphids are one of the most significant insect pests in winter high tunnel environments (Willden et al. 2024).

The significantly higher aphid densities under the covered treatments (PH and AH) at the end of row cover treatment suggested that these conditions created a more favorable environment for aphid reproduction during the winter and/or limited mortality effects related to climate and/or natural enemies. Winged aphids were observed resting on the row covers of the PH treatment at the time of their removal. Their subsequent dispersal within the high tunnel likely contributed to the rapid population increase observed in the NC treatment in March despite the observation that the aphid population was low on the plants within this treatment during the winter.

Conclusion

The results of this study indicate that row covers did not provide measurable benefits to overwintering strawberry production in high tunnels during the experimental years. While the use of row covers increased accumulated GDDs, this did not translate into higher yields. On the contrary, it may have encouraged early blooming, which is unlikely to produce marketable fruit and potentially reduce yield.

Row covers also facilitated the overwintering of TSSMs and created more favorable conditions for aphid reproduction, potentially increasing pest pressure and management challenges in the spring.

Although the findings suggest that row covers did not provide significant benefits during the experimental winters, they remain a valuable insurance measure during extremely cold periods. Additional years of evaluation, particularly during colder winters, are warranted to fully understand the role of row covers in the high tunnel and soil-based strawberry production system.

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