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A scientometric review of the peer-reviewed research on high tunnels in the United States

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Abstract

This study assessed the extant literature related to the use of high tunnels (HTs) in agricultural systems in the United States since the 2009 launch of the Natural Resources Conservation Service (NRCS) High Tunnel Initiative. This NRCS program led to an increase in HT adoption nationwide. The literature searches were conducted using the Web of Science (WoS) database. The final sample was 133 peer-reviewed articles published between 2009 and February 2023. We used CiteSpace 6.2.R1 and Gephi 0.9.2 to conduct co-citation, co-author, co-institution, and clustering techniques. The findings showed that the peer-reviewed literature about HT use has increased since 2009, substantially rising between 2017 and 2021. Horticulture was the top subject category in the literature, and most articles were published in peer-reviewed journals of the American Society for Horticultural Science (i.e., HortTechnology and HortScience). The research field evolved from general HT practices, nutrient management, and plant pathology to focus on trials of specific crops and integrated pest management. The institutions with the most contributions to the HT literature were Kansas State University, the University of Florida, Michigan State University, Purdue University, and the University of Minnesota. The patterns of HT research revealed in this study offer a greater understanding of the current state of knowledge to inform the focus of future research.

Introduction

Farmers face increasing challenges associated with the growing pressure to expand production amidst escalating challenges presented by climate change. Farmers can use protected structures exclusively or as part of their crop production systems to ensure consistent yields and thus protect their livelihoods in the face of climate uncertainty (Jensen and Malter, 1995; Blomgren and Frisch, 2007; Alabama Cooperative Extension System, 2015). High tunnels (HTs) are protected structures used for agricultural crop production (Lamont, 2009; Orzolek, 2013). Typically, HTs are structures with steel frames in various shapes covered in polyethylene plastic (Mefferd, 2017). A primary reason growers use protected structures as part of their crop production systems is for season extension. Extending the growing season allows farmers to enter markets with their crops earlier and stay in them later than in a typical open-field growing season (Johnny's Selected Seeds, n.d.; Mefferd, 2017). Farmers in colder climates can grow tomatoes in the winter under an HT (Mefferd, 2017), and farmers in hotter climates can use HTs to protect crops from rainfall events (Footer, 2020). HTs are a passive means of controlled production; e.g. ventilation and temperature control are naturally achieved by opening and closing sidewalls. Greenhouses, in contrast, are active protected crop production systems characterized by electrically powered ventilation (Gruda, Bisbis and Tanny, 2019). However, the use of space heaters and fans inside HTs on occasions of extreme temperatures has been reported. Closely related types of passively ventilated structures include polytunnels, hoop houses, and low tunnels. This study focused on passively ventilated structures exclusively and referred to all passively ventilated structures as HTs for simplicity. HTs can help manage climate risk and maintain and even increase yields compared to open fields (Belasco et al., 2013); they provide a controlled environment in the face of climate uncertainties and market dynamics.

The original use of protected structures dates back to 17th-century Europe (Mefferd, 2017). In Asia, Europe, and the Middle East, using HTs and other protected structures in farming operations was well-established for decades before gaining popularity in the United States. The first HT use reported in the United States was not until 1953 by Dr Emery Emmert at The University of Kentucky (Carey et al., 2009; Orzolek, 2013). HT use has increased meaningfully in the United States since the early 1990s when interest emerged in the utility of producing vegetables in HTs (Carey et al., 2009; Lamont, 2009). The information available at the time focused on HT production as a season extension in cold climates. The best practices of HTs in warm climates began to receive increased attention starting in the 2010s (Alabama Cooperative Extension System, 2015), as evidenced by the increase in peer-reviewed literature, gray literature, and adoption of HTs nationwide.

Generally, HTs are low-cost means for farmers to control for climate and market uncertainties compared with open-field production. HTs protect against crop damage from excessive rainfall, enhance crop vigor and soil quality, and provide protection from pesticide drift from nearby operations (National Resources and Conservation Service, [n.d.]b). HTs are highly customizable, meaning farmers are able to decide what specific features to invest in. For example, some HT structures have automated sidewalls that open or close based on temperature sensor readings. This feature is helpful when an HT is located in close proximity to a power source but may not be financially sound for a small acreage farm or a farm with few HT structures where sidewalls can be manually rolled up, and money can be best invested elsewhere.

High tunnels offer a relatively affordable way for farmers to extend the growing season of crops, although they require a considerable economic investment upfront. The Natural Resources Conservation Service (NRCS) offers cost-share funding for farmers in the United States to help pay for most of the cost of the structure and provides technical support for participants. The NRCS High Tunnel Initiative pilot program was launched in 2009; a major tenet of this program is cultivating and maintaining soil health by implementing soil conservation practices under the HT structure (Coleman, 1992). This cost-share program assists farmers interested in installing a high tunnel in their operation. Historically, underserved farmers are eligible for the highest rate of financial assistance. Program recipients must follow guidelines to receive assistance, including maintaining the structure for a minimum of 4 years, using pre-manufactured HT kits, growing crops directly in soil under the HT, and the structure must be 6 feet in height at minimum (National Resources and Conservation Service, [n.d.]b). Raised beds up to 12 inches are allowable under the NRCS program (United States Department of Agriculture, 2015). NRCS has local offices throughout the United States and territories that administer the program. Prospective participants work closely with NRCS service providers to apply to the program. Applications are then ranked by the projected benefit to resource conservation priorities (National Resources and Conservation Service, [n.d.]a).

There are, however, resource inefficiencies associated with using high tunnels. The intensive management (e.g. tilling) of soil repeatedly for continuously growing crops leads to the depletion of organic matter content and textural changes that can cause erosion (Perkus et al., 2022). One way to address this issue is to install a moveable tunnel, which is an HT on a track or rail that can be shifted to avoid intensively using the same soils, effectively implementing crop rotation strategies for the tunnel structure (Baumbauer and Burgess, 2020); the NRCS funding does not cover these kinds of high tunnels. Another way to conserve soil health would be to employ hydroponic methods inside the high tunnel, although NRCS does not allow this practice initially upon receipt of their funding. Also, no organic certification is available for hydroponic methods (Mefferd, 2017). Additionally, there are water-related inefficiencies associated with high tunnel use. The structure is covered, so the system relies entirely on irrigation. In other words, growers cannot take advantage of rainfall unless they employ some kind of rainwater harvesting method and irrigate with that harvested rainwater. Shading screens over the structure can also help conserve water (Gruda, Bisbis and Tanny, 2019).

The economic return on the initial investment in an HT structure and associated materials (e.g. plastic covering, irrigation system) and practices (e.g. grafting) via increased yields can vary by year (Nian et al., 2022), as with any investment resulting from a management-based decision. Farmers can couple the economic benefit of protected structures by employing biologically beneficial strategies, such as cover crops. The biological return on this strategy (e.g. improved soil health) can also take years (Digiacomo et al., 2023). Exploring the various management strategies employed in protected agriculture in the context of water and soil efficiency can inform viable solutions for meeting increased yield demand while ensuring resilience to climate and market uncertainties.

Generally, funding for the NRCS High Tunnel Initiative has steadily increased since the program's start (National Sustainable Agriculture Coalition, 2016). Figure 1 shows national data from 2016 through 2020 of the total contracts, financial obligation, and square footage from the NRCS High Tunnel Initiative. Funding increased over time from 2016 to 2020, with a peak in contracts, obligations, and square footage in 2019, leading to greater adoption of HTs over time and more agricultural research conducted in HTs. An assessment of the current knowledge to date is essential as the HT adoption trend continues nationally.

To date, there has been one systematic literature review of high tunnels in North America (Janke, Altamimi and Khan, 2017) and a meta-analysis of protected systems broadly as a response to climate change (Gruda, Bisbis and Tanny, 2019). To our knowledge, no previous bibliometric or scientometric analyses on the peer-reviewed HT literature have been published at the time of this publication. Bibliometrics is a quantitative approach to analyzing a collection of written works (Jones, 2016). Scientometrics can be considered synonymous with bibliometrics (Jones, 2016) or distinguished by a focus on scientific publications exclusively (Mejia et al., 2021) by quantifying a body of peer-reviewed literature. Quantitative methods of scientometrics include co-citation and cluster analysis. The metrics generated by scientometric methods show the evolution of a scientific discipline and reveal gaps to address with future research and inform policy. There is no agreed-upon definition of bibliometrics, scientometrics, or the closely related term informetrics, and these terms are treated as overlapping, interchangeable, and distinguished by the discipline they represent (Yang, Yuan and Dong, 2020). All the analyses described for the present study are referred to as scientometric. While meta-analyses use statistical analysis to analyze methodologies and findings across many studies (Moher et al., 2009), scientometrics analyzes the characteristics (i.e. keywords, authors, citations, institutions) of the group of studies exclusively. The co-citation analysis functionality in CiteSpace generates networks of cited references from the dataset over time. The links between the references signify the co-citation robustness. Cluster analysis in CiteSpace groups the references by assigning a keyword to each cluster that represents the fundamental domains within the overall scientific discipline of the dataset (Chen, 2017). The nodes in each network represent the number of metrics in the analysis, e.g. publications, authors, and institutions (Yang, Yuan and Dong, 2020). Overall, these analyses reveal the impacts and importance of advancements in a given field of science (Chen, 2017). The present study focuses on the status of HT literature in the United States to date since

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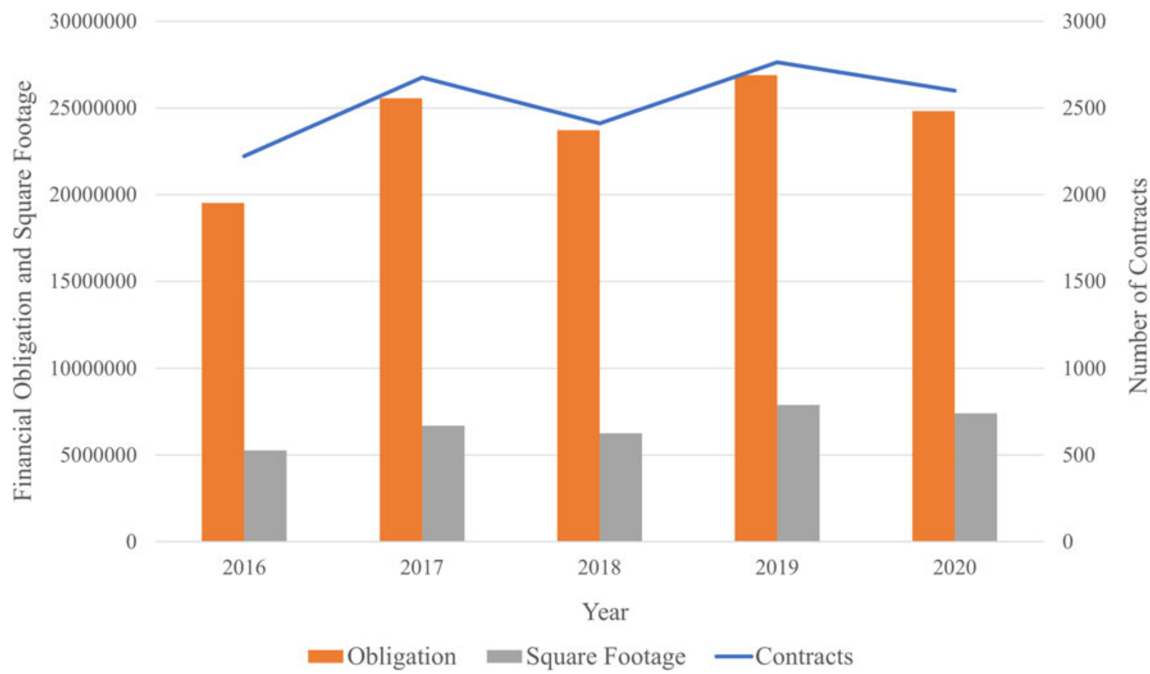

Figure 1. National totals of NRCS High Tunnel Initiative contracts, financial obligations, and square footage by year 2016–2020. Includes data from Environmental Quality Incentives Program (EQIP), Agricultural Management Assistance (AMA), and Regional Conservation Partnership Program (RCPP).

the launch of the NRCS program to identify trends and gaps in knowledge and direct further research.

Methods

Data collection

The initial search used the following keywords: 'high tunnel', 'crop', 'crops', 'cropping', 'quality', 'high-tunnel', 'hoop house', 'hoophouse', 'low tunnel', 'caterpillar tunnel', and 'season extension'. We based the selection of terms for the initial search on literature identified from key seminal papers and the research question. We assembled an expert panel of researchers that assisted in identifying appropriate search terms for validation and re-calibration of the initial search. We identified potential panel members from different agricultural disciplines based on their experience with research on high tunnel systems. The final sample of four included at least one researcher from each of the following disciplines: horticulture, entomology, and plant pathology. First, we sent a Qualtrics form to the panel members that asked them to enter and rank search terms they believed would capture the full scope of the body of knowledge on high tunnels. Then, a facilitated discussion was conducted based on the summarized responses the panel members submitted via the Qualtrics form. The objective of the discussion was to generate an agreed-upon list of the final search terms for this study. Institutional Review Board (UFIRB202102347) approval was obtained for the expert panel. The following keywords were added based on the expert panel input: 'plant health', 'soil quality', 'pest', 'disease', and 'crop performance'. No additional articles emerged. This study used the Web of Science (WoS) database to search the literature on crop production in high tunnels (HTs). The search was delimited to peer-reviewed journal articles published in English with studies conducted in the United States between 2009 and 2023. The search was last performed on 27 February 2023. The search yielded a total of 133 records. Table 1 details the search parameters of the present study.

Research design and analysis

This study used scientometric analysis methods to evaluate the published literature on the effects of HT systems on crop vigor and quality. This type of analysis maps the characteristics of a body of knowledge mathematically and graphically. Scientometrics has been used across scientific disciplines to identify the development of a field of research over time (Olawumi and Chan, 2018). We used WoS for descriptive analysis and CiteSpace 6.2.R1 and Gephi for network analyses. Specifically, we visualized the document co-citation and collaboration networks among authors and institutions. This scientometric

Table 1. Detailed search setting parameters

Source	Web of Science Core Collection
Citation	Conference Proceedings Citation Index—Science (CPCI-S), Emerging Sources Citation Index (ESCI), Science Citation Expanded (SCIE) and Social Sciences Citation Index (SSCI)
Search steps	TS = (['high tunnel'] and [crop*] and ['quality'] or ['high-tunnel'] or ['hoophouse'] or ['hoop house'] or ['low tunnel'] or ['caterpillar tunnel'] or ['season extension']) AND LANGUAGE (ENGLISH) AND DOCUMENT TYPES:(Article)
Time span	2009–2023
Qualified records	133

Searches for any words and variants of that word that includes that stem. For example, crop includes crops and cropping.

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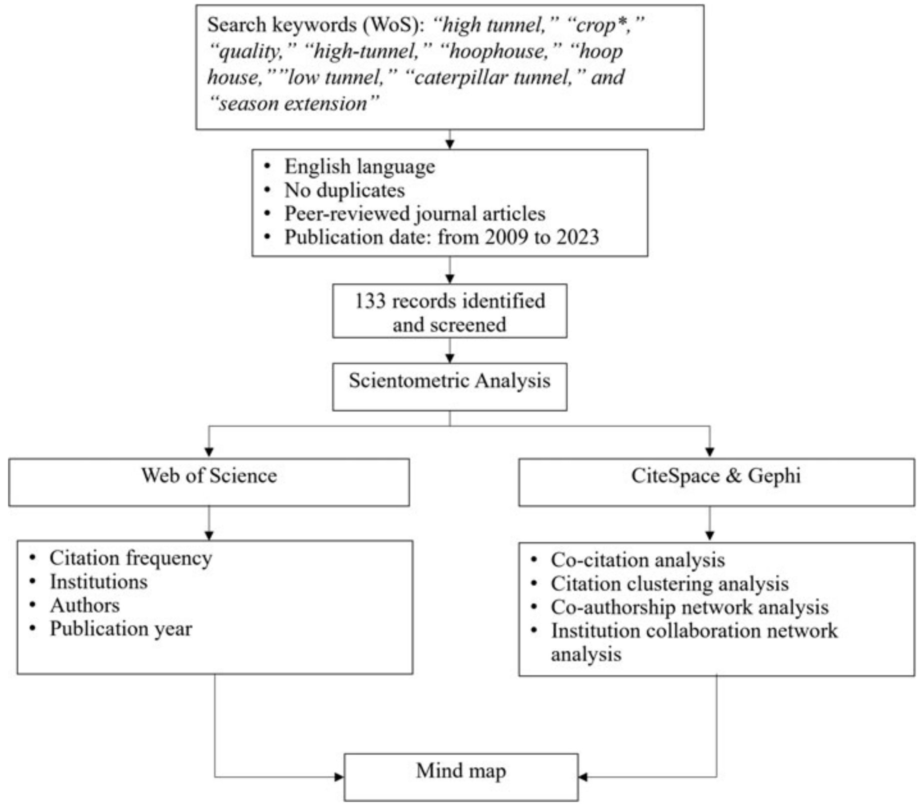

Figure 2. Diagram of the research design.

analysis provided an overview of the HT literature to assess the current knowledge dating from the NRCS High Tunnel Initiative program launch in 2009. This study's data analysis approach was informed by Zhang et al. (2018) and Liu et al. (2022). We conducted co-citation network analysis using the CiteSpace software to elucidate the relationships among the literature by revealing pairs of articles cited by other publications. The strength of these relationships is directly related to the number of co-citations (Cho, Kim and Park, 2021). Then, we conducted citation clustering to identify the prominent research areas. We employed clustering to distinguish distinct thematic areas for analysis within the HT literature. Additionally, we conducted co-author, co-institution network analysis to determine the primary relationships between authors and institutions. Figure 2 summarizes the research design. This study presents and assesses networks through visualizations and reports the network density, betweenness centrality, and closeness centrality.

We conducted scientometric analyses in the present study using CiteSpace 6.2.R1 and Gephi 0.9.2. We used CiteSpace to create network visualizations for the present study. CiteSpace is available to download at http://cluster.cis.drexel.edu/~cchen/citespace/ (accessed on January 15, 2023) and was developed by Chen, Ibekwe-SanJuan and Hou (2010). We used CiteSpace to conduct the co-citation network analysis. The time frame employed was 2009–2023 with a one-year slice length. We set the top N per slice to five to identify the top five most cited publications by each year over time. The threshold was set at 19. We used Gephi to generate the network density, betweenness centrality, and closeness centrality statistics reported in the present study. Gephi is available for download at https://gephi.org/ (accessed on January 15, 2023).

Results and discussion

Descriptives of publication years and cited journals

We used WoS for descriptives of the publication years and cited journals. One hundred thirty-three peer-reviewed articles about the effects of HT use on crop production in the United States have been published since the NRCS High Tunnel Initiative launched in 2009. Figure 3 shows the number of citations and publications each year from 2009 through February 2023. The number of citations grew consistently from 2013 through 2021, while the number of publications increased consistently from 2017 through 2021. Generally, the number of citations and publications in the United States has increased steadily since 2009, which reflects increased funding of HT research, interest from researchers in crop production in HTs, and adoption of HT systems over time.

Table 2 lists the top five peer-reviewed journals for articles about HT crop production. The journal with the greatest number of HT publications is HortTechnology, with over 30% of all publications since 2009. HortScience was the next leading journal, with over 20% of the HT articles. Both journals are published by the American Society for Horticultural Science (ASHS). Horticulture is the predominant discipline of the top journals with HT publications.

Table 3 lists the top five subject categories for the peer-reviewed HT literature. Horticulture was the highest subject category of the HT literature. This is consistent with the leading journals housing these articles, with horticulture being in the title of four out of the top five journals. All the subject categories fall under the general scientific discipline of agriculture.

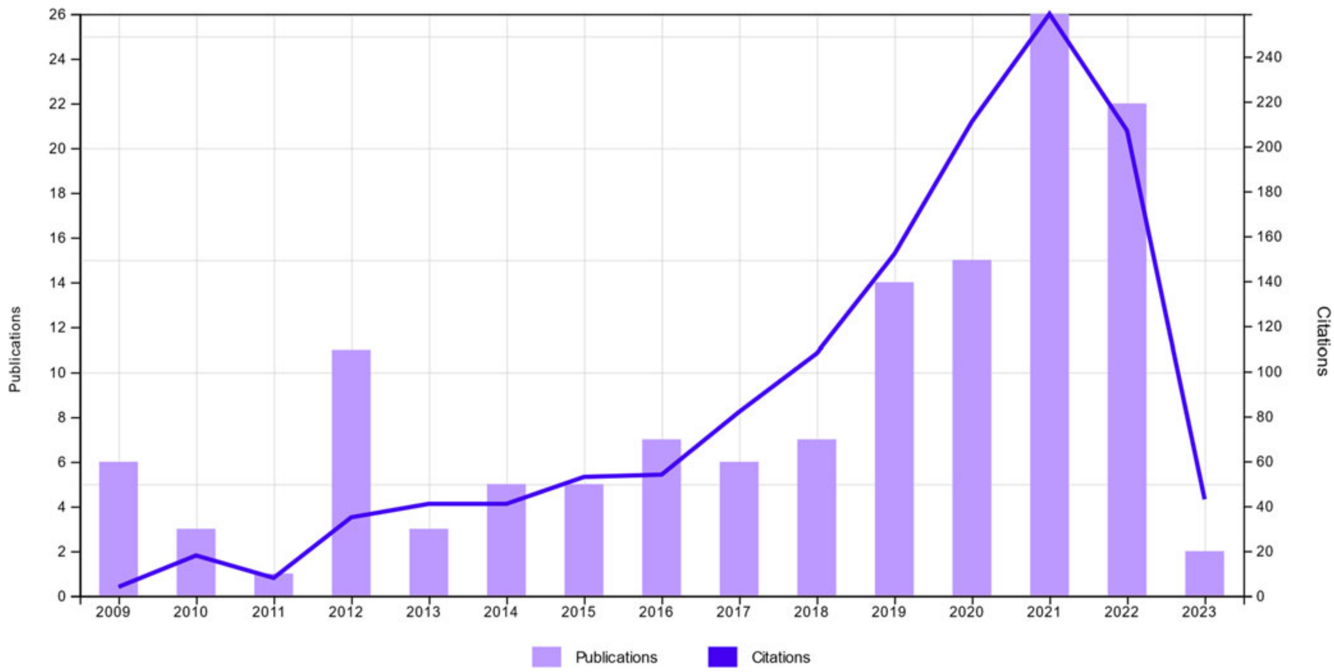

Figure 3. WoS visualization showing the number of publications and citations for HT literature published in the United States from 2009 to February 2023.

Co-citation network analysis

Figure 4 shows the co-citation network (214 nodes, 763 edges, 7.131 average degrees, and 0.033 network density). Co-citation has increased steadily since 2019 alongside the number of publications (see Fig. 3). The co-citation frequency peaked in 2021 and 2022, consistent with the distribution of the number of publications in Figure 3. There were only two articles with citation bursts in the dataset. Figure 5 shows these two articles, which both focus on tomato production in high tunnels.

The top five most cited articles based on co-citation are in Table 4. Carey et al. (2009) is the most co-cited article with a frequency of 43. The subsequent most co-cited publication was Lamont (2009), with a frequency of 42. Both articles provide general information about crop production in high tunnels in the United States and globally.

Citation clustering network analysis

We employed the 'All in one' feature in CiteSpace to generate clusters for the co-citation network by keyword. Figure 6 and Table 5 show the results of the citation-clustering network analysis for the co-citation network. Table 5 reports the cluster size, which is the number of publications belonging to that cluster. The silhouette values reported in Table 5 are a value of 1 or close to 1, representing a high quality of clusters. Values at or close to 1 mean the clusters are distinct from each other, and the terms within each cluster are homogenous (Rousseeuw, 1987). The year column in Table 5 is the mean year of publications within that cluster.

We categorized clusters into two distinct time periods based on the mean year, 1 (prior to 2005) and 2 (2005 onward). In Category 1, the literature focused on nutrient management, plant pathology, and general characteristics of protected structures. The top five terms in each cluster (see Table 5) show the various recurring iterations of HT ('hoop housed low tunnel') and the term 'anthracnose', which demonstrate the research emphasis in Category 1. The more recent studies in Category 2 centered on trials of specific crops and integrated pest management in HTs. Recurring terms in Category 2 included 'rubus idaeus' and 'integrated pest management', which characterize the research focus in this more recent time period. The trend in articles more recently published focusing on specific crops is consistent with the only two articles with citation bursts noted earlier, focusing on tomato production in high tunnels.

Table 2. Top 5 journals with peer-reviewed articles about HTs

Journal	Impact factor	Frequency	%
HortTechnology	1.387	41	30.827
HortScience	1.874	28	21.053
Horticulturae	2.923	11	8.271
Scientia Horticulturae	4.342	6	4.511
Renewable Agriculture and Food Systems	2.915	4	3.008

Table 3. Top five subject categories of peer-reviewed HT articles

Subject	Frequency	%
Horticulture	90	67.669
Agronomy	11	8.271
Food Science Technology	10	7.519
Plant Sciences	10	7.519
Entomology	9	6.767

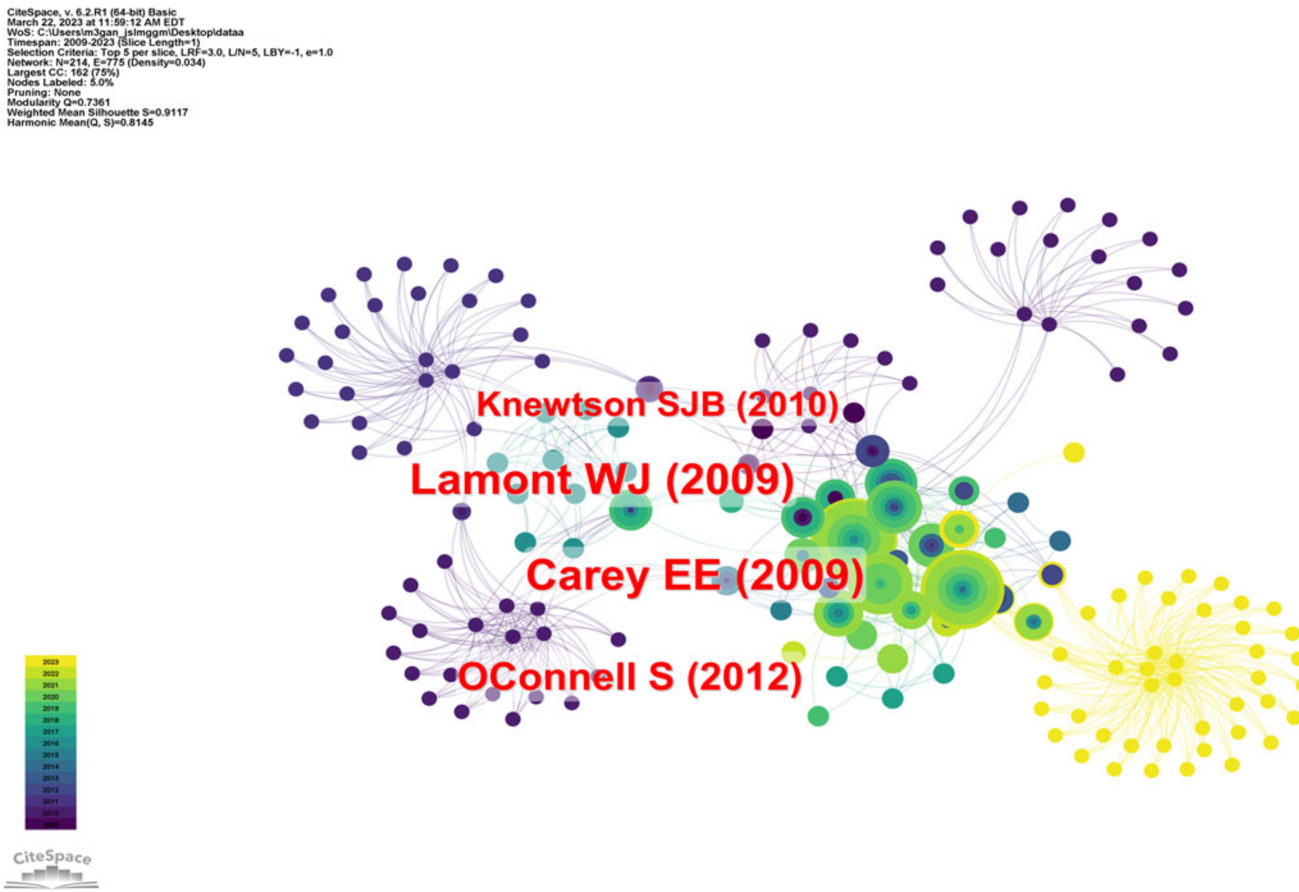

Figure 4. The co-citation network visualization from CiteSpace.

Co-authorship network analysis

Figure 7 shows the collaboration network (241 nodes, 430 edges, 3.568 average degrees, and 0.015 network density) among authors for the literature about crop production in high tunnel systems in the United States. The average degree and network density suggest that the prominent researchers who published HT research generally do not collaborate on publications with one another. Table 6 reports the degree centrality, betweenness centrality, and closeness centrality for the top five authors in the co-authorship network. The leading researchers publishing literature about the effects of using HTs on crop vigor and quality were Dr Cary Rivard (Professor of Horticulture and Natural Resources at Kansas State University), Dr Eleni D. Pilakoni (Professor of Urban Food Production and Postharvest Handling at Kansas State University), Dr Xin Zhao (Professor of Horticultural Sciences at the University of Florida), Dr Roberto G. Lopez (Associate Professor, Department of Horticulture at Michigan State University), and Dr Dan Drost (Professor of Horticulture, Department of Plants, Soils and Climate at Utah State University).

Institution collaboration network analysis

Figure 8 shows the collaboration network (90 nodes, 212 edges, 4.711 average degrees, and 0.054 network density) among institutions for the HT literature. The average degree and network density indicate there is slightly more collaboration among institutions than authors, although the institution collaboration network is still quite dispersed. The degree centrality, betweenness centrality, and closeness centrality for the top five institutions in the collaboration network are reported in Table 7. The principal institutions publishing HT literature were Kansas State University, the University of Florida, Michigan State University, Purdue University, and the University of Minnesota. The first two authors listed in Table 6 are affiliated with Kansas State University, reinforcing the high impact and influence of the HT literature coming out of this institution.

Conclusions

The present study conducted network analysis using CiteSpace and Gephi software to investigate the salient research areas and

References	Year	Strength	Begin	End	2009 - 2023
Both AJ, 2007, HORTTECHNOLOGY, V17, P467, DOI 10.21273/HORTTECH.17.4.467, DOI	2007	3.47	**2009**	2014	
OConnell S, 2012, HORTSCIENCE, V47, P1283, DOI 10.21273/HORTSCI.47.9.1283, DOI	2012	4.23	**2019**	2021	

Figure 5. Top two references with the Strongest Citation Bursts visualization from CiteSpace.

Table 4. Top five articles based on co-citation frequency

Authors and Publication Year	Title	Journal	DOI	Frequency
Carey et al. (2009)	Horticultural Crop Production in High Tunnels in the United States: A Snapshot	HortTechnology	10.21273/ HORTSCI.19.1.37	43
Lamont (2009)	Overview of the Use of High Tunnels Worldwide	HortTechnology	10.21273/ HORTSCI.19.1.25	42
O'Connell et al. (2012)	High Tunnel and Field Production of Organic Heirloom Tomatoes: Yield, Fruit Quality, Disease and Microclimate	HortScience	10.21273/ HORTSCI.47.9.1283	26
Knewtson et al. (2010)	Management Practices of Growers Using High Tunnels in the Central Great Plains of the United States	HortTechnology	10.21273/ HORTTECH.20.3.639	18
Wells and Loy (1993)	Rowcovers and High Tunnels Enhance Crop Production in the Northeastern United States	HortTechnology	10.21273/ HORTTECH.3.1.92	17

collaboration networks in the peer-reviewed literature about the effects of HT use on crop vigor and quality. We used WoS to acquire our final dataset ($N = 133$) of the HT literature published in the United States since the launch of the NRCS High Tunnel Initiative in 2009. Figure 9 maps the dataset of peer-reviewed publications analyzed in the present study to assess the current HT body of knowledge and inform trends and future research trajectories.

Generally, there has been an increase in the peer-reviewed HT literature that followed a rise in NRCS High Tunnel Initiative contracts, financial obligations, and square footage over time as shown in Figures 1 and 3, respectively. A notable rise in NRCS HT investment in 2019 likely contributed to a subsequent increase in HT literature citations and publications in 2021. The literature centered around seven primary topics, with the bulk of the publications focusing on the characteristics of HTs, nutrient management experiments, trials of specific crops (e.g., raspberries, tomatoes, cut flowers) in HTs, or comparing open field production to HT production, plant pathology, and pest management in HT production. We organized the literature based on salient

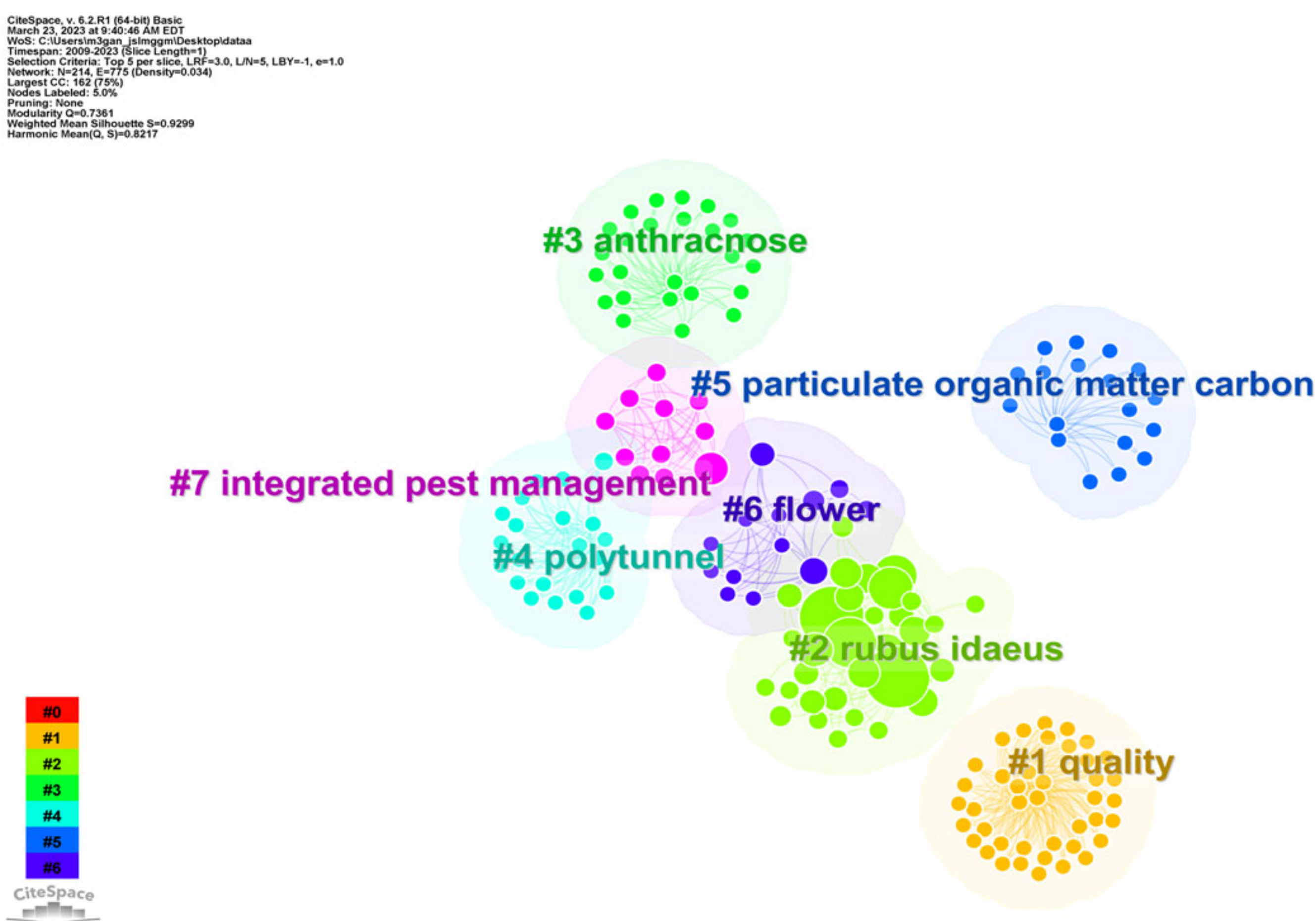

Figure 6. Co-citation network keyword clusters visualization from CiteSpace.

Table 5. Top five terms in co-citation network clusters

Cluster-ID	Cluster label	Size	Silhouette	Year	Top five terms
1	Quality	41	1	2005	Quality, anemone coronaria, carmel, galilee, yield
2	*Rubus idaeus*	33	0.721	2009	*Rubus idaeus*, integrated pest management, survey, spotted wing drosophila
3	Anthracnose	25	1	1998	Anthracnose, *Didymella applanata*, *Elsinoe veneta*, off-season, powdery mildew
4	Polytunnel	21	0.976	2004	Polytunnel, anthracnose, low tunnel, sensitivity analysis, leafy greens
5	Particulate organic matter carbon	18	1	1998	Particulate organic matter carbon, total carbon, survey, salinity, hoophouse
6	Flower	13	0.894	2001	Flower, survey, vegetable, organic, protected agriculture
7	Integrated pest management	11	0.975	2013	Integrated pest management, spotted wing drosophila, *Rubus idaeus*, exclusion netting, invasive species

clusters: Category 1 (prior to 2005) and Category 2 (2005 onward). In Category 1, the publications centered on general information about HT structures, nutrient management, and plant pathology. On the other hand, Category 2 contained literature that focused on specific crop trials and integrated pest management in HTs. The high-impact articles were Carey et al. (2009), Lamont (2009), with these articles belonging to Category 2. The primary journals that published HT literature in the United States since 2009 were HortTechnology, HortScience, Horticulturae, Scientia Horticulturae, and Renewable Agriculture and Food Systems. Our findings revealed the leading HT researchers were Dr Cary Rivard, Dr Eleni D. Pilakoni (both from Kansas State University), Dr Xin Zhao (University of Florida), Dr Roberto G. Lopez (Michigan State University), and Dr Dan Drost (Utah State University). The top institution publishing HT literature since 2009 was Kansas State University.

The findings from this study provide guidance for future directions of HT research. Season extension technologies, such as HTs, were historically more prevalent in cooler climates. With the rapid increase in high tunnel adoption nationally, due in part to the

Figure 7. Co-authorship network visualization from CiteSpace.

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Table 6. Top five authors in the co-authorship network

Author	Frequency	Degree centrality	Betweenness centrality	Closeness centrality
Rivard, C.	11	25	969.75	0.582
Pilakoni, E. D.	7	16	90.25	0.453
Zhao, X.	6	11	198.583	0.342
Lopez, R.	6	9	38	0.909
Drost, D.	6	8	11.5	1

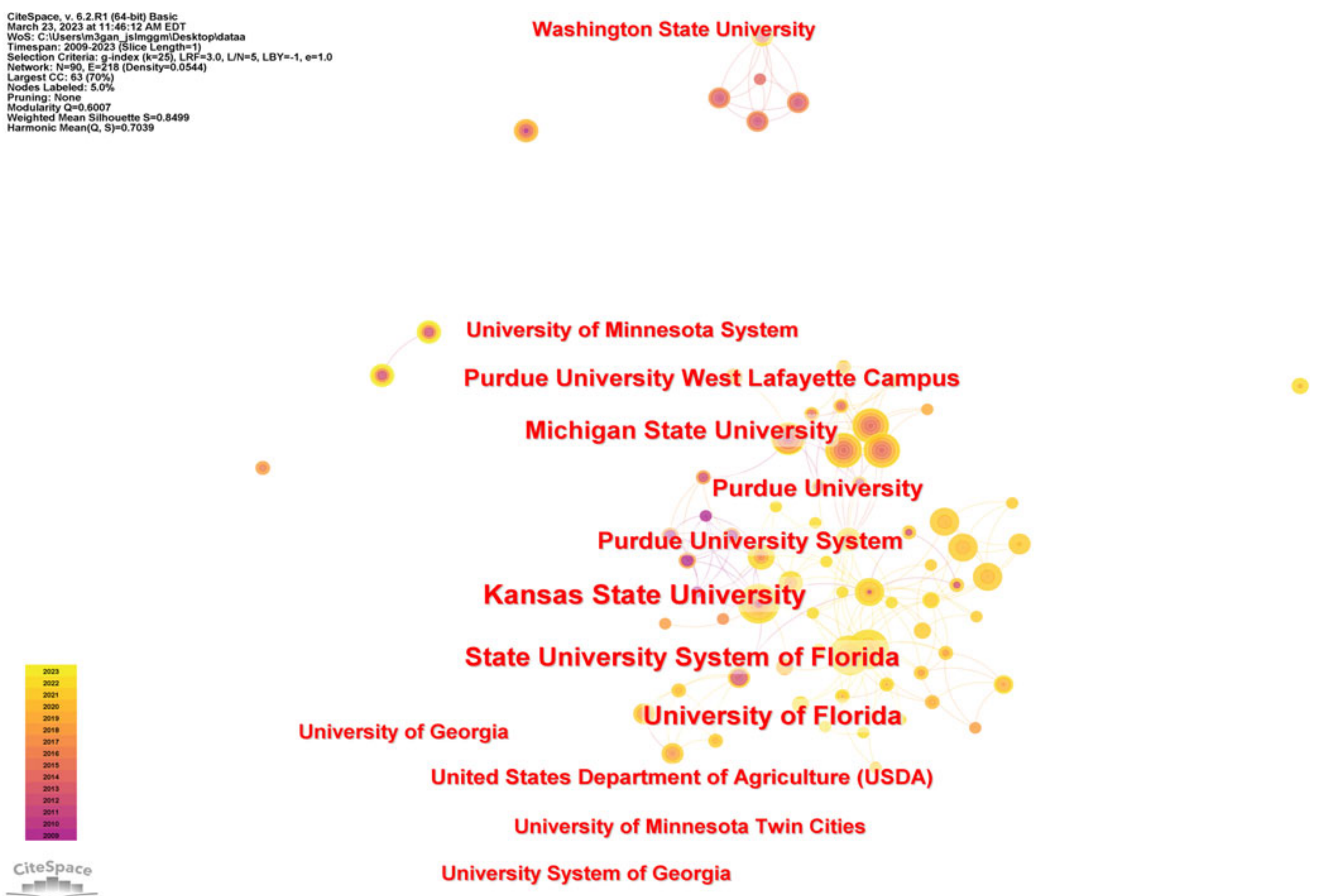

Figure 8. Institutional collaboration network visualization from CiteSpace.

NRCS High Tunnel Initiative, farmers have been using HTs in hotter climates more over time (Ernst et al., 2020). Manipulating the timeline of the growing season with the help of a protected structure in warm climates allows farmers to have access to the consumer demand for seasonal crops at times when those crops are traditionally considered out of season

Table 7. Top five institutions in the collaboration network

Institution	Frequency	Degree centrality	Betweenness centrality	Closeness centrality
Kansas State University	17	12	278.435	0.473
University of Florida	15	16	260.314	0.5
Michigan State University	13	7	107.021	0.346
Purdue University	11	9	58.307	0.337
University of Minnesota	8	13	196.52	0.466

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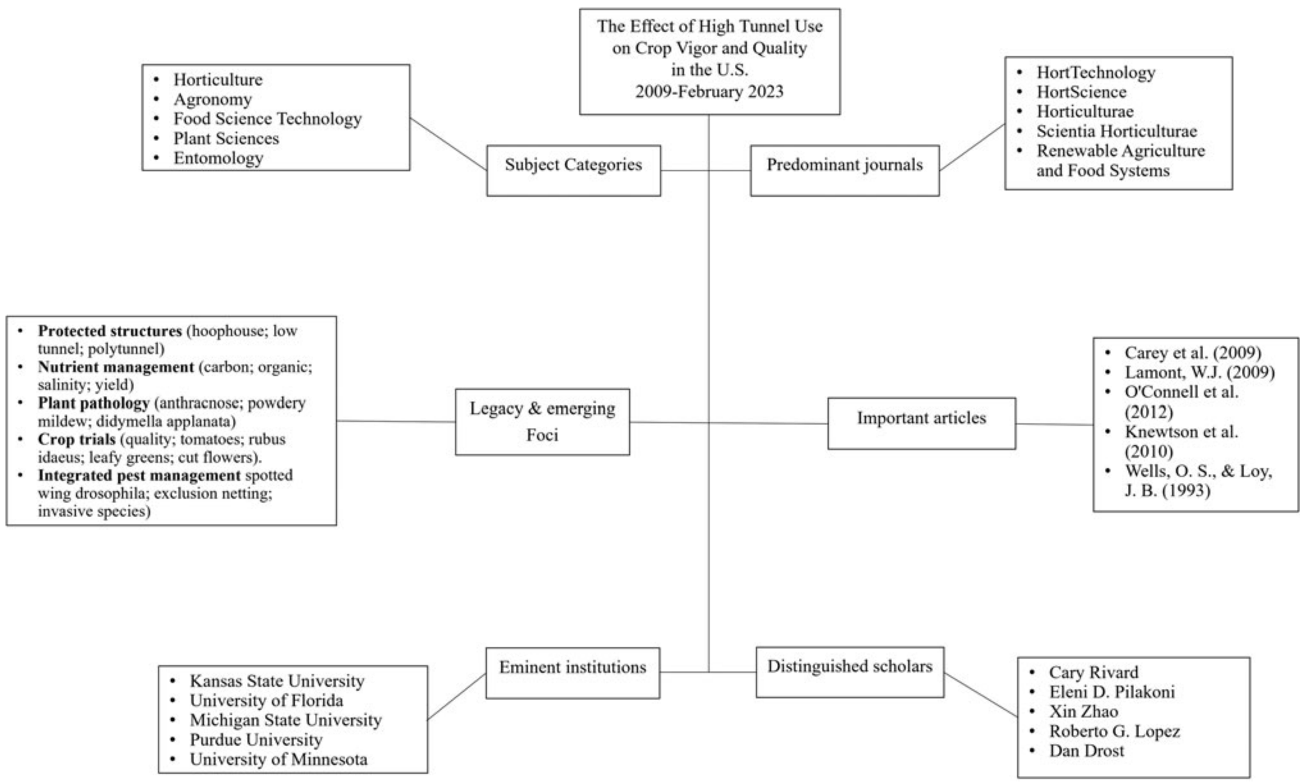

Figure 9. Mind map of present study.

for field conditions. The information about HT best practices historically centered on season extension in cold climates (Mefferd, 2017), leaving a considerable opportunity to explore and establish best practices for hotter climates. Our findings are consistent with this overall trend, with Kansas State University being the leading institution and the two top authors, Dr Cary Rivard and Dr Eleni D. Pilakoni, both being faculty members at Kansas State University. A notable exception is the University of Florida, landing in the second spot among the top five institutions in the collaboration network. Dr Xin Zhao from the University of Florida ranked third among leading researchers publishing literature about the effects of using HTs on crop vigor and quality. This result reveals an interest in investigating best practices for higher temperatures in the scientific literature since 2009. There is added pest and disease pressure in hotter climates (Alabama Cooperative Extension System, 2015; Frey et al., 2020), and farmers using HTs in these areas would benefit from well-established best practices for managing pest and disease pressure over time. Cover cropping, grafting, and solarization techniques can be used to maintain soil health and control pests and diseases (Digiacomo et al., 2023; Gamliel and van Bruggen, 2016; Nian et al., 2022; Rodriguez Izaba, Guan and Torres, 2021). The tenets of integrated pest management (IPM) can be helpful for high tunnel systems in both regions of cooler and hotter climates (Pottorff and Panter, 2009), which is consistent with recent HT literature trends as evidenced in the present study's cluster analysis. Considerations for managing climate start with the choice of the structure itself (i.e., materials, height, design) and the type of plastic covering material. For instance, farmers in hurricane-prone areas might focus on features for reinforcing sidewalls; in contrast, farmers in areas with significant snowfall annually might select a gothic HT roof designed to withstand large loads of snow (Mefferd, 2017). Besides climate considerations, there is considerable variance across soil textures and levels of organic matter across the United States. This has implications for water resource management and, thus, decisions about irrigation type and scheduling warrant further investigation.

The prospect of agricultural disciplines outside of horticulture exists to explore the effects of HT use on crop vigor and quality, such as entomology, plant pathology, agricultural economics, and the social sciences. Contributions to the HT body of literature across various scientific disciplines would enhance our understanding of the use, benefits, and challenges of using HT in farm operations. For example, the long-term economic impact of HT maintenance and inputs compared to market yield and sales could help HT users make important management decisions over time. Finally, there is also a lot of possibility regarding collaboration across institutions and authors, as evidenced by the study's findings. The majority of the top authors had their departmental affiliation in horticulture, which is consistent with the crop-specific focus of HT research. Continued HT research could benefit from additional publications by authors in scientific fields outside of horticulture. Generally, there is considerable opportunity to assess the long-term economic and environmental implications of HT use in hotter climates. These perspectives could potentially offer exciting new methodologies, findings, and directions for HT crop production systems in the United States

Limitations and future directions

The peer-reviewed literature represents only a fraction of published information about HT use. Besides peer-reviewed publications, data and information on HT research are also disseminated in technical reports from the United States Department of

Agriculture (USDA), Sustainable Agriculture Research and Education (SARE), and Cooperative Extension. These technical reports offer considerable information about selected best practices for crop production in high tunnels at various regional and local scales. Also, the focus on literature published in the United States and since 2009 substantially limited the amount of data for analysis. There is a significant amount of established literature on high tunnel use globally. However, the focus of this study was justified by the unique effect the NRCS High Tunnel Initiative program had on HT use in the United States. Findings from this study may be of interest to scholars conducting HT research and those who make funding decisions about research. The present study offers a foundation to be built along a needs assessment by involving farmers and stakeholders (e.g. crop consultants, NRCS representatives, HT manufacturers) in what future research may be needed to complement current and past programmatic efforts. HT adoption is a practice that contributes to sustainable agriculture by responding to the need to produce in smaller spaces as the global population continues to increase over time, placing extreme demand on agricultural production systems. Future scientometric analyses could broaden the scope of all literature published globally and in languages other than English and include records (i.e. technical reports and bulletins) from the gray literature that could inform the potential scope (e.g. region-specific, crop-specific, revenue-specific) for systematic reviews.

Data availability statement. Data used for this study came from WoS.

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