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Critical Review of the Dynamics of *D. citri* in Persian Lime (*Citrus* × *latifolia* Tan): Foundations for Predictive and Adaptive Management in Central Veracruz, Mexico
Revisión Crítica de la Dinámica de *D. citri* en Limón Persa (*Citrus* × *latifolia* Tan): Fundamentos para un Manejo Predictivo y Adaptativo en el Centro de Veracruz, México

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SUMMARY

The spatiotemporal dynamics of pest and disease development are closely linked to ecological factors. In the case of Huanglongbing (HLB) disease and its vector, the Asian citrus psyllid (*Diaphorina citri*), it depends on the host plant's phenology, such as that of the Persian lemon (*Citrus* × *latifolia* Tan). Globally, the presence of this insect has increased in various citrus-growing regions, notably in Mexico's Gulf Coast, particularly in central Veracruz. Despite extensive research on *D. citri*, no studies have reported specific data on the implementation of management strategies in the citrus region of Martínez de la Torre-Misantla, Veracruz. Nor have modeling and life cycle projection studies of the psyllid been developed to enable a comprehensive understanding of this area. This study aims to conduct a critical review of research from the past 10 years on *D. citri* in citrus-growing areas where it is present, with an emphasis on the center of Veracruz, Mexico, and to highlight relevant methodological findings for the prevention, management, and control of the insect. Results from different regions of the world are compared, identifying similarities that have facilitated effective management and gaps in the application of new techniques for its control. To achieve this, a search was conducted across various bibliographic databases, limiting results to the last ten years and adjusting inclusion criteria to obtain pertinent information. Subsequently, a specific sample was selected to identify the documents most relevant to the study's objective. Opportunities to strengthen integrated vector management are discussed, along with the necessary lines of research for developing predictive management schemes in the center of Veracruz.

Index words: *Asian psyllid, integrated pest management, population dynamics, spatiotemporal dynamics, vector ecology.*

RESUMEN

La dinámica espaciotemporal en el desarrollo de plagas y enfermedades está estrechamente relacionada con factores ecológicos y, en el caso de la enfermedad Huanglongbing (HLB) y su vector, el *psílido* asiático de los cítricos (*Diaphorina citri)*, depende de la fenología de la planta hospedante, como el limón persa (*Citrus* × *latifolia* Tan). A nivel mundial, la presencia de este insecto ha aumentado en diversas regiones citrícolas, destacándose, en México, la zona del Golfo de México, en particular, el centro de Veracruz. A pesar de la amplia investigación existente sobre

D. citri, no se ha reportado ningún estudio que aporte datos específicos para la implementación de estrategias de manejo en la región citrícola de Martínez de la Torre-Misantla, Veracruz. Tampoco se han desarrollado estudios de modelado y proyección del ciclo de vida del *psílido* que permitan un entendimiento integral de esta área. El objetivo de este estudio es realizar una revisión crítica de las investigaciones de los últimos diez años sobre *D. citri* en áreas citrícolas donde esté presente, con énfasis en el Centro de Veracruz, México, y destacando hallazgos metodológicos relevantes para la prevención, el manejo y el control del insecto. Se comparan los resultados obtenidos en distintas regiones del mundo, identificando similitudes que han favorecido un manejo efectivo, así como vacíos en la aplicación de nuevas técnicas para su control. Para ello, se realizó una búsqueda en diversas bases de datos bibliográficas, limitando los resultados a los últimos 10 años y ajustando los criterios de inclusión para obtener información pertinente. Posteriormente, se realizó una muestra específica para seleccionar los documentos que mejor se relacionan con el objetivo del estudio. Se discuten oportunidades para fortalecer el manejo integrado del vector, así como las líneas de investigación necesarias para desarrollar esquemas de manejo predictivo en el centro de Veracruz.

Palabras clave: *psílido asiático, manejo integrado de plagas, dinámica poblacional, dinámica espacio-temporal, ecología de vectores.*

INTRODUCTION

The production of Persian lime (*Citrus x latifolia* Tanaka) is a key agricultural export activity in Mexico and a significant source of rural employment and income in central Veracruz, particularly in the Martínez de la Torre–Misantla region. Its economic value depends on continuous supply, fruit quality, ease of postharvest handling, and access to international markets. However, Huanglongbing (HLB) poses the main threat to this activity, as it reduces yield and quality, shortens the longevity of plantations, increases management costs, and affects producers' profitability (Ghosh *et al.*, 2022; Rodríguez-Aguilar, López, Soto, Vargas, and García, 2023).

HLB is a bacterial disease caused by *Candidatus Liberibacter asiaticus*, which is mainly transmitted through the *Asian citrus psyllid*, *Diaphorina citri*. Globally and locally, interactions among the host, pathogen, and vector, along with the transport of plant material, have facilitated the spread of the disease and the vector. In places like Veracruz, where flowering is common and large agricultural areas are present, the vector finds ideal conditions to maintain viable populations, which, in turn, facilitate the transmission of the pathogen (Bayles, Thomas, Simmons, Grafton, and Daugherty, 2017; Cifuentes-Arenas, de Goes, de Miranda, Beattie, and Lopes, 2018; Neves, Wetterich, Sousa, and Marcassa, 2023). The spatiotemporal dynamics of *D. citri* describe how their abundance, distribution, and movements vary over time and space. Studying, recording, and understanding these variations are essential for anticipating peaks in infection risk and coordinating sampling, control, and management strategies. Evidence indicates that cyclical patterns related to budding and climatic factors influence control effectiveness (Álvarez-Ramos *et al.*, 2022; Gomez-Marco, Gebiola, Baker, Stouthamer, and Simmons, 2019; Bassanezi, and Primiano, 2021). Various factors are involved in this dynamic: agroclimatic factors (temperature, humidity, precipitation) regulate the development, survival, and activity of the vector (Antolínez, Olarte-Castillo, Martini, and Rivera, 2022); phenological factors (budding and flowering) determine the availability of tender tissue for oviposition and feeding; and biotic factors, such as natural enemies (*Tamarixia radiata*) and alternate hosts (for example, *Murraya paniculata*), directly impact psyllid populations. In subtropical regions like Veracruz, the combination of seasonal rains, diverse microclimates, and varied agricultural practices generates highly changing responses among orchards and production cycles (Cifuentes-Arenas *et al.*, 2018; Antolínez, Moyneur, Martini, and Rivera, 2021; Gómez-Marco *et al.*, 2019; Álvarez-Ramos *et al.*, 2022; Rodríguez-Aguilar *et al.*, 2023).

Although literature is abundant at the global level, specific knowledge about the production systems of Persian lime in Veracruz remains limited due to a lack of integrated local data that connect the regional and zonal climates, the phenology of budding, and field data obtained through inspections, traps, and diagnostics. This lack of information limits the availability of predictive models tailored to the region that can guide timely control (Bassanezi, and Primiano, 2021; Rodríguez-Aguilar *et al.*, 2023; Ghosh *et al.*, 2023; Bayles *et al.*, 2017).

Therefore, conducting a critical review of the available evidence is essential to establish the foundations of an adaptive, integrated management approach that incorporates predictive ecological models to prioritize sampling and thus mitigate the impact of HLB on the profitability of citrus cultivation in this region. In this context, this article aims to critically analyze the evidence on the spatiotemporal dynamics of *D. citri* and its relationship with agroclimatic, phenological, and biotic factors in citrus crops, with an emphasis on Persian lime production systems in subtropical regions, to support strategies for adaptive integrated management based on predictive ecological models for citrus plantations in central Veracruz, Mexico. To achieve this, a bibliographic review methodology is proposed that follows systematic criteria established in the PRISMA 2020 Declaration and uses visualization tools and bibliometric analysis.

MATERIALS AND METHODS

This research is qualitative, documentary, exploratory, and descriptive in nature (Hernández-Sampieri, Fernnandez and Baptista, 2014) and was conducted through a systematic review to identify, review, and compile literature on the spatiotemporal dynamics and ecological determinants of *D. citri* in Lima Persa. To develop this review, the criteria established in the PRISMA 2020 statement (Page *et al.*, 2021) and in the manual by Chandler, Cumpston, Li, Page, and Welch. (2019) for conducting systematic reviews were followed. Previous studies—both qualitative and quantitative—were used as references for the proper analysis of the collected information, as they are related to the objectives and research questions of this review.

The databases consulted for this study and analysis were Scopus, Google Scholar, and PubMed. In these databases and search engines, a Boolean expression was used, developed from keywords selected for this review. First, the expression used was: ("*Diaphorina citri*" AND "Huanglongbing" AND (spatial OR temporal) AND dynamics AND (agroclimatic OR climate) AND "citrus" AND (management OR control)). The search was conducted on January 30, 2025; however, due to its high specificity, it yielded only two results. For this reason, the Boolean expression was adjusted to broaden the search and obtain better results, resulting in the following: (huanglongbing OR "*Diaphorina citri*") AND (agroclimatic OR climate OR spatial OR temporal OR dynamics OR management OR control OR citrus). This search was performed on February 24, 2025, yielding a total of 4430 references, which form the database for the review presented in this article (Table 1).

In detail, the Scopus database stands out for having the largest number of references (2854); however, results from searches on other academic platforms were also integrated. For its part, Google Scholar, due to its accessibility and broad thematic coverage, enabled the collection of an extensive dataset of 1000 references using the Publish or Perish software (Harzing, 2023). In the case of PubMed, with 576 references, although this academic platform does not focus on agronomy, it proved useful for its coverage of microbiology, biological control, environmental impact, and soil-microbiota relationships, which are especially relevant for ecological and entomological analyses of vectors like *D. citri*. Finally, the 4,430 references obtained were managed with Mendeley Reference Manager (Elsevier, 2023) for organization, cleaning, and filtering according to the inclusion and exclusion criteria defined (Table 2).

Once the inclusion and exclusion criteria established by the PRISMA 2020 statement (Page *et al.*, 2021) were applied, 978 articles were obtained for the systematic review. This process is shown graphically in Figure 1. However, given the large number of documents that met the exclusion criteria outlined in the Prisma statement (Figure 1), a decision was made to create a representative, homogeneous, and intentional sample of sources. This aligns with the methodological approach described by De Salvo *et al*. (2025), which enables thorough analysis without compromising validity, representativeness, or scientific rigor. The selection was based on criteria such as thematic relevance, recency (within the last 10 years), and applicability to the study's object.

Table 1. Results from the systematic search in the databases.

No.	Databases	Boolean expression	Search Results
1	Scopus	(huanglongbing OR "Diaphorina citri") AND (agroclimatic OR climate OR spatial OR temporal OR dynamics OR management OR control OR citrus)	2854
2	Google Scholar	(huanglongbing OR "Diaphorina citri") AND (agroclimatic OR climate OR spatial OR temporal OR dynamics OR management OR control OR citrus)	1000
3	PubMed	(huanglongbing OR "Diaphorina citri") AND (agroclimatic OR climate OR spatial OR temporal OR dynamics OR management OR control OR citrus)	576
Total			4430

Table 2. Inclusion and exclusion criteria were used for bibliographic selection.

Inclusion criteria	Exclusion criteria
Studies related to Huanglongbing and its vector D. citri	By title (keywords)
Studies addressing pest and disease management.	Duplicate Documents
Studies analyzing the climatic factors in citrus crops.	Year (≤ 2014)
Studies on modeling, estimations, and mathematical projections in agronomy.	Without affinity with the subject.
Studies involving AI, UAVs, satellite mapping, and spectral images.	Type of document (Thesis, mini-thesis, evidence, conferences, posters).
Type of document (review articles or results).	Idiomatic (not in Spanish or English)

Subsequently, to obtain a representative sample, new selection criteria were established to systematically include relevant literature for the objective of this review (Table 3). As a result of this process, a total of 115 documents were obtained as a representative sample, which ultimately forms the database for this systematic review.

After obtaining the representative sample, the database for the systematic review comprised 115 documents, and four additional documents were included because they were identified as being relevant to the original search results generated by the Boolean expression. Finally, the database, comprising these 115 references, was imported into VosViewer (Van-Eck and Waltman, 2023) in RIS format to map and visualize correlations and conduct bibliometric analysis for this research. Complementarily, additional visualizations were created using the *Bibliometrix* package (Aria and Cuccurullo, 2017) in *RStudio v*. 2023.6.1.524 (Posit Team, 2023) for the 2854 results from the Scopus search, as it is one of the types of bibliographic data sources accepted by *Bibliometrix*, to analyze scientific collaborations between countries and identify emerging countries and topics.

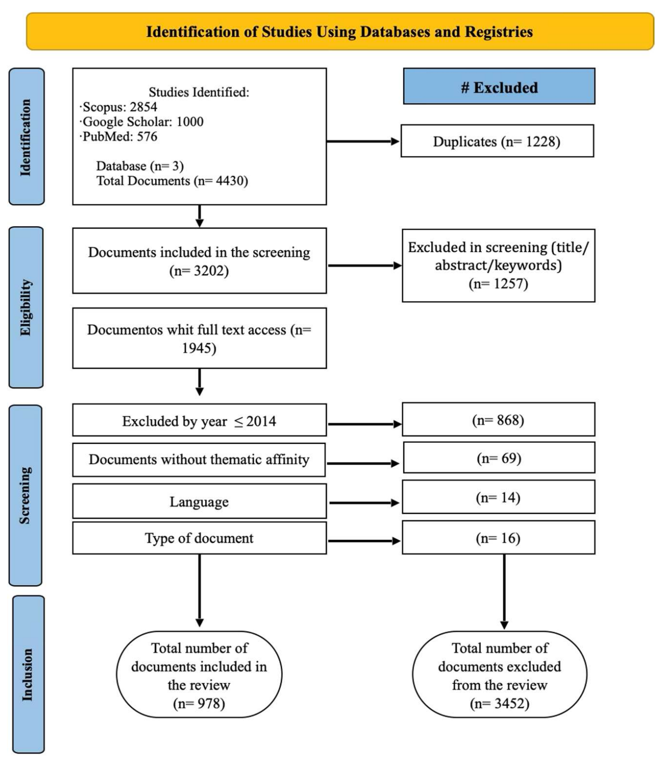

Figure 1. Diagram for selecting documents in accordance with the Prisma 2020 statement.

Table 3. Criteria for selecting the sample.

C1 (Title)	C2 (Key points)	C3 (Another)
Diaphorina citri	Climatic factors	Detection methods, sampling methods, treatment methods, Artificial Intelligence (AI), Machine Learning, modeling, precision agriculture, dynamics, sensors, algorithms, projection, prediction, field selection, seasonal distribution, temporal distribution, Unmanned Aerial Vehicle (UAV), spectral imaging.
Asian citrus psyllid	Climate changes	
Huanglongbing	Pest control	
HLB	Disease management	
Candidatus Liberibacter asiaticus	Distribution	
Citrus greening	Models	

RESULTS AND DISCUSSION

The results of the literature review incorporate the most recent findings on *D. citri* as a vector and transmitting agent of Huanglongbing (HLB). The main advances in detection methods, sampling strategies, and treatments used in managing this disease are highlighted. Additionally, the most innovative approaches developed to date are analyzed, with particular emphasis on precision agriculture technologies, unmanned aerial vehicles (UAVs), sensors, spectral imaging, and predictive models based on artificial intelligence and machine learning. As part of the analysis, correlation and density maps are generated between scientific articles, allowing the identification of thematic trends and relevant research clusters related to the study of HLB and its vector (Figures 2, 3, and 4). Figure 2 visualizes the identified thematic correlations, with the size of each node representing the importance of each topic and the thickness of the connecting lines indicating the strength of their relationships with other topics. From this analysis, four main clusters are identified, detailed in ANNEX 1.

Four clusters are observed, which display two important conceptual cores: the vector (*Diaphorina citri*, in green) and the disease (HLB, in blue). These cores are connected through diagnostic and management terms. The green cluster focuses on vector dynamics and biological control strategies (parasitoids, bioassays), while the blue cluster groups diagnosis and control (PCR, machine learning, Support Vector Machine) for

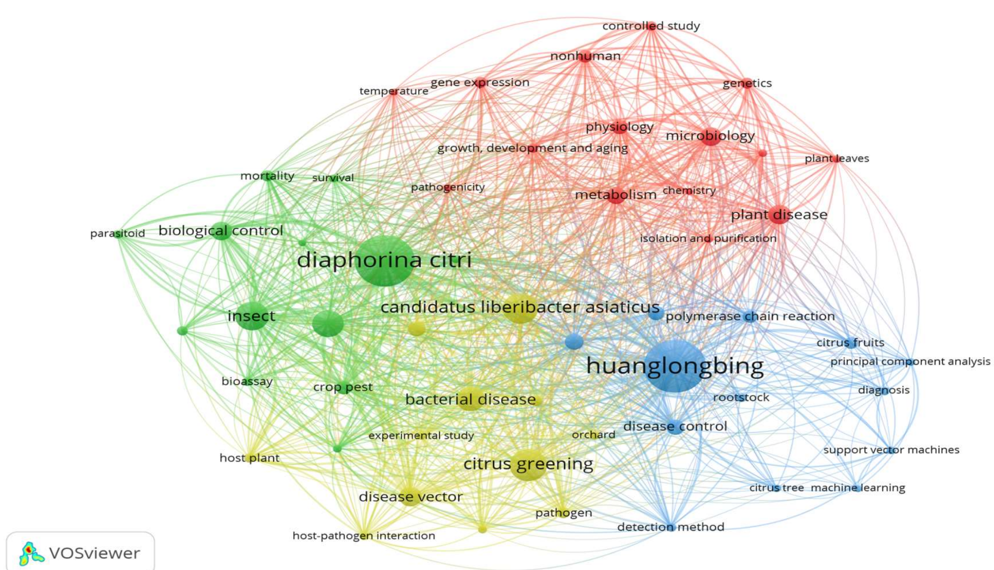

Figure 2. Thematic co-occurrence map (method: co-occurrence; normalization: association strength; counting fractional; color: cluster; node size: frequency; line thickness: strength of the link), created in VosViewer.

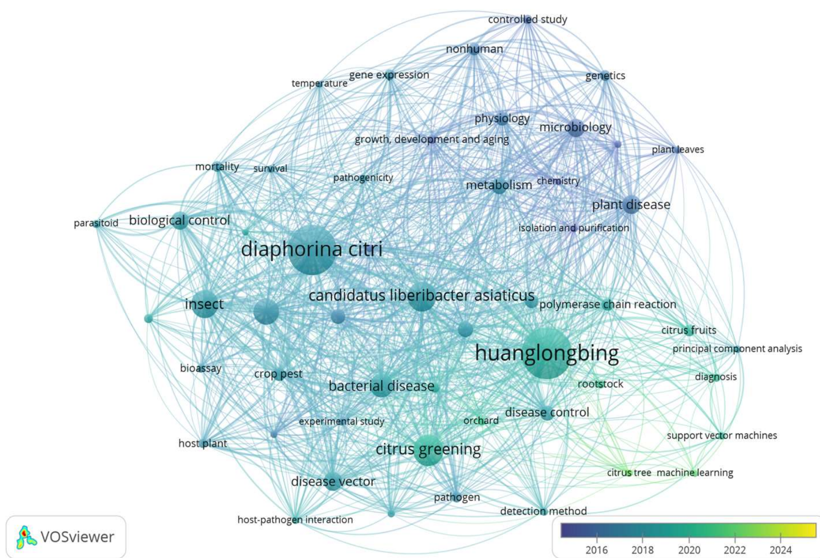

Figure 3. Visualization of the thematic co-occurrence map with a temporal overlay (2015-2025). (Method: co-occurrence, normalization: strength of association, color: average publication year – purple for the oldest, yellow for the most recent, node size: frequency, line thickness: strength of the link) generated in VosViewer.

surveillance, monitoring, and decision-making. The red cluster includes the microbiological/physiological basis (genetics, metabolism, microbiology), and the yellow functions as a semantic bridge (host-pathogen). ANNEXES 2 and 3 highlight the topics with the greatest relevance and thematic frequency in agronomy, plant pathology, and entomology related to citrus, such as "citrus," "huanglongbing," "*Diaphorina citri*," 'hemiptera," "plant disease," and "*Candidatus Liberibacter asiaticus*," which dominate the literature and constitute the prioritized areas of interest in the field of study.

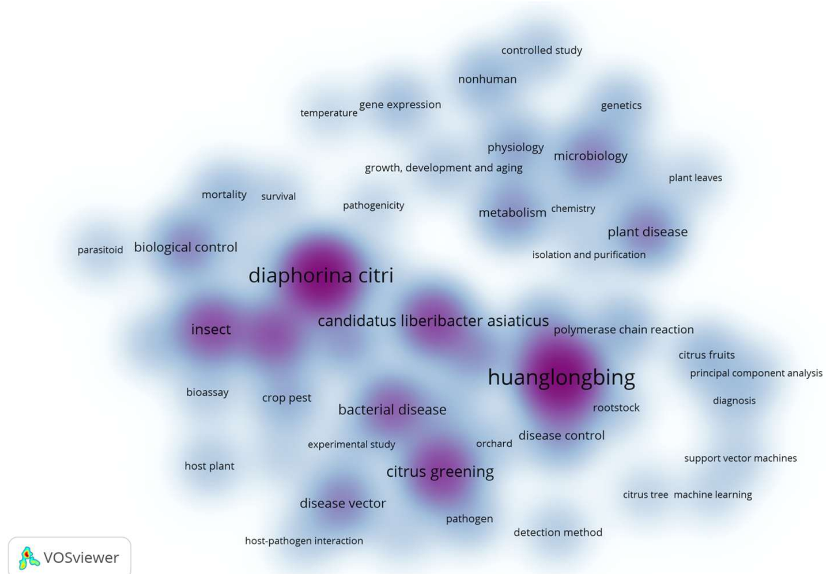

Figure 4. Visualization of the term co-occurrence density map (method: co-occurrence, count: fractional, normalization: association strength) for thematic density analysis of the bibliography generated in VosViewer.

Figure 3 presents the temporal map generated in *VosViewer*, which allows identifying the periods during which the greatest scientific production on *D. citri* and HLB was concentrated, based on the search criteria used. A progressive increase in publications is observed since 2016, reaching a peak in relevance between 2016 and 2024. This pattern suggests a growing scientific interest in developing detection, monitoring, and management tools for HLB, coinciding with the disease's expansion across various citrus-growing regions worldwide. This figure illustrates three thematic focuses (vector, disease, and 'greening' of citrus), as well as a more recent approach centered on machine-learning-assisted detection and diagnosis. This pattern indicates a process of thematic maturation—from biological fundamentals to operational surveillance tools and decision-making—and is consistent with the spread of HLB and the increasing need for early detection in producing areas.

Likewise, Figure 4 shows the item-level information density map, which visualizes the concentration and relevance of studies within the analyzed literature set. This visualization supports the robustness of the employed documentary base and provides adequate backing for the objectives of this review. Therefore, the information obtained is relevant, objective, and current regarding the topic addressed. The density map highlights two main cores, *D. citri* and HLB, which structure the field and connect most of the co-occurrences. Secondary key points appear in the greening of citrus, disease control, and diagnostic/detection terms, while other, less dense areas (machine learning, Support Vector Machine) suggest emerging lines that are still underexplored.

Figure 5 shows the collaborative frequency relationships between countries, as determined through bibliometric analysis, with the thickness and color of the lines representing the intensity of co-authorship. The main highlighted nodes are Australia, Brazil, China, and the United States, which demonstrate their central roles in international networks. The visualization reflects patterns of intercontinental cooperation, with some low-intensity or negative connections, distinguished by thin lines or cooler colors (e.g., Mexico has low-intensity connections with Canada, Argentina, Chile, and Cuba). Overall, Figure 5 illustrates the structure and dynamics of global scientific production and collaboration on the topic, emphasizing the importance of strengthening international links to enhance academic impact and advance knowledge.

Likewise, Table 4 presents the hierarchy of the international scientific collaboration network on citrus topics, *D. citri*, and Huanglongbing. First, the United States and China lead the global core of production and regional collaboration. In contrast, nodes from countries such as Brazil, Spain, South Africa, Australia, and Italy continue to play a role as regional powers, leading their respective regions and serving as conduits to the global core. Meanwhile, nodes in countries such as Mexico, Turkey, Pakistan, France, and the United Kingdom serve as connectors, facilitating collaborative flows between various geopolitical blocks. Finally, nodes from nations such as Colombia, Ghana, and Egypt stand out for their emerging presence and projection within the network, as future centers of connection and intermediaries of international scientific collaboration.

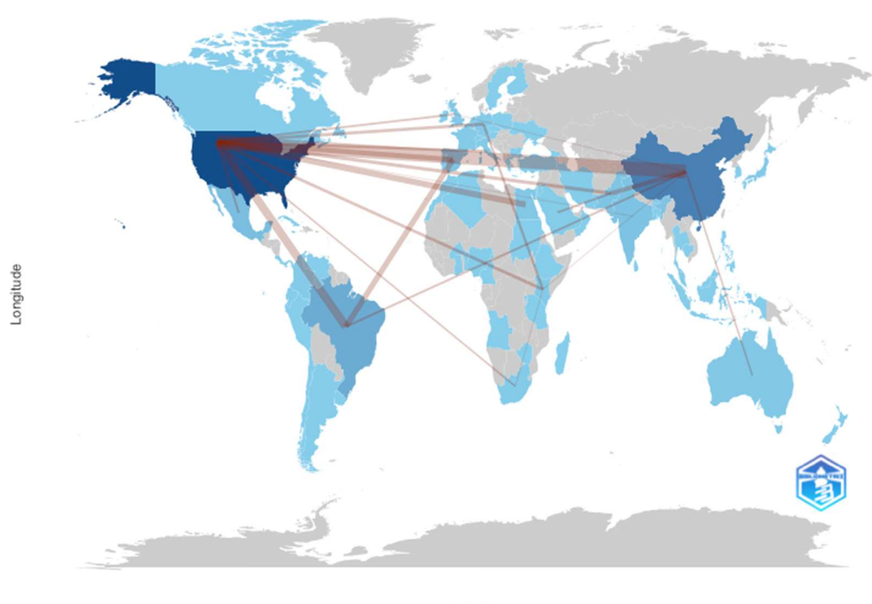

Figure 5. Structure and dynamics of collaborations between countries focused on the theme D. citri and Huanglongbing, as well as global scientific collaboration (generated with *Bibliometrix*).

Table 4. Impact on the international scientific collaboration network.

Rank	Country	PageRank*	Region	Role in Collaboration Network
1	USA	0.1976	North America	Global node
2	China	0.1291	Asia	Global node
3	Brazil	0.0674	Latin America	Potencial Regional
4	Spain	0.0427	Europa	Potencial Regional (Bridge with Latin America)
5	Pakistan	0.0366	Asia	Actor Connector South-South
6	Kenya	0.0325	Africa	Regional Bridge Node
7	Australia	0.0222	Oceania	Regional Power in Oceania
8	South Africa	0.0229	Africa	African Regional Power
9	Italy	0.0211	Europa	Regional Power
10	Egypt	0.0209	Africa	Mediterranean Strategic Node
11	Saudi Arabia	0.0179	Asia	Regional Actor (Middle East)
12	United Kingdom	0.0155	Europa	Global Connector
13	France	0.0158	Europa	Global Connector
14	México	0.0148	Latin America	Regional Connector
15	Turkey	0.0134	Asia-Europa	Regional Transition Node
16	Ghana	0.0132	Africa	Emergente Regional
17	Japan	0.012	Asia	Consolidated Scientific Node
18	Switzerland	0.0079	Europa	High Specialization Scientific Node
19	Colombia	0.0087	Latin America	Emergente Regional
20	Germany	0.0214	Europa	Potencia Científica Tradicional

* It is an indicator or measure of the structural influence within the scientific collaboration network.

A description of the citrus activity in terms of its productive aspects is shown in Figure 6, and traditional botanical characteristics are included in Figure 7. Additionally, Figure 8 shows the disease triangle and the *D. citri* vector, thereby strengthening the study's scope.

In the context of the infectious triangle, also known as the disease triangle, this concept helps us understand and guide the management of any disease (Figure 8). This model states that the disease results from the interaction of three essential factors (Figure 8a): a susceptible host, favorable environmental or climatic conditions, and a virulent pathogen (Pedraza-Herrera, Sánchez, Arias, Moreno, and Sánchez, 2022). Understanding the conditions and factors, both biotic and abiotic, that determine the spatial distribution of pests and diseases, as well as the temporal variation of their populations, is a valuable tool for their control. This facilitates optimized management and efficient resource use, focusing efforts on specific areas and times (Guo *et al.*, 2024). The study of HLB requires a comprehensive understanding of the pathosystem that constitutes it. This pathosystem is defined by the interaction among the pathogen *Candidatus Liberibacter asiaticus* (*CLas*), the host – in this case, *Citrus* × *latifolia* (Persian lime) –, the insect vector *D. citri* Kuwayama (Figure 8b), and the environmental conditions that modulate this interaction (Figure 8). This conceptualization is consistent with the disease triangle, a well-known epidemiological model that examines the key factors involved in the development and spread of disease in complex agricultural systems (Bassanezi, and Primiano, 2021).

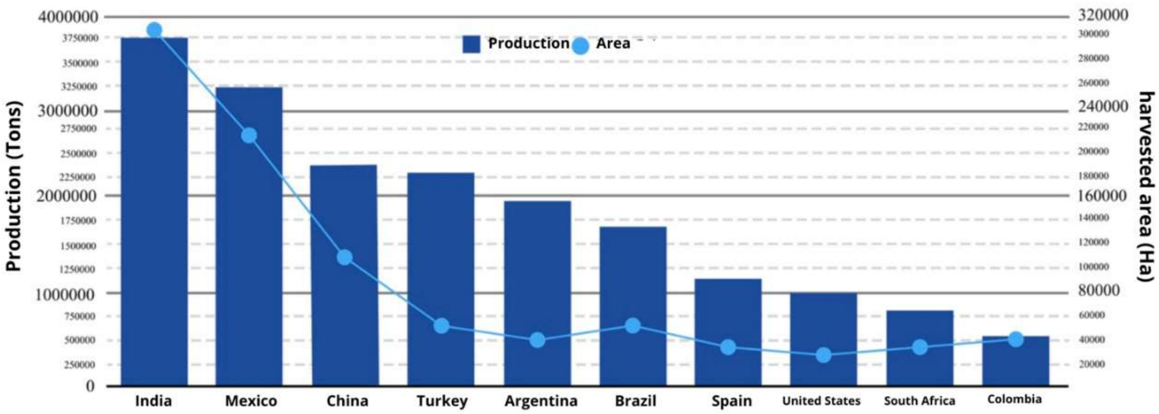

Figure 6. The leading producers of lemons and limes worldwide, based on FAO data from 2025 (FAO, 2025). The difference in lemon and lime production between India and Mexico is mainly due to the extent of the planted area, since the total harvested area in India (312,000 hectares) exceeds that of Mexico (210 735 hectares) by 32.46% to produce these citrus fruits.

Huanglongbing (HLB) Disease and Agroclimatic Drivers of HLB

Huanglongbing (HLB) disease, along with its vector, *D. citri*, constitutes one of the most significant phytosanitary challenges for global citrus production (Boa, 2023). Control strategies are classified into chemical, physical, biological, thermal, and antibiotic methods, each with varying scope and adaptability depending on the context (Álvarez, Rohrig, Solís, and Thomas, 2016; Ghosh *et al.*, 2023; Curk, Luro, Hussain, and Ollitrault, 2022). The first formal report on HLB dates to 1919, describing it in southern China (Reinking, 1919; Zheng, Chen, and Deng, 2018). Although compatible symptoms had been reported in India, they were not documented in official scientific publications until that date. In Mexico, the first official case associated with HLB was recorded in 2009 in Tizimín, Yucatán (SAGARPA, 2009). Currently, the disease has spread throughout all citrus-growing regions of the country, affecting 352 municipalities in 23 federal entities (SENASICA, 2019). However, despite efforts, HLB remains uncontrolled in Mexico; the strategies implemented so far have been insufficient to recover previous yields and have increased production costs (Suh, Niu, Wang, Gmitter Jr, and Wang, 2018; Sétamou, Alabi, Kunta, Dale, and da Graça, 2020; Villar-Luna, Santos, Rodríguez, Méndez, and Leyva, 2024).

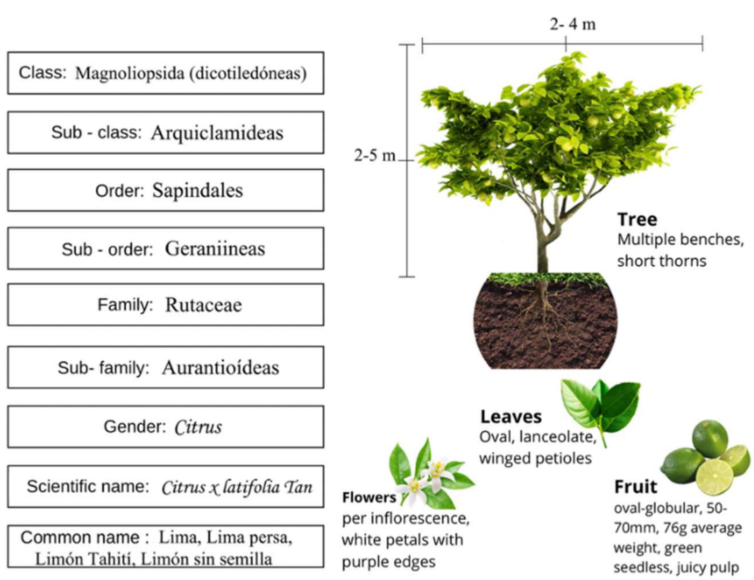

Figure 7. Botanical classification and description of the Persian lime. This figure presents a schematic overview of the botanical characteristics of Persian lime based on information from MBG (Missouri Botanical Garden, s. f.).

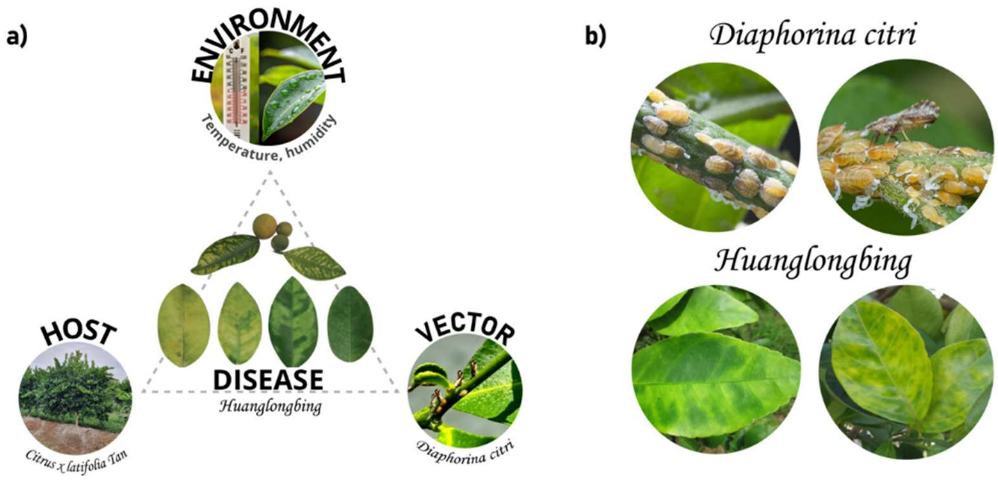

Figure 8. Dynamics of the HLB pathogen system: a) host-vector-environment interactions; and b) presence of *D. citri* and HLB symptoms, based on Pedraza-Herrera *et al*. (2022). The infectious triangle, also known as the disease triangle, is a fundamental concept that allows us to understand and guide the management of any disease. This model states that the disease results from the interaction of three essential factors: a susceptible host, favorable environmental or climatic conditions, and a virulent pathogen. (Pedraza-Herrera *et al*., 2022).

The causal agent, *Candidatus Liberibacter asiaticus* (*CLas*), colonizes the plant's phloem, causing overproduction of starch, alterations in secondary metabolites, and a significant decrease in the absorption of essential nutrients such as manganese, zinc, potassium, and copper (Suh *et al*., 2018; Gómez-Flores, Garza-Saldaña, and Varela-Fuentes, 2019). A notable feature in the literature is the disparity in the use of climate variables among studies. For example, Rodríguez-Aguilar *et al*. (2023) use variables such as average annual temperature and accumulated precipitation to model, using *MaxEnt* software, the current and future distribution of the vector (Yang, Nie, and Yao, 2022), projecting an 11.4% increase in favorable areas for *D. citri* in Mexico by 2030. In contrast, other studies, such as that by Garza-Saldaña, Varela-Fuentes, and Gómez-Flores (2017), omit direct climate analysis and focus on molecular detection or imaging methods (Pourreza, Lee, Ehsani, Schueller, and Raveh, 2015a). Studies analyzing seasonality, such as those by López-Buenfil *et al*. (2017), have identified peaks in the Asian citrus psyllid population during summer and autumn, with autumn increases being indirectly related to climatic variables, including minimum temperature and relative humidity. Although strong correlations with individual variables were not established, these results suggest recurring climatic patterns that warrant further study in tropical areas (Sétamou *et al*., 2020). Predictive modeling tools are infrequent; so far, only a few groups have applied ecological distribution models to anticipate the vector's expansion (McNeill, Golan, Shanthan, Mankin, and Liao, 2024; Rodríguez-Aguilar *et al*., 2023). On the other hand, some authors rely on observational data and descriptive analyses without conducting predictive simulations (López-Buenfil *et al*., 2017). Regarding spatiotemporal dynamics, marked seasonality has been reported, with differences in the vector's preference for young versus mature leaves, as well as a gradual expansion into tropical regions (López-Buenfil *et al*., 2017; Rodríguez-Aguilar *et al*., 2023). However, these studies lack detailed phenological monitoring and precise timing of budding, limiting the ability to anticipate risk and inform effective management. Regarding early detection, molecular techniques such as qPCR have become widespread (Pourreza, Lee, Etxeberria, and Banerjee, 2015b; López-Buenfil *et al*., 2017; Aswini and Vijayakumaran, 2023), complemented by optical sensors, RGB images, and hyperspectral imaging (Garza-Saldaña *et al*., 2017).

Regarding control methods for HLB, managing HLB and its vector, *D. citri*, remains a significant challenge (Valdés *et al*., 2016; Chavarro-Mesa, Delahoz, Fennix, Ángel, and Jiménez, 2020). There is no single solution; international experience shows that combining multiple tactics is necessary to achieve acceptable results (Ayres, Belasque, and Bové, 2015; Gasparoto, Hau, Bassanezi, Rodrigues, and Amorim, 2018). A more extensive description is included in Figure 9. In general, these methods demonstrate that no single strategy is sufficient to control HLB (Atta, Morgan, Hamido, Kadyampakeni, and Mahmoud, 2020). Chemical control acts quickly but can induce resistance; thermal methods are promising but require precise technique; antibiotics extend the lifespan of trees but do not solve the disease; and physical and biological controls are sustainable, although they require patience and technical support (Shi *et al*., 2019; Liao, Gao, Yan, and Zhou, 2021; Zhang, Gao, and Liu, 2022). However, further local research is needed to link the dynamics of *D. citri* with climate and crop phenology (Boa, 2023; Sáenz-Pérez *et al*., 2019). This gap presents an opportunity to design strategies tailored to the reality of Persian lime in Veracruz by leveraging field data, climate sensors, and the flowering calendar.

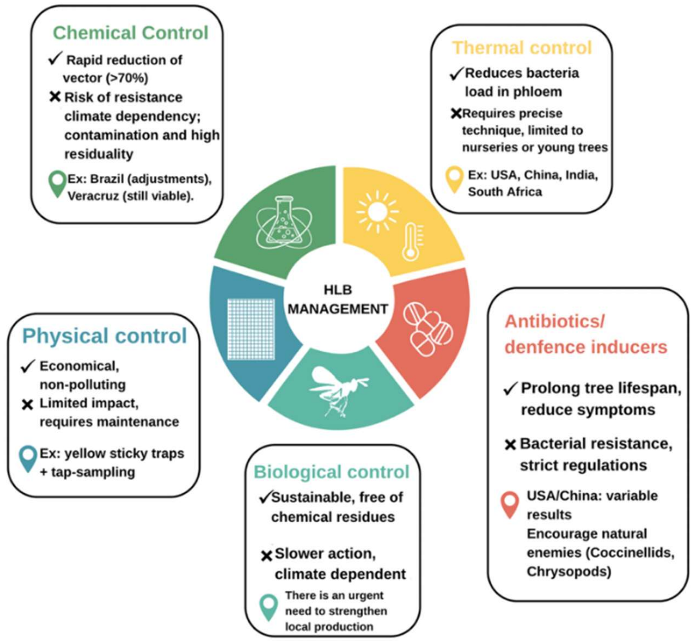

Figure 9. Graphical diagram of Huanglongbing (HLB) management.

Prospections and New Studies

Effective control of HLB requires the development of sustained regional strategies that combine removing infected trees (Craig, Cunniffe, Parry, Laranjeira, and Gilligan, 2018), reducing *D. citri* vector populations, and, when feasible, using biological control (Lee *et al*., 2015). The seasonal dynamics of the vector and climatic suitability determine critical intervention windows (Holford *et al*., 2022), so constant monitoring and a precise territorial approach are key elements to maximize the effectiveness of the implemented tactics (Ayres *et al*., 2015; Gasparoto *et al*., 2018; López-Buenfil *et al*., 2017; Villar-Luna *et al*., 2024). In the field of epidemiological modeling, recent proposals such as the global modeling with time delay proposed by Liu *et al.* (2023) and the mathematical analyses aimed at simulating control strategies (Díaz-Padilla, López, Guajardo, and Sánchez, 2021) stand out. These advances provide a solid foundation for developing predictive systems and adaptive management plans that respond to the actual dynamics of the pathogen system. Likewise, the development of dynamic models and flexible regressions is a fundamental pillar for integrating climate and epidemiological forecasts into early warning systems (Maldonado, Almaguer, Álvarez y Robledo, 2008; Estrella-Maldonado *et al*., 2023; Zuñiga *et al*., 2020).

Currently, research focuses on integrating high-resolution data acquisition technologies with advanced artificial intelligence algorithms to detect HLB and its vector, *D. citri*, at an early stage (Xu, Su, Sun, and Cai, 2025). Notable are the hyperspectral techniques integrated with machine learning models (McRoberts *et al*., 2019; Moriya *et al*., 2019) and portable mass spectrometry combined with machine learning (Wetterich, Neves, R. F. de O., Belasque, Ehsani, and Marcassa, 2016; Li, Yao, Wu, and Hu, 2015; Wu *et al.,* 2025), which offer high diagnostic accuracy in situ, opening opportunities for their application in rapid monitoring programs. Additionally, automation for detecting psyllids through web platforms (Martínez-Carrillo *et al*., 2016; Thomas, Simmons, and Daugherty, 2017) and artificial vision systems applied directly in the field (Dai *et al*., 2022) represents a participatory and scalable approach, especially suitable for improving phytosanitary surveillance. The refinement of algorithms for automatic counting and detection of *D. citri* (Álvarez-Ramos *et al*., 2022) underscores the importance of standardizing and diversifying training datasets to ensure these tools are adaptable to diverse local conditions.

The integration of computer vision methods, such as texture analysis in the visible spectrum (Dong *et al*., 2024; Dong *et al*., 2025) and feature extraction using neural networks like BPNN (Liu *et al*., 2019; Zuñiga *et al*., 2020; Liu *et al*., 2020), facilitates large-scale automatic detection. However, these systems still face challenges in differentiating HLB symptoms from other abiotic stresses or diseases with similar manifestations (Van Steenderen, Mauda, Kirkman, Faulkner, and Sutton, 2024). Regarding portable technologies, fluorescence spectroscopy combined with classification algorithms, such as support vector machines (SVM) and neural networks

(Luo, Gao, Ge, and Luo, 2017), guides and strengthens the trend toward rapid, accessible, and adaptable diagnostics for various conditions in specific regions. Meanwhile, AI-driven automation for the timely detection of HLB and its vector is becoming a major area of research (Inoue *et al.*, 2020; Xie, Feng, and Zhang, 2024). Zhang *et al.* (2022) and Liu *et al.* (2023) highlight the high accuracy and speed of real-time symptom identification. However, they note that these systems require adjustments to optimize performance under specific lighting conditions and regional varietals. Additionally, the complementary use of advanced optical sensors and field-vision systems (Lan *et al.*, 2020) enables diagnoses with a low false-positive rate. However, environmental factors such as dust accumulation and climate variability continue to pose significant challenges (Paris *et al*., 2017). Meanwhile, recent research on screening therapeutic molecules offers promising prospects for the curative management of HLB (Li *et al.*, 2019; Li *et al.*, 2015), although validating their efficacy and safety under real agricultural conditions remains a key challenge (Liu *et al.*, 2019; Wang, Cai, and Cao, 2021; Wang *et al.*, 2023).

Current methodologies emphasize the use of multiple data sources and advanced predictive tools. For example, machine learning models applied in Colombia (Gómez-Flores, Garza-Saldaña, and Varela-Fuentes, 2022) and approaches based on periodic transmission Li *et al.*, 2015) allow for highly accurate forecasting of infection scenarios, facilitating the planning of interventions tailored to local phenological cycles. Additionally, there is an increasing incorporation of multispectral aerial sensors (da Cunha *et al.*, 2022; Martínez-Carrillo *et al.*, 2016) and hyperspectral sensors (Dong *et al.*, 2025), as well as the use of high-resolution satellite imagery (da Cunha *et al.*, 2024; Liu, Gao, Chen, and Liu, 2024), which broadens large-scale surveillance capabilities. However, their usefulness is still limited by adverse weather conditions and the difficulty in detecting early stages of infection. In this context, Table 5 presents the thematic conceptual network of the discipline and highlights innovations and emerging focuses related to citrus and HLB.

Recent approaches include the integration of multispectral and thermal images from unmanned aerial vehicles (UAVs), the adaptation of drones and portable devices for frequent and rapid monitoring, using multi-input neural network models that have shown great potential for accurately tracking the spread of HLB (Sanchez, Pant, Irey, Mandadi, and Kurouski, 2019; Tu *et al.*, 2019; Li *et al.*, 2015; Qiu *et al.*, 2022). Additionally, the use of UAVs equipped with RGB cameras (Xiaoling, *et al.*, 2016; Deng, Lan, Hong, and Chen, 2016) and the calculation of the Triangular Greenness Index (TGI) (Deng, Huang, Zheng, Lan, and Dai, 2019) have proven useful for the simultaneous detection of phytosanitary issues such as HLB (Pandey, da Costa, and Wang, 2021; Djeffal, Djilali, Gul, Ahmad, and Saeed, 2023; Mariano, Briones, and Villaverde, 2024) and Phytophthora, providing a basis for the implementation of integrated field diagnostic systems (de Moraes *et al.*, 2020; Garza *et al.*, 2020). Regarding vector control, the sterile insect technique using X-ray irradiation has shown significant reductions in the reproductive capacity of the psyllid *D. citri*, making it a viable alternative in areas with high infestation pressure (Liu *et al.*, 2023; Ferrater *et al.*, 2024). Overall, all these advances point toward integrated management models that combine rapid on-site testing for confirmation, predictive models to plan interventions at critical moments, and visual detection algorithms for surveillance at various scales. These approaches leverage multiple technologies to analyze local data and account for climatic and phenological factors, thereby enhancing the effectiveness of HLB control and vector management (Yang, Wang, Hu, Lan, and Deng, 2021).

Table 5. Central thematic nodes and emerging themes in co-words (*Bibliometrix*).

Central Theme	Centrality (betweenness, PageRank)	Related topics	Emerging trends
Diaphorina citri (vector plaga)	Very high	Hemiptera, psyllidae	Machine learning, AI applied
Candidatus Liberibacter asiaticus (patógeno)	Very high	Bacterial disease, gene expression	Metabolomics, transcriptómica
Citrus greening (enfermedad)	High	Insecticide, disease vector	Advanced molecular techniques
Plant disease	High	Biological control, vector control	Neural networks, bioinformatics
Gene expression	Moderate	Polymerase chain reaction	Machine learning
Machine Learning (emerging)	Emerging	Support Vector Machines	Increase in predictive modeling

Final Considerations

Although several studies recognize the state of Veracruz as a vulnerable region to Huanglongbing (HLB), there are few specific analyses for the Martínez de la Torre–Misantla area, despite its importance in national citrus production (Pérez *et al.*, 2016; Sun *et al.*, 2021). This positions the region as both strategically relevant and highly susceptible to the disease. However, the Veracruz citrus sector has adopted management plans that promote planting frameworks with high tree densities, notably 4x5 m, 3x6 m, and 3.5x5 m, with 500, 555, and 588 trees per hectare, respectively. Nevertheless, in a context of presence and vulnerability to HLB (Kennedy *et al.*, 2023), these plantations intensify the adverse effects associated with them, as the orchards remain conducive to the proliferation of *D. citri*, which increases the bacterial pressure on the plantations (Taylor, Mordecai, Gilligan, Rohr, and Johnson, 2016; Yan *et al.*, 2025).

The most frequently evaluated environmental factors for the management and monitoring of *D. citri* and HLB have been temperature (minimum and maximum) and humidity (precipitation and relative humidity) (Kistner *et al.*, 2017; Milosavljević, McCalla, Morgan, and Hoddle, 2020; Ternes *et al.*, 2024). Studies focused on evaluating these factors have concluded, among other aspects, that there is an increasing risk due to the expansion of suitable areas for the vector, the differentiation of high and low epidemic intensity zones, inferences about seasonal risk, the assessment of the infectious density threshold for transmission, and the probability of climate and temporal detection (López-Buenfil *et al.*, 2017; Suaste-Dzul *et al.*, 2017; Shimwela *et al.*, 2018; Raiol-Junior, Cifuentes, Cunniffe, Turgeon, and Lopes, 2021; Rodríguez-Aguilar *et al.*, 2023; Olvera-Vargas, Quiroz, Contreras, and Aguilar, 2020; Villar-Luna *et al.*, 2024; Wang *et al.*, 2023; Paudyal, 2015; Ukuda-Hosokawa *et al.*, 2015). On the other hand, a significant group of studies approaches the problem from different perspectives, without emphasizing climatic variables (Zavala-Zapata *et al.,* 2022). For example, Garza-Saldaña *et al.* (2017) and Soto-Plancarte *et al.* (2024) evaluated the presence of *D. citri* and the distribution of citrus hosts, noting a high risk due to the lack of rapid detection methods (Lyu *et al.*, 2023). Gasparoto *et al.* (2018) considered the agricultural environment and orchard structure but did not account for climatic factors. Pérez-Zárate, Osorio, Ortega, Martínez, and Villanueva (2024) mention the influence of tropical/subtropical climate and prevailing winds on the dispersal and incidence of the vector (Horton *et al.*, 2019; Jiang *et al*., 2021; Kwakye and Kadyampakeni, 2023), highlighting that these climates favor the proliferation of *D. citri* and, consequently, the presence of HLB.

In Mexico, distribution models of *D. citri* indicate that tropical and coastal areas are highly suitable for its establishment, likely due to a favorable thermal gradient. Additionally, projections suggest that climate change could expand suitable areas, shifting toward higher and more temperate zones (Rodríguez-Aguilar *et al.*, 2023), an aspect that warrants monitoring. From an economic and social perspective, Rocha-Peña *et al.* (1995) and Pérez-Zárate *et al.* (2024) identified areas affected economically, without explicitly modeling the climate, but concluded that economic losses are significant at the national level and that the risk increases due to rapid dispersal, especially in Veracruz. Therefore, Sáenz-Pérez *et al.* (2019) warn about the need to strengthen detection and surveillance capacity in this region, given the conducive conditions for the vector. However, although studies evaluate individual factors affecting *D. citri*, none integrate the vector's dynamics with specific phenological data on Persian lime cultivation and local agroclimatic factors (Pérez-Zarate, Osorio-Acosta, Villanueva-Jiménez, Ortega-Arenas, and Chiquito-Contreras, 2016; Pérez-Otero, Pérez-Turco, Neto, and Fereres, 2024). A notable discrepancy across studies is the importance attributed to climate: while research using ecological and modeling approaches includes key climatic variables to explain the vector's development and adaptation (Vasconcelos, Lopes, Arenas, and das Graças, 2024), other works, more focused on detection and diagnosis, do not. This gap is significant, as crop phenology, particularly budding, has been shown to affect the vector's oviposition and feeding preferences. Integrating these factors would enable the design of more precise management strategies tailored to the specific conditions of the plantations in Veracruz. Therefore, since the current recommendations for the region have not yet yielded conclusive, fully favorable results, alternative monitoring, early detection, alert, and control technologies remain underexplored and require further research.

CONCLUSION

This review shows that, although there is growing global scientific concern about HLB and its spread through the vector *D. citri*, significant methodological and geographic gaps remain in the study of this problem. It is recognized that climate and seasonality directly influence vector dynamics; however, the application of predictive models and spatiotemporal studies remains limited. A key identified gap is the lack of comprehensive research linking local agroclimatic data, specific crop phenology, and vector dynamics, as well as the need to include new molecular and remote-sensing detection tools. Additionally, crop genetic improvement has great potential. It is expected to play an important role in providing sustainable solutions to this issue, which affects multiple citrus-growing regions in Mexico and worldwide.

Therefore, strengthening and continuing research in these areas will be essential to generate knowledge that helps reduce the damage and losses caused by HLB, contributing to the sustainability of citrus production agroecosystems. The approach this review provides focuses on in situ monitoring of climatic variables, as these influence the crop's physiological and phenological processes, the conditions for the development of *D. citri* in new citrus-growing regions, and the specific moments to make decisions to mitigate the spread of HLB.

ETHICS DECLARATION

Not applicable.

CONSENT FOR PUBLICATION

Not applicable.

DATA AVAILABILITY

The bibliographic database used in this study and the files generated during the bibliometric analysis with Bibliometrix/Biblioshiny are available from the corresponding author upon reasonable request. These files constitute analytical outputs supporting the study and are not part of the published Supplementary Material.

CONFLICT OF INTEREST

The authors declare that they have no competing interests.

FINANCING

Not applicable.

AUTHORS' CONTRIBUTION

Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft preparation, Writing – review and editing, and Visualization: U.B.Q. and O.R.M.P.; Formal analysis and Writing – review and editing: S.D.M. and D.L.A.; Formal analysis, Supervision, and Writing – review and editing: R.A.M.A.; Supervision, Writing – review and editing, and Project administration: M.C.L.M.

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ANNEX 1. Clusters created by VosViewer through keyword correlation.

Cluster 1 (15 items)	Cluster 2 (13 items)	Cluster 3 (13 items)	Cluster 4 (12 items)
Chemistry	Asian Citrus Psyllid	Citrus Fruits	Bacterial Disease
Controlled Study	Bioassay	Citrus Greening Disease	Bacteria (Microorganism)
Gene Expression	Biocontrol Agent	Citrus Tree	*Candidatus Liberibacter asiaticus*
Genetics	Biological Agent	Detection Method	Citrus greening
Growth, Development, and Aging	Biological Control	Diagnosis	Disease incidence
Isolation and Purification	Crop Pest	Disease Control	Disease vector
Metabolism	*Diaphorina citri*	Fruit	Experimental Study
Microbiology	Disease Transmission	Huanglongbing	Host Plant
Nonhuman	Feeding Behavior	Machine Learning	Host-Pathogen Interaction
Pathogenicity	Insect	Polymerase Chain Reaction	Infectious Disease
Physiology	Integrated Pest Management	Principal Component Analysis	Orchard
Plant Disease	Mortality	Rootstock	Pathogen
Plant leaves	Parasitoid	Support Vector Machines	
Procedures	Survival		
Temperature			

ANNEX 2. Word cloud of the top discussed topics (created with *Bibliometrix*).

ANNEX 3. Visualization of relevant words and their percentage of occurrence in the most recent articles on the topic of *D. citri* and Huanglongbing (generated with *Bibliometrix*).