The Asian Citrus Psyllid (*Diaphorina citri*) and Huanglongbing: A Comprehensive Review of Biology, Impact, Management, and Data Resources

I. Executive Summary

The Asian citrus psyllid (ACP), *Diaphorina citri* Kuwayama, and the devastating disease it vectors, Huanglongbing (HLB), represent the most significant threats to global citrus production. ACP, a small sap-feeding insect, causes minor direct damage but is an exceptionally efficient vector of *Candidatus Liberibacter* bacteria, the causative agents of HLB also known as Citrus Greening. This bacterial infection, leads to severe tree decline, deformed and bitter fruit, and ultimately, tree mortality, often within five years of infection. There is currently no known cure for HLB, and its spread has resulted in billions of dollars in economic losses and widespread job displacement in major citrus-producing regions worldwide, including Florida and California.

Effective management of this complex pathosystem necessitates a multi-pronged, integrated pest management (IPM) approach. This includes rigorous monitoring and early detection, judicious application of chemical controls, strategic deployment of biological control agents, and the implementation of robust cultural practices such as the use of protective screen houses. Regulatory frameworks and quarantine programs are also critical to mitigate the spread of both the vector and the disease. Advancements in scientific research, particularly in genomics, molecular diagnostics, and the development of novel therapeutic and resistance strategies, are crucial for developing sustainable long-term solutions. This report provides a comprehensive overview of the biology of ACP, the pathology and impact of HLB, current management paradigms, and a detailed catalog of available datasets and resources vital for ongoing research and control efforts.

II. Introduction

The global citrus industry stands as a cornerstone of agricultural economies worldwide, providing substantial contributions to national Gross Domestic Products (GDPs) and supporting countless livelihoods. For example, the citrus industry in California alone generated an estimated total economic impact of $7.6 billion in 2020-21, contributing $1.9 billion to the state's GDP and sustaining over 24,000 full-time equivalent jobs.[1] This immense economic significance underscores the critical imperative to safeguard citrus crops from pervasive threats.

Among the most formidable challenges confronting the citrus industry is the Asian citrus psyllid (ACP), *Diaphorina citri* Kuwayama. This small insect, typically measuring 3-4 mm in length, feeds on the phloem (sap) of citrus and related host plants.[2] While direct feeding damage can lead to symptoms such as stunting and distortion of new shoot growth, the primary concern associated with ACP is its unparalleled efficiency as a vector for the bacterium responsible for Huanglongbing (HLB).[3]

Huanglongbing, commonly known as citrus greening disease, is globally recognized as one of the most severe bacterial infections affecting citrus plants.[2] Once a tree is infected, there is no known cure, and the disease typically leads to tree mortality within as little as five years.[2] The consequences of HLB have been catastrophic, marked by progressive declines in citrus production, billions of dollars in lost revenue, and significant job losses in affected regions. Florida, for instance, has experienced a devastating impact, with citrus production falling by 75% since HLB was detected in 2005.[15]

This comprehensive report aims to provide an expert-level review of the Asian citrus psyllid and Huanglongbing. It delves into the intricate biology of the psyllid, the pathology and profound economic consequences of the disease, and the current integrated management strategies employed to combat this threat. Furthermore, the report compiles and details available datasets and resources, including critical image datasets, which are indispensable for research and control efforts. Finally, it explores the promising avenues of ongoing research and prospects for ensuring the long-term sustainability and protection of the global citrus industry.

III. Biology and Identification of the Asian Citrus Psyllid (*Diaphorina citri*)

The Asian citrus psyllid, scientifically designated as *Diaphorina citri* Kuwayama (Hemiptera: Psyllidae), is widely recognized by its common name, ACP.[2] While sometimes referred to as 'citrus psylla,' this term can cause confusion with *Trioza erytreae*, the African citrus psyllid, which also affects citrus.[18]

Life Cycle: Egg, Nymph, and Adult Stages

The life cycle of citrus psyllids follows a typical hemipteran progression: egg, nymph, and adult.[2] Under optimal environmental conditions, *D. citri* can complete an impressive number of generations, potentially up to 30 per year.[4] The developmental period from egg to adult is remarkably short, approximately 15-17 days at a temperature of 25°C.[9] Adult psyllids typically have a lifespan of 1-2 months, influenced by temperature and host plant availability.[3] Psyllid population densities tend to be lower when active plant growth is not occurring, as the nymphal stages are highly dependent on and thrive exclusively on newly emerged or flushing vegetation.[4]

The rapid life cycle of the Asian citrus psyllid, characterized by its quick progression from egg to adult in just over two weeks and the potential for numerous generations annually, presents a significant and dynamic challenge for effective pest management. This accelerated reproductive capacity means that psyllid populations can rebound with extreme rapidity following any intervention, necessitating continuous and precisely timed management efforts. The dependence of the nymphal stages on the new flush growth of host plants further intertwines psyllid population dynamics with the physiological growth cycles of citrus trees. This linkage implies that control strategies, such as the application of pesticides, must be carefully synchronized with these plant growth phases, which can vary regionally and seasonally. Without such precise timing and sustained effort, the efficacy of control measures can be significantly diminished, leading to a rapid resurgence of psyllid populations and an increased risk of disease spread.

Physical Description and Distinguishing Features

The Asian citrus psyllid exhibits distinct morphological characteristics across its life stages, which are crucial for accurate identification.

- **Adults:** Adult psyllids are small insects, measuring between 3-4 mm (0.12-0.16 inches) in length.[3] Their bodies are mottled yellowish-brown, with brown legs and a light brown head, and a greenish-white underside.[4] A highly diagnostic feature is their characteristic feeding posture: they feed with their heads lowered, almost touching the leaf surface, while their bodies are distinctly lifted at an approximate 45° angle.[3] Their wings are mottled brown [5], or can be transparent with white spots, or light-brown with a central beige band, with the forewings being widest near the tip.[4] They possess short antennae with black tips.[4] A whitish, waxy secretion often covers the entire insect, giving it a dusty appearance.[4] Gravid female psyllids are identifiable by their bright yellow-orange abdomens.[3] When disturbed, adults will jump or fly a short distance [3], though they are generally poor fliers, rarely traveling more than 100 meters at a time.[19]
- **Eggs:** ACP eggs are minute, approximately 0.01-0.15 mm in size.[4] They are bright yellow-orange, almond-shaped, thicker at the base, and taper towards the opposite end.[3] Eggs are typically deposited on the tips of growing shoots, within the crevices of young leaves, or at the base of newly formed leaf buds.[4]
- **Nymphs:** Nymphs are generally yellowish-orange [7] and can be difficult to observe due to their small size.[5] A key distinguishing characteristic is their production of waxy, white excretions, which are tubule-like structures that direct honeydew away from their bodies.[5] There are five nymphal instars, each increasing in size after molting, with later instars developing prominent wing pads.[4] Nymphs move slowly and exhibit a characteristic upward flicking of their abdomens when disturbed.[7]

The characteristic 45° feeding angle of adult psyllids and the distinctive white, waxy honeydew tubules produced by nymphs are more than mere descriptive details; they serve as critical diagnostic indicators for field identification. These unique physical and behavioral traits are essential for non-experts, such as backyard growers and agricultural scouts, to visually identify the pest. This visual recognition is paramount for early detection, especially given the prolonged latent period of HLB. Furthermore, the observation that adult psyllids are weak fliers, rarely traveling more than 100 meters at a time, yet the species has achieved widespread global distribution, points to a crucial underlying dynamic: long-distance dispersal is primarily facilitated by human-assisted movement of infested plant material. This highlights the indispensable role of stringent regulatory measures and quarantines in containing the spread of both the psyllid and the devastating HLB disease. The discrepancy between limited natural flight and extensive global spread underscores that robust biosecurity measures and public awareness regarding plant movement are as vital as localized pest control efforts.

Host Plants and Feeding Behavior

ACP feeds on the phloem (sap) of host plants using specialized, highly modified mouthparts called stylets.[2] The host range of *D. citri* is restricted to the plant family Rutaceae, encompassing approximately 25 genera.[3] Preferred hosts include species within the genera *Citropsis*, various *Citrus* species (such as grapefruit, kumquat, lemons, limes, mandarin, orange, pomelo, and tangelo), and *Murraya* species (including orange jasmine and curry tree).[3]

Heavy infestations of psyllids on new shoot growth can cause significant direct damage, leading to stunting, distortion, twisting, and curling of leaves, and in severe cases, shoot dieback.[3] As phloem-feeding insects, psyllids excrete copious amounts of sugary honeydew. This honeydew coats leaves and other plant surfaces, providing a substrate for the growth of sooty mold fungi, which can turn the affected leaves black.[9] Notably, ants are often observed tending to psyllid nymphs, feeding on the honeydew and inadvertently protecting the psyllids from natural enemies.[4]

Geographical Distribution (Global and United States)

The Asian citrus psyllid is native to southern Asia.[4] From its native range, it has spread globally, establishing populations in tropical and subtropical Asia, Afghanistan, Saudi Arabia, Reunion, Mauritius, various parts of South and Central America, Mexico, and the Caribbean.[3] More recently, ACP has been detected in close proximity to Australia, specifically in Timor Leste and Papua New Guinea.[2]

Within the United States, *D. citri* was first identified in Palm Beach County, Florida, in June 1998.[3] By 2001, it had rapidly disseminated to 31 counties in Florida, with much of this spread attributed to the movement of infested nursery plants.[3] An accidental introduction into the Rio Grande Valley of Texas occurred in 2001 [3], and the psyllid was first detected in San Diego County, California, in 2008.[7] Currently, ACP is also established in Alabama, Arizona, Georgia, Guam, Hawaii, Louisiana, Mississippi, Puerto Rico, South Carolina, and the U.S. Virgin Islands.[1] To contain its spread, quarantines have been implemented across various states and territories.[18]

Table 1: Key Characteristics of Asian Citrus Psyllid Life Stages

Life Stage	Size (approx.)	Color/Appearance	Key Distinguishing Features	Typical Location
Eggs	0.01-0.15 mm	Bright yellow-orange	Almond-shaped, thicker at base, tapering end	Tips of growing shoots, leaf folds, base of new leaf buds
Nymphs	0.25-1.7 mm	Yellowish-orange	Produce white, waxy, thread-like excretions; later instars have wing pads; move slowly, flick abdomen when disturbed	Exclusively on newly emerged or flushing vegetation

Adults	3-4 mm	Mottled yellowish-brown; gravid females have bright yellow-orange abdomen	Characteristic 45° feeding angle; mottled brown wings (or transparent with white spots/light brown with beige band); short antennae with black tips; appear dusty from waxy secretion; jump/fly short distances when disturbed	Underside of leaves, new flush growth

IV. Huanglongbing (HLB): The Citrus Greening Disease

Huanglongbing (HLB), also known as citrus greening disease, is a devastating bacterial infection that poses the most serious threat to citrus production globally.

Causative Agents: *Candidatus Liberibacter* Species

HLB is caused by phloem-restricted bacteria, primarily *Candidatus Liberibacter asiaticus* (CLas).[2] The "Candidatus" designation signifies that the organism has not yet been successfully cultured in a laboratory setting and is characterized based on its DNA properties.[22] Beyond CLas, two other related forms of the bacterium exist: *Candidatus Liberibacter americanus* (CLam), which has been reported in Brazil and Florida, and *Candidatus Liberibacter africanus* (CLaf), found predominantly in Africa and the Middle East.[2] CLas and CLam are known to be heat-tolerant, enabling their spread in warmer climates, while CLaf is heat-sensitive, typically found in cooler, elevated areas.[22]

Mechanism of Transmission by ACP

The Asian citrus psyllid is recognized as an exceptionally efficient vector of these *Candidatus Liberibacter* bacteria.[3] Transmission occurs when psyllids feed on an infected tree, acquire the bacteria through their phloem-feeding stylets, and subsequently move to and feed on an uninfected tree, injecting the pathogen with their saliva.[19] Once inside the plant, the pathogen resides and multiplies within the phloem tissue, which is responsible for nutrient transport.[4] Psyllids can acquire the bacteria during their nymphal stages and remain capable of transmitting it throughout their adult lifespan.[25] Adults can acquire the HLB bacterium within as little as 15 minutes of feeding on infected plants, although longer feeding periods are typically required for effective acquisition.[20] Notably, infected nymphs develop into infected adults, and these adults serve as the primary means of disease dissemination.[24]

Interestingly, the HLB pathogen appears to actively manipulate its psyllid vector in complex and sometimes contradictory ways. Infected psyllids reportedly thrive, exhibiting accelerated generation times and increased egg laying, suggesting a pathogen-induced enhancement of vector fitness that directly promotes disease spread.[24] This manipulation of the psyllid to become a more prolific and mobile vector is a significant driver of the disease's rapid dissemination. However, paradoxically, infected psyllids have been observed to be less responsive to certain insect traps, such as those baited with acetic acid.[28] This reduced trap responsiveness means that traditional monitoring methods, like yellow sticky traps, might significantly underestimate the true prevalence of infected vectors, making accurate disease detection and risk assessment more challenging. Conversely, infected adult psyllids have been found to possess lower protein and esterase levels, rendering them more susceptible to certain insecticides.[24] This physiological alteration presents a nuanced opportunity for disease management, suggesting that targeting infected psyllids could potentially be a more efficient chemical control strategy, or that resistance development might differ between infected and uninfected psyllid populations. Beyond insect vectors, the HLB pathogen can also be transmitted through the grafting of infected plant material and, potentially, through citrus seeds.[3]

Symptoms of HLB on Citrus Trees

HLB is notoriously difficult to detect in its early stages, as infected trees can remain symptomless for an extended period, ranging from months to several years.[5] A latent period of 1-2.5 years typically precedes the appearance of visible symptoms.[24] This extended asymptomatic phase is a critical factor that fundamentally complicates disease management. During this period, infected trees, despite showing no outward signs of illness, serve as active reservoirs for bacterial transmission, allowing psyllid vectors to widely disseminate the pathogen to numerous other healthy trees.[24] This "quiet spread" explains why HLB is often widespread within an orchard or region by the time visual symptoms trigger detection efforts, making localized eradication efforts on their own less effective. The bacterium's multiplication within the tree's vascular system progressively chokes off the supply of nutrients, leading to a decline in overall health, twig dieback, stunting, and premature fruit drop.[4] Ultimately, the tree's vascular system is compromised, leading to its death, often within a few years of infection.[5]

- **Leaf Symptoms:** An early and highly characteristic symptom of HLB is the development of blotchy, yellow, asymmetrical mottling on the leaves.[5] These yellow patches typically cross the leaf veins and are lop-sided, meaning they are often more prominent on one side of the leaf than the other.[29] These blotchy mottle symptoms are most evident on newly hardened leaves and tend to fade as the leaves age.[29] The disease can also manifest as yellow shoots on single, random branches [22] and, in some cases, cause corky veins.[21]
- **Differentiation from Nutritional Deficiencies:** HLB symptoms are frequently confused with nutritional deficiencies, particularly zinc deficiency.[4] However, distinct differences exist: HLB-induced yellowing is asymmetrical and appears randomly on branches, whereas nutritional deficiencies typically cause more symmetrical yellowing that is often vein-delimited and uniformly distributed throughout the tree canopy.[4] In severe infections, HLB can lead to the formation of "rabbit ears"—small, upright shoots characterized by unusually short internodes.[29]
- **Fruit Symptoms:** Infected trees yield small, irregularly shaped, often lop-sided fruits with thick, pale peels.[4] A distinctive symptom that gives the disease its common name is the retention of green color at the navel end of the fruit, even when fully mature.[21] The juice from affected fruit is characterized by low soluble solids, high acidity, and an abnormally bitter taste, rendering the fruit commercially valueless for fresh consumption and suitable only for juicing.[5] Affected fruit may also contain dark-colored, aborted seeds.[25]

Visual aids, such as images depicting HLB-affected leaves with characteristic blotchy mottle and asymmetrical yellowing, and HLB-affected fruit showing greening at the navel end, lopsided shape, and general deformation, are invaluable for field identification. Comparative images illustrating symptoms of nutritional deficiencies, such as zinc deficiency, are also crucial for distinguishing HLB from other common citrus ailments.[21]

Disease Progression and Economic Impact (Case Studies: Florida, California)

The bacterium's proliferation within the tree's vascular system effectively chokes off nutrient supply, progressively weakening and ultimately killing the plant.[22] The extended latent period means that by the time visual symptoms become apparent, the disease has likely been present in the region for up to 10 years and widely distributed.[24]

- **Florida:** Since its initial detection in 2005, HLB has inflicted catastrophic damage upon Florida's citrus industry. Production has experienced a progressive decline, resulting in an estimated $4.55 billion in lost revenue and over 8,000 job losses since 2011.[2] Orange production has plummeted by 75%, and grapefruit production by a staggering 90%.[15] Specifically, orange acreage and yield decreased by 26% and 42% respectively from 2005 to 2014.[30] By 2013, 100% of commercial orchards in Florida were reported as HLB positive.[10] Surveys conducted in 2016 indicated that, on average, 90% of citrus acres and 80% of trees in Florida operations were infected, with an average 41% yield loss directly attributed to HLB.[30] Overall, Florida's citrus production declined by over 80% from 1998 to 2021, and the economic loss from 2015-2020 was estimated to exceed $1 billion annually.[10] Industries supporting citrus production, such as packing houses and processing plants, have experienced a dramatic 90% decrease in operations.[10]
- **California:** HLB was first confirmed in California in 2012.[22] The state's substantial $3 billion-a-year citrus industry faces a significant and growing threat from the disease.[23] Over 8,600 HLB-positive trees have been identified and removed since 2012.[32] Risk models have accurately

predicted HLB emergence in various areas, and recent data indicate an exponential increase in new detections of HLB infections in both ACP and citrus trees across the state.[31]

- **China:** The spread of HLB, largely facilitated by ACP, has also resulted in enormous economic losses within China's citrus production sector.[16]

Geographical Distribution of HLB (Global and United States)

Historically, HLB was confined to Africa and Asia.[26] However, its global footprint has expanded considerably. The disease was first recognized in Brazil in 2004, followed by its detection in Florida, USA, in 2005.[26] Currently, HLB is known to occur in nearly 50 countries across Asia, Africa, the Americas, and Europe.[12]

Within the United States, HLB was not present until its 2005 detection in Florida.[3] Since then, it has been reported in Louisiana (2008), South Carolina (2009), Texas (2012), and California (2012).[22] The disease is now established throughout Georgia, Florida, Puerto Rico, and the U.S. Virgin Islands, and in specific portions of Alabama, California, Louisiana, South Carolina, and Texas.[5]

V. Management and Control Strategies

Effective management of the Asian citrus psyllid and Huanglongbing requires a comprehensive and adaptive strategy, primarily rooted in Integrated Pest Management (IPM) principles.

Integrated Pest Management (IPM) Principles for ACP and HLB

An IPM program is considered essential for the successful control of ACP and HLB.[6] The fundamental steps in an IPM framework include identifying the pest, systematically monitoring pest populations, establishing clear pest management goals (such as prevention, suppression, or eradication), executing an integrated plan that combines multiple tactics, and rigorously evaluating the results of the management efforts.[6] A multi-pest control strategy is often recommended, given that many citrus pests, including ACP, exhibit population dynamics that are closely influenced by the flush cycle of the host plant.[33]

Monitoring and Early Detection Methods

Consistent monitoring is paramount for successful management with minimal environmental disruption.[6] Adult psyllids can be effectively captured using yellow sticky traps, a common tool for surveillance.[24] Regular visual inspection, ideally every 14 days or monthly, of new flushes is crucial for detecting the presence of eggs, nymphs (identifiable by their characteristic white waxy threads), and adults (recognized by their distinctive 40-degree feeding angle).[19] Given the prolonged latent period of HLB, during which infected trees remain asymptomatic but infectious, molecular tests, such as quantitative real-time polymerase chain reaction (qPCR), are indispensable for confirming the presence of the HLB bacterium in both trees and insects.[27] These advanced diagnostic tools enable detection before visible symptoms appear, which is critical for proactive intervention.

Chemical Control Approaches

Pesticides are frequently employed in HLB management and, in some contexts, may be the only immediately effective control method available.[6] However, the severity of HLB has led growers to resort to intensive chemical applications, sometimes involving as many as 6 to 15 foliar and 1 to 2 systemic treatments per year.[24] This high frequency and volume of pesticide use have unfortunately resulted in the development of pesticide resistance within psyllid populations.[24] Moreover, such broad-spectrum applications likely cause collateral damage to beneficial insects, disrupting natural biological controls.[24] This highlights a critical challenge: the primary reactive control method is losing efficacy, creating secondary problems (resistance), and failing to achieve its core objective of preventing HLB spread. This situation underscores the urgent need for a truly integrated, sustainable IPM approach that minimizes broad-spectrum pesticide use and incorporates diverse tactics. To mitigate these issues, the use of horticultural oils is suggested as a lower-impact alternative.[24]

In response to these challenges, newer insecticide products are continually being developed and registered. These include formulations with multiple active ingredients, such as cyantraniliprole combined with abamectin, acetamiprid with pyriproxyfen, buprofezin, and fenpyroximate.[12] Furthermore, emerging technologies are revolutionizing chemical delivery. Nano-insecticides, for instance, are being developed for controlled release of active ingredients like thiamethoxam. Another significant advancement is Trecise™ technology, which employs a minimally invasive approach to directly deliver active ingredients into the tree's vascular system, potentially reducing overall chemical use by up to 90%.[12]

Biological Control

Biological control, which involves the strategic use of natural enemies, including other insects and pathogens, is a vital component of sustainable pest management.[6] A prominent example in ACP management is the tiny parasitoid wasp, *Tamarixia radiata*. This wasp has been imported and released in affected areas, demonstrating successful establishment in Florida.[6] Another wasp species, *Diaphorencyrtus aligarhensis*, was also introduced, but *T. radiata* proved more successful in establishing populations.[7] In addition to parasitoids, two species of lady beetles, *Olla v-nigrum* and *Harmonia axyridis*, have been identified as important predators of ACP nymphal populations in Florida.[7] These natural enemies play a crucial role in suppressing psyllid populations and reducing reliance on chemical interventions.

Cultural Control Practices

Cultural control involves modifying environmental conditions around the host plant or site to prevent or suppress pest infestations.[6] Key practices include careful variety selection, optimized irrigation management and timing, and rigorous sanitation protocols.[6] The removal of infected trees is a critical and mandatory measure to prevent the further spread of HLB, as these trees serve as reservoirs for the bacterium.[2] To prevent the introduction of infected plant material, it is vital to purchase trees exclusively from reputable, licensed nurseries and to use only registered budwood with proper source documentation for grafting.[21] Proper disposal of plant clippings, such as drying or double-bagging them before removal, also helps to prevent psyllid dispersal.[32]

A significant innovation in cultural control is the Citrus Under Protective Screen (CUPS) system. These psyllid-excluding screen houses have demonstrated remarkable success in Florida, enabling the profitable production of HLB-free citrus. CUPS systems lead to higher growth rates, improved fruit quality, and increased yields, while simultaneously reducing the need for chemical pesticides, fertilizers, and irrigation water.[15] The success of CUPS systems in Florida, despite the severe HLB impact in that region, demonstrates a viable path for profitable citrus production in endemic areas. The development of targeted delivery systems could revolutionize chemical control by minimizing resistance development and environmental impact, aligning perfectly with sustainable IPM principles. This highlights the critical importance of continued investment in research and development for such innovative, long-term solutions.

Regulatory Frameworks and Quarantine Programs

Strict regulatory measures and quarantine programs are fundamental to preventing and limiting the spread of ACP and HLB. A federal quarantine is in place, restricting the movement of plants belonging to the Rutaceae family from infested areas.[25] In California, the Citrus Pest and Disease Prevention Program (CPDPP), jointly administered by the California Department of Food and Agriculture (CDFA), the United States Department of Agriculture (USDA), and county agricultural commissioners, implements a comprehensive statewide action plan.[1]

The CPDPP's program elements include: ACP eradication in areas where feasible, ACP suppression using pesticides, ACP population reduction through the deployment of biocontrol agents, HLB eradication, and robust early detection programs for both the psyllid and the disease.[1] HLB quarantine areas are typically established as a 5-mile radius around detected infected trees in affected counties, such as Los Angeles, Orange, Riverside, San Bernardino, San Diego, and Ventura in California.[1] Within these quarantine zones, stringent restrictions are enforced, prohibiting the movement of citrus plants, plant parts (including stems and leaves), or equipment used to harvest citrus outside the designated area.[32] Fruit harvested within these areas may also require additional mitigation steps before transport.[32] Furthermore, it is illegal to bring citrus fruit or plant material into California from other states or countries.[38] Mandatory removal of HLB-infected trees is enforced to eliminate disease reservoirs and protect nearby healthy trees and the broader industry.[32]

The entire state of California is designated as an eradication area for both ACP and HLB.[39] Additionally, areawide treatments for ACP are coordinated by the CDFA in specific high-risk areas.[32]

VI. Available Datasets and Resources

The availability of comprehensive datasets is crucial for understanding the biology, spread, and management of the Asian citrus psyllid and Huanglongbing. These resources support research, inform policy, and enable the development of advanced detection and control technologies.

Image Datasets for ACP and HLB Detection

Image datasets are vital for training machine learning (ML) and deep learning (DL) models for automated detection and classification of HLB symptoms and ACP presence.

- **HLB Leaf Image Datasets:**
    - An "Orange Leaves Images Dataset for the Detection of Huanglongbing" is available, consisting of 649 orange leaf images, categorized into 379 healthy control images and 270 images of HLB-affected leaves.[40] These images, captured with smartphones and processed to remove backgrounds, are valuable for developing ML and DL models for leaf segmentation and abnormality detection.[40]
    - Another significant dataset, initially comprising 751 original images, was enhanced and expanded to 6008 images, uniformly resized to 512x512 pixels, specifically for training and testing ML models.[41] This dataset has been instrumental in training YOLOv8n-DE models, which have achieved high classification accuracy (97.6%), recall (91.8%), and mean Average Precision (mAP) (97.3%) for HLB detection.[41]
    - The "CitrusUAT_dataset" provides 953 color images of *Citrus sinensis* leaves, meticulously categorized into 12 classes, including HLB, various nutritional deficiencies, and other pest symptoms.[27] This dataset includes ground-truth binary masks to identify regions of interest and has been validated with quantitative real-time polymerase chain reaction (qPCR) tests for the presence of *Ca. L. asiaticus*, making it highly useful for training, validating, and comparing citrus abnormality detection algorithms based on image analysis and machine learning.[27]
- **ACP Image Datasets:**
    - General visual resources provide detailed images of ACP eggs (yellow-orange, almond-shaped), nymphs (distinguished by white waxy threads), and adults (showcasing wing patterns and their characteristic 45-degree feeding position).[4]
    - For computer vision applications, specialized datasets of psyllids captured on yellow sticky traps have been developed.[35] These images are often cropped and balanced to include both psyllid and non-psyllid classes. Techniques like Mosaic data augmentation are employed to address issues related to limited sample sizes and constrained positioning.[36] Such datasets have been successfully used to train improved YOLO v8 models for ACP recognition, demonstrating high performance with a recall rate of 88.64%, an F1 score of 87%, and a precision of 84.78% in field experiments.[36]

Table 2: Overview of Key Image Datasets for ACP and HLB Detection

Dataset Name	**Primary Focus**	**Number of Images**	**Key Features / Purpose**	**Source (if specified)**
Orange Leaves Images Dataset for HLB Detection	HLB leaf symptoms	649 (379 healthy, 270 HLB)	Smartphone-acquired, background-processed; valuable for ML/DL	

			leaf segmentation & abnormality detection	
Expanded HLB Image Dataset	HLB leaf symptoms	6008 (from 751 original)	Uniformly sized (512x512); used for training YOLOv8n-DE models for high accuracy HLB classification	
CitrusUAT_dataset	Citrus abnormalities (HLB, deficiencies, pests)	953	12 classes of *Citrus sinensis* leaves; includes ground-truth binary masks & qPCR validation for HLB; useful for ML/DL detection algorithms	Orange groves in Tamaulipas and San Luis Potosi, Mexico [27]
ACP Sticky Trap Datasets	ACP detection on traps	Varies (e.g., 1-30 psyllids per image)	Cropped, balanced for psyllid/non-psyllid; used for training YOLO v8 models for automated ACP recognition	São Paulo, Brazil [35];
General ACP Life Stage Images	ACP morphology	Various	Visual identification of eggs, nymphs (waxy threads), and adults (feeding posture, wing patterns)	Lucidcentral.org [19], IDTools.org [4], IUCN GISD [9]

Genetic and Genomic Datasets

Genetic and genomic resources are foundational for in-depth research into ACP biology, evolution, population dynamics, and the development of advanced, targeted control strategies.

- **ACP Genome Sequencing:** The genome of *Diaphorina citri* has been selected for sequencing by the USDA.[42] An "Official Gene Set v1.0" (Dcitr_OGSv1.0.tar.gz) is publicly available, providing comprehensive genomic data, including Gff3 files, protein fasta sequences, RNA fasta sequences, and CDS fasta sequences.[8] This dataset is accessible through the NCBI BioProject database under Accession Number: PRJNA29447.[42] Extensive manual curation efforts have been undertaken to identify and refine gene models, with a particular focus on genes that play crucial functional roles in *D. citri* biology and its complex interactions with *Candidatus Liberibacter asiaticus*.[8]
- **Population Genetic Diversity:** Studies investigating the genetic diversity and population structure of ACP have utilized molecular markers such as the mitochondrial cytochrome oxidase subunit I (COI) gene.[16] One such dataset comprises 721 COI sequences collected from 27 distinct geographic sites in China. Analysis of this data has revealed low haplotype and nucleotide diversity across the entire population, which is indicative of recent founder events, and has also shown significant genetic differentiation in the Southwest China population.[16] The identification of polymorphic microsatellite loci further supports detailed population genetic studies.[42] These genetic studies are invaluable for understanding the invasion routes of ACP and predicting patterns of population expansion, which are critical for designing effective quarantine and control strategies.

Table 3: Key Genetic and Genomic Datasets for Asian Citrus Psyllid

Dataset Name	Type of Data	Key Contents / Purpose	Access Information	Data Contact (if specified)

Asian Citrus Psyllid Genome Sequencing Project	Genomic	Whole genome sequence data	NCBI BioProject database, Accession: PRJNA29447 [42]	
Diaphorina citri Official Gene Set v1.0	Genomic (Annotated)	Gff3, protein fasta, RNA fasta, CDS fasta files; manually curated gene models focused on key biological functions & CLas interactions	Ag Data Commons, DOI: 10.15482/USDA.ADC/1345524 [8]	Surya Saha, ss2489@cornell.edu [8]
Chinese ACP Population Genetic Diversity	Population Genetic (COI gene)	721 sequences from 27 sites; haplotype & nucleotide diversity, genetic differentiation, demographic expansion analysis	Published in PMC10776205 [16] (data within article or supplementary)	
Polymorphic Microsatellite Loci from ACP	Genetic Markers	12 polymorphic microsatellite loci for population genetic studies	Molecular Ecology Notes (doi: 10.1111/j1471-8286.2007.01831.x) [42]	

Population Monitoring and Disease Incidence Data

Beyond genetic and image data, comprehensive records of psyllid populations and HLB disease incidence are essential for tracking spread, assessing risk, and evaluating the effectiveness of control programs.

- **ACP Population Data:**
  - The California Department of Food and Agriculture (CDFA) provides publicly accessible ACP detection data, including extensive trapping records dating back to 2008.[37] This data is visualized on a zoomable map, allowing users to see psyllid densities at the section level (one-mile square).[37] This map is regularly updated, with the latest ACP detection data available as of October 23, 2024.[37]
  - The Mexican trapping program for *D. citri* has accumulated a vast amount of data, comprising 3,264,660 records from weekly inspections of 86,004 yellow sticky traps distributed across the country.[34] This extensive dataset has been used to develop sequential sampling plans for decision-making regarding interventions, demonstrating that the psyllid exhibits aggregated spatial distribution.[34]
- **HLB Disease Incidence Data:**
  - **Florida:** Since HLB was first detected in Florida in 2005, the state's citrus production has faced severe impacts.[15] By 2013, all commercial orchards were HLB positive.[10] Surveys

conducted in 2016 indicated that, on average, 90% of citrus acres and 80% of trees in Florida operations were infected with HLB, resulting in an average 41% yield loss attributed to the disease.[30] The total acreage of oranges and grapefruits decreased by approximately 55.6% from 2004 to 2023, and overall citrus production dropped by over 80% from 1998 to 2021.[10]
    - **California:** HLB was confirmed in California in 2012.[22] The CDFA provides regularly updated HLB detection data, available on the same zoomable map as ACP detection data.[37] As of April 4, 2025, detailed tables show the number of HLB positive sites, trees, and ACP samples in various cities across Los Angeles, Orange, Riverside, San Bernardino, San Diego, and Ventura Counties.[1] Risk models, developed in Florida and adapted for California, have accurately predicted HLB emergence based on variables like census data, topography, land use, and known incidence of ACP and HLB.[31] These models have indicated a dramatic increase in the rate of new HLB infections in both ACP and citrus trees since June 2017, demonstrating an exponential increase in the intensity and geographic extent of the HLB epidemic.[31]

- **General Repositories:** The University of California Agriculture and Natural Resources (UC ANR) Repository and the Lindcove Research and Extension Center maintain resources related to citrus production and pest management, including information on ACP and HLB.[43] These platforms offer access to research programs, extension materials, and general information about citrus pest management.

VII. Ongoing Research and Future Prospects

The ongoing global challenge posed by Huanglongbing and its vector, the Asian citrus psyllid, continues to drive extensive research efforts aimed at developing more effective and sustainable control strategies. The complexity of the HLB-ACP pathosystem necessitates a multi-faceted approach, often likened to "curing cancer" due to the absence of a single "silver bullet" solution.[15]

Novel Therapeutic and Resistance Strategies

Significant research is focused on enhancing the natural resistance of citrus trees to pathogens and developing novel therapeutics. Approaches include conventional breeding and advanced gene editing techniques to build host resistance against *Candidatus Liberibacter* species.[12] Researchers are exploring antimicrobial therapeutics to suppress the growth of the bacteria within infected trees.[11] A groundbreaking innovation involves the development of RNA vector products, which utilize a mild, non-transmissible virus reprogrammed to express a natural antimicrobial peptide from spinach. This technology significantly reduces yield losses caused by HLB without altering the genetics of the citrus trees or fruits.[12] Another promising avenue is the development of nano-carrier technology, designed to deliver antibiotics directly to the plant's phloem and roots, overcoming the challenge of accurately targeting the phloem-limited bacteria.[12]

Advanced Detection Methods

Improving the speed and accuracy of HLB and ACP detection remains a high priority. Research continues to advance computer vision models, such as improved YOLOv8 models, for automated recognition of psyllids on traps and early detection of disease symptoms on leaves.[36] These technologies aim to provide real-time monitoring capabilities, enabling more timely preventive actions and reducing economic losses.[36]

Understanding Vector-Pathogen-Host Interactions

Deeper understanding of the intricate interactions between the psyllid vector, the bacterial pathogen, and the citrus host is critical for developing smarter control strategies.[13] Recent discoveries indicate that the

HLB bacteria can disrupt the psyllid's sense of smell, rendering certain insect traps (e.g., acetic acid baited traps) less effective.[28] This finding opens new research avenues into vector behavior and highlights the need for adaptive monitoring strategies that account for such pathogen-induced changes. Conversely, research has also shown that infected psyllids may exhibit lower protein and esterase levels, potentially making them more susceptible to certain insecticides.[24] These complex physiological and behavioral alterations in the vector due to pathogen infection represent a dynamic area of study, offering potential for highly targeted control measures.

Sustainable Management Integration and Long-Term Vision

The future of HLB management hinges on the integration of new biotechnological tools, fostering international cooperation, and developing adaptive, sustainable strategies.[13] The success of the Citrus Under Protective Screen (CUPS) system in Florida demonstrates a viable pathway for profitable citrus production in HLB-endemic areas by physically excluding the psyllid vector.[15] This approach, combined with precision delivery systems for therapeutics and insecticides, aims to significantly reduce the overall chemical load in orchards while maximizing efficacy.[12]

The long-term vision for the citrus industry involves not only effective control of the disease's progression but also the ultimate goal of finding a cure for HLB.[12] This requires continued investment in interdisciplinary scientific research, collaborative efforts among growers, researchers, and regulatory agencies, and a commitment to implementing integrated strategies that are both economically viable and environmentally sound.

VIII. Conclusions

The Asian citrus psyllid and Huanglongbing disease pose an existential threat to the global citrus industry, characterized by devastating economic losses and the absence of a direct cure for infected trees. The rapid life cycle of the psyllid and its exclusive reliance on new flush growth necessitate continuous and precisely timed management interventions, as populations can rebound quickly. Furthermore, the extensive global spread of the psyllid, despite its limited natural flight capabilities, underscores the critical role of human-assisted movement of infested plant material. This highlights the indispensable need for stringent regulatory frameworks and robust quarantine programs to contain further dissemination.

A significant challenge in HLB management is the prolonged latent period of the disease. Infected trees can remain symptomless for months to years, serving as hidden reservoirs for bacterial transmission. This asymptomatic phase allows the pathogen to spread widely before visible symptoms trigger detection efforts, often rendering reactive eradication measures insufficient on their own. This complex dynamic is further compounded by the pathogen's ability to manipulate its psyllid vector, potentially enhancing vector fitness while paradoxically altering its responsiveness to traps and susceptibility to certain insecticides. Such intricate interactions demand sophisticated, adaptive monitoring tools and targeted control strategies that can account for these nuanced biological responses.

Current reliance on intensive chemical control, while providing short-term suppression, is proving unsustainable due to the rapid development of pesticide resistance and negative impacts on beneficial insects. This necessitates a fundamental shift towards a truly integrated pest management (IPM) approach that prioritizes biological controls, cultural practices like the highly effective Citrus Under Protective Screen (CUPS) systems, and the development of precision chemical delivery technologies. These innovations represent a strategic move towards more targeted, environmentally controlled interventions, offering a path to more durable and sustainable citrus production.

Ultimately, safeguarding the global citrus industry requires a multi-pronged, collaborative effort. This includes continued investment in cutting-edge research to develop novel therapeutics, enhance host resistance through genetic advancements, and refine advanced detection methods. Simultaneously, the diligent implementation of comprehensive IPM strategies, supported by robust regulatory frameworks and public awareness, remains paramount. Only through such integrated, adaptive, and scientifically informed approaches can the citrus industry hope to mitigate the devastating impact of HLB and ensure its long-term viability.

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