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Optimization and Artificial Vision: Innovative Tool for Detecting Huanglongbing in Citrus

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ABSTRACT

Huanglongbing (HLB), or "citrus greening," is a bacterial disease transmitted by the Asian citrus psyllid (Diaphorina citri) that poses a severe threat to global citrus production, causing significant economic losses. This study explores advanced detection methods based on artificial vision and machine learning, such as hyperspectral cameras and drones, achieving accuracies of up to 99.72%. These technologies enable more efficient and scalable early detection compared to traditional methods like PCR and visual inspections. Despite challenges in implementation and cost, these innovations offer promising solutions to mitigate the impact of HLB and safeguard the global citrus industry.

Keywords: Huanglongbing (HLB), Citrus, Artificial Vision, Drones, Early Detection

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1. Introduction

Citrus fruits have significant economic and social importance worldwide due to their common use in diets and their major contribution to agriculture. The citrus industry is fundamental for employment, trade, and food security, particularly in countries such as Florida, California, Brazil, and parts of Asia. The global citrus market is valued in billions of dollars, with oranges, lemons, and limes ranking among the most harvested fruits [3]. However, this market struggles against diseases, with Huanglongbing (HLB), also known as 'citrus greening disease', being a major adversary. HLB is a bacterial disease attributed to the scientific name Candidatus

Liberibacter asiaticus (CLas), which affects the nutrient transport system of citrus trees, leading to a decline in fruit quality and tree health [18]. The disease causes yellowing of leaves, stunted growth, and premature tree death, posing a significant threat to citrus growers worldwide [27].

The main objective of this work is to provide a synthesis of the current knowledge on HLB, addressing topics such as its impact on citrus production, detection techniques, detection challenges, management strategies, and future plans. HLB originated in East Asia, where it was discovered several centuries ago. The disease was first detected in China in the 19th century and has since spread to various citrusproducing regions globally, including Africa and the Americas [26]. Its widespread geographical distribution has raised concerns about potential collateral damage if not addressed in time [7].

The causal agent of HLB, Candidatus Liberibacter asiaticus, is a phloem-limited bacterium transmitted by the Asian citrus psyllid (Diaphorina citri). The bacterium colonizes the phloem tissue, blocking nutrient transport and inducing physiological changes in affected trees [18]. The causal agent plays a fundamental role in the spread of the disease, as it feeds on the sap of infected crops and consequently transfers the bacteria to healthy vegetation [23]. The first signs of HLB begin with a yellowish discoloration of the leaves, presenting as spots or mottling, and the failure of fruits to mature, leading to premature fruit drop [2]. The disease results in a fatal quality of life for the fruits, reduced yield, and the death of the disease carrier, posing a significant challenge to maintaining citrus orchards [27]. Furthermore, the physiological effects of HLB on citrus trees include poor nutrient absorption and transport, which further exacerbate the constant deterioration of tree health [11].

The economic impact of HLB on citrus production is alarming, with estimated losses amounting to billions of dollars annually due to decreased yield and increased management costs [3]. In regions such as Florida, HLB has severely reduced orange production, and many growers have reported their groves becoming unviable within a decade of the disease's arrival [3]. HLB not only affects production levels but also the quality of the fruit, making it less marketable [28]. On a global scale, the consequences of HLB extend beyond economic losses; they affect entire supply chains and threaten the livelihoods of millions of citrus farmers. The reduced lifespan of infected trees has led to increased cultivation costs and changes in agricultural practices as farmers seek ways to manage the disease [16]. The snowball effect of HLB on the citrus industry underscores the urgent need for efficient detection and management techniques.

2. Huanglongbing (HLB)

2.1 Origin and Geographical Distribution

HLB originated in Guangdong, China [7]. It belongs to the phloem-restricted Candidatus Liberibacter group, comprising three distinct species: the Asian strain (Candidatus Liberibacter asiaticus), the African strain (Candidatus Liberibacter africanus), and the Brazilian strain (Candidatus Liberibacter americanus). These bacteria are transmitted through citrus psyllid species, namely the Asian citrus psyllid (Diaphorina citri Kuwayama) and the African citrus psyllid (Trioza erytreae) [1].

2.2 Causal Agent

Candidatus Liberibacter (CLas) is the causal agent of HLB. Phylogenetic analysis of the 16s rRNA region has shown that it belongs to the - proteobacteria. CLas measures 0.2 to 0.3 microns in diameter, has a Gramnegative membrane, a thin peptidoglycan layer, and no flagella. It resides in the phloem sieve tubes and takes a rounded shape upon completing its cellular cycle. It is transmitted by vector insects, where it remains in the hemolymph and salivary glands. Additionally, it can spread through sprouts, grafting, and rarely through infected seeds. According to the International Standards for Phytosanitary Measures (ISPM) No. 5 Glossary of Phytosanitary Terms, CLas is classified as a ”quarantine pest” and primarily affects plants of the Rutaceae family (Citrus) [21]. Figure 1 shows an image of the Asian citrus psyllid, the HLB vector.

2.3 Life Cycle of the Bacteria and Vector

The Asian citrus psyllid requires new citrus shoots to survive and develop. Female D. citri lay eggs only on unaffected tissues, depositing up to 800 eggs throughout their life cycle. The larvae hatch within four days, undergo five developmental stages over approximately 15 days, and then mature into adults. Temperature plays a crucial role in the life cycle, which typically spans between 15 and 47 days [1].

2.4 Symptoms and Effects on Citrus Trees

When citrus trees are affected by HLB, initial symptoms include yellow shoots and mottled leaves that may be mistaken for nutrient deficiencies. Affected branches produce small, misshapen fruit with aborted seeds that fail to ripen properly and drop prematurely. As the disease progresses, the citrus tree gradually loses functionality, with branches dying off, and the tree lifespan is reduced to 5-8 years with unmarketable fruit. Figure 2 illustrates the damage caused by HLB in citrus trees.

3. Impact of HLB on the Citrus Industry

Orange cultivation originated in the Eastern Hemisphere, primarily in China, and later expanded commercially. In 2022, global production reached 49 million metric tons (MMT), with Brazil producing 16.9 MMT, followed by China (7.6 MMT), the European Union (6.1 MMT), Mexico (4.5 MMT), and the United States (3.5 MMT). However, the largest producers of orange juice are Brazil (1.1 MMT), the U.S. (190,000 tons), and Mexico (170,000 tons) [21].

Unfortunately, the citrus industry has been severely affected by HLB, first identified in China in the 19th century and globally known as ”Citrus Greening” or ”Yellow Dragon Disease.”

4. Artificial Vision Methods

4.1 Monochromatic Camera

In 2014, Pourreza et al. [22] developed a vision sensor for real-time identification of HLB using a monochromatic camera (DMK 23G445) with a Sony ICX445 CCD sensor, a 6 mm wide-angle lens, a rotating linear polarizer, an LED panel with 10 LEDs, two 12V car batteries, five LED drivers, a linear polarizing film, and an SVM algorithm. The setup was housed in a wooden box. The dataset used consisted of four types of sweet orange “Hamlin” leaves (HLB-positive, HLB-negative, HLB-positive with Zinc deficiency, and HLB-negative with Zinc deficiency) from the Citrus Research and Education Center (CREC) at the University of Florida, Lake Alfred. The classification accuracy achieved was between 95.5% and 98.5%, utilizing descriptors such as Mean, Standard Deviation of grayscale values, and the SVM classifier. Figure 3 illustrates their project results, including HLB-positive cases, HLB-positive cases with Zinc deficiency, and HLB-negative cases.

4.2 Thermal and Infrared Cameras

In 2013, Sankaran et al. [24] employed thermal and near-infrared imaging techniques to detect HLB in citrus trees. The equipment included two multispectral cameras (MCA and MIC-005) with channel ranges of 440 nm to 900 nm and an uncooled thermal camera (Tau 640) mounted on a support platform. Vegetation indices such as NDVI (Normalized Difference Vegetation Index), VOG (Vogelmann Red Edge Index),and mSR (Modified Red Edge Simple Ratio) were analyzed, showing acceptable separation between healthy and infected groups. Classification metrics like "Accuracy," "Specificity," "Sensitivity or Class Recall," and "Class Precision" were used to evaluate four classifiers: LDA (Linear Discriminant Analysis), QDA (Quadratic Discriminant Analysis), BDT (Boosted Decision Tree), and SVM (Support Vector Machine). Table 1 shows the results for each classifier.

Figure 1. Asian citrus psyllid, the HLB vector [25]

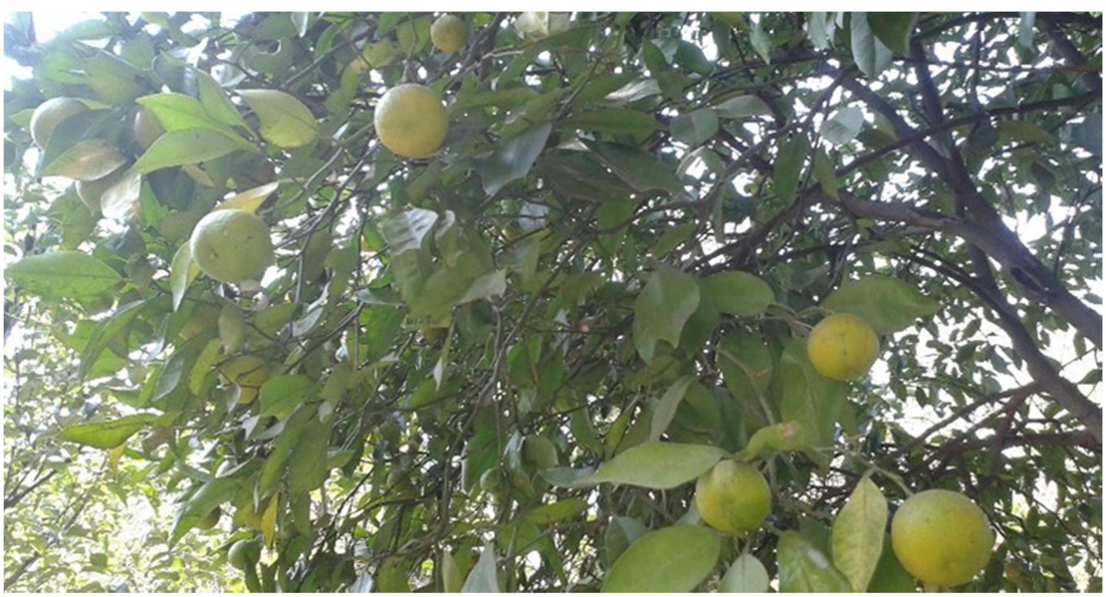

Figure 2. HLB damage in citrus trees [5]

Classification Results	LDA	QDA	BDT	SVM
Accuracy (%)	81 ± 6	80± 6	80 ± 3	87± 3
Specificity (%)	85± 17	78 ± 22	93 ±6	89 ± 11
Sensitivity or Class Recall (%)	78 ±19	81 ±13	67 ± 11	85 ± 17
Class Precision (%)	87 ± 14	82 ± 17	91 ± 8	90± 9

Table 1. Evaluation metrics results of the classifiers

4.3 Airplane-Based Detection

In 2012, Kumar et al. [13] developed a method to identify citrus orchards affected by HLB using hyperspectral images from the AISA Eagle camera (2007 and 2009) and multispectral images from the XMV-4021 CCD camera (2009), both taken from an airplane in various cultivation areas in Florida. Ground validation included soil measurements and visual inspection of citrus trees for 2007 images, and more accurate PolymeraseChain Reaction (PCR) tests were performed for selected trees in 2009. They employed spectral libraries and techniques such as Matched Filtering (MTMF), Spectral Angle Mapping (SAM), and Linear Spectral Unmixing for analysis. MTMF accuracy was higher compared to other techniques, and SAM accuracy was 87% for multispectral images. Tables 2 and 3 summarize the results from SAM and MTMF methods for 2009.

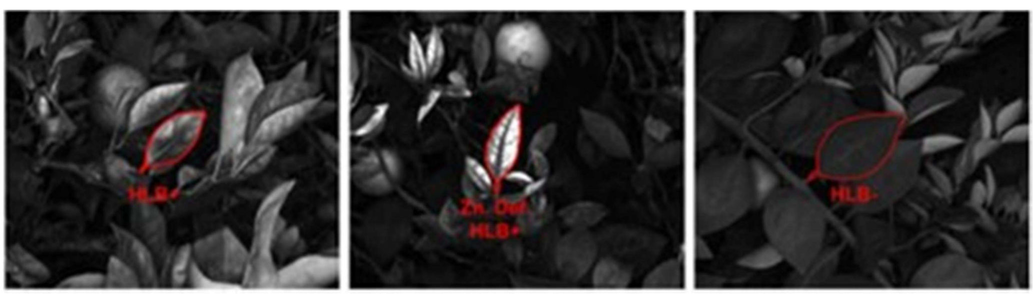

Figure 3. Representation of HLB in a positive case, a positive case with Zinc deficiency, and when it is not positive

Site	Imagen type	PCR HLB	MTMF PCR HLB	Precision (%)
E1- West	HS	15	11	73.3
El-East	HS	15	12	80

Table 2. Results of the application of the SAM method in 2007 with a hyperspectral camera

Site	Imagen type	PCR HLB	SAM PCR HLB	Precision (%)
E1- West	HS	15	9	60
El-East	HS	15	10	66.6
E1- West	MS	5	12	80
El-East	MS	15	13	86.6

Table 3. Results of the application of the SAM method in 2009 with a hyperspectral and a multispectral camera

4.4 Hyperspectral Drone

In 2020, Deng et al. [6] created a tool to detect HLB stress in citrus trees using a Cubert S185 hyperspectralcamera with bands 468 nm to 852 nm mounted on a UAV DJI Matrice 600 Pro. An ASD Handheld2 spectrometer was also used to validate UAV data. The proposed detection methods (based on multiple vegetation indices and spectral canopy properties in a Stacked Autoencoder Neural Network) achieved a classification accuracy of 99.33% for the training dataset and 99.72% for the validation dataset. This shows that the use of hyperspectral cameras has great scalability for the detection of HLB in citrus trees since having an accuracy very close to 100% favors and becomes a better option than traditional methods for the investigation of hosts with this disease.

4.5 Multispectral Drone

In 2019, Dadras et al. [4] used a Micasense RedEdge multispectral camera with spectral bands (Red, Green,Blue, Red Edge, and NIR) mounted on a Hexacopter UAV to detect citrus greening (HLB). Image features were analyzed using the SIFT (Scale-Invariant Feature Transform) algorithm, and 16 vegetation indices (SIPI, mSR, NDVI, RDVI, GI, among others) were calculated. The SVM algorithm was used to classify images in two steps: first, distinguishing trees from non-trees, and then identifying healthy and diseased trees. The overall accuracy for tree detection was 95.5%, while the accuracy for healthy and diseased tree classification was 81.75%. Tables 4 and 5 show confusion matrices and precision measures for both classifications.

In 2012, Garcia et al. [9] compared a UAV (HiSystems GmbH) equipped with a miniMCA multispectral camera with six bands to an airplane carrying hyperspectral AISA EAGLE VNIR camera to evaluate the effectiveness of both methods in detecting HLB infected citrus trees. The six spectral bands ranged from 530 nm to 900 nm. They used seven vegetation indices based on the selected bands to monitor plant health and photosynthesis progress (NDVI, GNDVI, SAVI, NIR – R, R/NIR, G/R, NIR/R). Stepwise regression analysis was employed to identify the most significant features of the acquired images. Algorithms such as LDA (Linear Discriminant Analysis), QDA (Quadratic Discriminant Analysis), and SVM (Support Vector Machine) with and without Kernel were implemented. Table 6 presents result for aerial and UAV data, including classification accuracy and False Negative (FN) rates after ten iterations.

In 2020, Lan et al. [14] conducted a study to assess the reliability of remote sensing at different altitudes for detecting HLB in citrus orchards. They used a multispectral ADC-lite camera and a DJI M100 UAV to collect

Confusion Matrix (%)			
Classified data	**Test data**		**Total row result**
	Tree	**No Tree**	
Tree	52.26	3.79	56.05
No Tree	0.71	43.24	43.95
Total column result	52.97	47.03	100

Class/ Precision	**User (%)**	**Producer (%)**
Tree	93.24	98.66
No Tree	98.38	91.94

Table 4. Results of tree detection with the SVM algorithm

Confusion Matrix (%)			
Classified data	**Test data**		**Total row result**
	Tree	**No Tree**	
Tree	41.26	4.88	46.14
No Tree	13.37	40.49	53.86
Total column result	54.63	45.37	100

Class/ Precision	**User (%)**	**Producer (%)**
Tree	89.42	75.53
No Tree	75.18	89.24

Table 5. Results of HLB detection in citrus trees with the SVM algorithm

Dataset	LDA		QDA		SVM		SVM (Kernel)	
	Precision	FN	Precision	FN	Precision	FN	Precision	FN
AN - I	62	45	64	28	63	45	63 (2.0)	38
AN - II	68	37	73	40	68	40	71 (2.0)	40
AN - III	-	-	-	-	61	37	74 (2.0)	37
AN -IV	68	37	74	30	70	37	74 (2.0)	37
UAV -I	75	23	67	28	74	27	85 (1.3)	11
UAV -II	79	1 7	74	23	77	22	84 (0.9)	15
UAV -III	69	20	-	-	78	7	75 (1.5)	17
UAV -IV	82	32	76	23	80	20	80 (1.3)	2 5

Table 6. Results of the classifiers in HLB detection with an aircraft and UAV

images in Green, Red, and NIR bands. Methods such as linear-stretch for noise reduction, vegetation indices, correlation analysis, PCA (Principal Component Analysis), and AutoEncoder were applied to discern significant patterns. Machine learning algorithms, including SVM (Support Vector Machine), kNN (k-Nearest Neighbors), LR (Logistic Regression), Naive Bayes, Ensemble Learning (AdaBoost), and Neural Network, were used to evaluate performance. Metrics like Accuracy, Recall, Precision, Specificity, and F1-Score were employed. Table 7 shows the results of each classifier's evaluation metrics.

5. Molecular Methods

5.1 PCR (Polymerase Chain Reaction)

In 2009, Futch et al. [8] conducted a study to evaluate the effectiveness of various survey methods in different citrus-growing regions in DeSoto, Florida. They used five different teams to survey citrus greening through methods such as walking, all-terrain vehicles, platforms, and platforms with transportation. Each team marked suspected HLB areas using flags based on visual identification. Subsequently, the DNA laboratory method (PCR) was used to confirm whether the trees contained HLB bacteria. Results indicated that walking and platforms with transportation achieved 47% effectiveness, platforms without transportation achieved 59%, and all-terrain vehicles achieved 61% effectiveness.

5.2 Real-Time PCR (qPCR)

In 2006, Li et al. [15] developed a quantitative Taq- Man PCR test using TaqMan probe-primer sets based on 16S rDNA specific to the various CLas types. Additionally,a second primer-probe set targeting plant cytochrome oxidase (COX) was used as a positive internal control to assess the effectiveness of DNA extractions. Their results showed that HLB bacterial DNA could be effectively detected using 20 ng of symptomatic central vein tissue samples.

Algorithm (Limit)	SVM (65%)	KNN (55%)	LR (68%)	Naive Bayes (58%)	Ada Boost (90%)	Neural network (80%)
Accuracy	79.76	81.27	72.2	80.06	100	97.28
Specificity	33.33	42.47	27.96	34.69	100	88.89
Precision	88.57	85	76.07	88.57	100	97.86
Recall	87.63	92.24	89.49	87.94	100	98.91
F1-Score	88.1	88.48	82.24	88.26	100	98.38
Cohen Kappa	34.86	50.09	27.12	33.28	100	92.2

Table 7. Evaluation metrics results of the classifiers for HLB detection

5.3 LAMP (Loop-Mediated Isothermal Amplification)

In 2005, Okuda et al. [19] performed an asymmetric thermal interlaced PCR (TAIL-PCR) to amplify uncharacterized regions adjacent to the KAJLB gene cluster of the HLB-causing organism in citrus from Japan and Indonesia. They also developed a LAMP assay based on the stored KAJLB gene sequence to detect HLB. The method was confirmed to be useful for laboratories with minimal equipment, such as extension centers and quarantine offices.

6. Other Methods

6.1 Serological: ELISA (Enzyme-Linked Immunosorbent Assay)

In 1987, Garnier et al. [10] developed hybridoma clones that secreted monoclonal antibodies (mAb) specific to the bacterial-like microorganism associated with citrus greening disease. This was achieved by homogenizing damaged phloem tissues and using them as immunogens to immunize mice. Differential ELISA and immunofluorescence were used to identify hybridomas that secreted mAb against the HLB microorganism. They successfully obtained two hybridoma clones that produced specific mAb for HLB. No crossreactions were observed with other studied phloemlimited prokaryotes or healthy plant material.

6.2 Biological: Vector-Based Detection (Infected Psyllids)

In 2014, Keremane et al. [12] documented the development of a field detection kit designed to study psyllids for the presence of CLas using LAMP (Loop-Mediated Isothermal Amplification) technology. Their method allowed the analysis of six samples simultaneously, including one positive and one negative control, within approximately 30 minutes—10 minutes for crude extraction and 20 minutes for target DNA amplification. For the LAMP assays, they used a Smart-DART detection unit managed via an Android device. The LAMP technique for identifying CLas was about 100 times more sensitive than real-time PCR. Additionally, the methodology was efficient for detecting CLas in plant DNA extractions.

7. Challenges in Detecting HLB

7.1 Difficulties in Early Detection

Currently, there is no fully effective method to combat HLB. The best option, as in many cases, is to prevent trees from becoming infected. Early detection is essential for producers to implement control actions since,once the disease is identified, the main decisions involve removing the affected crop or applying treatment and control techniques [20].

Visual identification of this disease is complicated due to its long development time in trees, which depends on their age and health. Consequently, asymptomatic trees may go unnoticed. Therefore, implementing science and technology solutions that enable producers to confirm HLB in their orchards at an early stage will help mitigate the potential damage caused by the disease.

For this reason, research processes, treatment methods, and data analysis from scientific and technological datasets have become an efficient approach to finding innovative solutions that strengthen decision-making for citrus producers.

7.2 Vector Control (Psyllids)

Winter Management Using Broad-Spectrum Products: CLas relies on young shoots for immature stages to grow, as its larvae can only develop on young plant tissue.During winter, due to the absence of new shoots,only hibernating adults can be found. This period presents an opportunity to reduce the CLas populationby applying contact insecticides. Conversely, natural enemies of the psyllid mainly target immature stages,making them less effective in winter. Research conducted by the University of Florida demonstrated that one or two applications of broad-spectrum products in December and January significantly reduced psyllidpopulations in spring. Producers were recommended to apply an organophosphate for the first treatment and a pyrethroid for the second due to their lower residual activity [17].

Developing Biorational Schedules During Growth Periods: During spring and summer, when crops are budding and new psyllid generations are developing, it is advised to apply more selective active ingredients compatible with treated fauna. To prevent resistance, rotating modes of action as much as possible is necessary. Producers who base their management programs on scheduled applications should select biorational products to optimize control of CLas and other pests.

7.3 Low-Volume Applications with Paraffinic Oils

An alternative to synthetic chemical products is fortnightly treatments using 20 liters per hectare of mineral oils mixed with the same amount of water and applied at speeds up to 10 km/h. This approach has resulted in similar reductions in psyllid populations as constant synthetic insecticide applications. This option provides a more environmentally friendly solution.

8. Discussion

Huanglongbing (HLB) represents a significant threat to the global citrus industry due to its economic impact and the difficulty of early detection. Traditional methods,such as visual inspections, face substantial limitations, including reliance on the evaluator's expertise and susceptibility to error. In this context, computer vision has emerged as a revolutionary tool that overcomes these challenges.

Table 8 provides a detailed comparison of the computer vision methods used to detect HLB in citrus trees, highlighting the study objectives, equipment used, implemented techniques, and achieved precision levels. This analysis evaluates the relative effectiveness of approaches ranging from hyperspectral and multispectral cameras to drones and advanced algorithms like SVM, SAE, and neural networks. Table 8 demonstrates how these technologies improve early HLB detection,offering more precise, automated, and scalable tools for farmers. The notable advantages of computer vision methods include:

Accuracy and Consistency in Detection: Computer vision, utilizing multispectral, thermal, and hyperspectral cameras, has achieved precision levels up to 99.72%, as seen in the work of Deng et al. (2020). These results far exceed manual or visual methods, ensuring reliable and consistent diagnosis regardless of environmental conditions or operator expertise.

Automation and Scalability: Using drones equipped with hyperspectral cameras and advanced algorithms like SVM and neural networks allows large-scale monitoring of agricultural areas in a short time. This capability is crucial for detecting HLB early and limiting its spread. For example, UAVs used by Dadras et al. (2019) achieved 95% accuracy in identifying infected trees.

Advanced Data Analysis: Integrating vegetation indices and spectral analyses enhances HLB detection by identifying patterns invisible to the human eye. Techniques like NDVI and mSR have been key in distinguishing healthy trees from infected ones, enabling more efficient crop management.

Cost Reduction Over Time: While computer vision methods require an initial investment, their ability to prevent massive crop losses makes them a cost-effective solution. Detecting HLB before irreversible damage occurs allows producers to take preventive measures,reducing the costs associated with tree removal and replanting.

Innovation and Flexibility: The adaptability of computer vision to various agricultural scenarios underscores its potential. From drones to ground-based sensors,these methods can be tailored to the specific needs of producers, regardless of scale.

9. Conclusion

In conclusion, artificial vision methods not only overcome the limitations of traditional techniques, such as visual inspections and molecular tests, but also provide a comprehensive solution for the early and accurate detection of Huanglongbing (HLB). Their ability to analyze large volumes of data in real-time, identify patterns invisible to the human eye, and differentiate between healthy and diseased trees position them as key tools in mitigating the impact of this devastating disease on citrus crops. The scalability of these technologies, from the use of drones equipped with multispectral cameras to automated ground platforms, allows for their implementation

Research	Objective	Study team	Techniques used	Precision (%)
Bouzary et al. [22	HLB detection with a realtime vision sensor	Monochromatic camera DMK 23G445 with a CCD Sony ICX445 sensor. Tools: Wooden box, a 6 mm wide lens, among other components.	SVM	95.5% - 98.5%
Sankaran et al. [24]	HLB detection with thermal and infrared imaging techniques	Multispectral camera MCA y MIC 005, - Uncooled thermal camera Tau 640. Tool: Support platform.	SVM, QDA, BDT, LDA	SVM: 87%; QDA: 82%; BDT: 80%; LDA: 81%
Kumary et al. [13]	Detection of areas in citrus orchards with HLB	Hyperspectral camera AISA Eagle y XMV-4021 CCD.	SAM	Hyperspectral: 89%; Multi spectral: 87%
Deng et al. [6]	HLB detection in citrus trees	UAV DJI Matrice 600 Pro. Hyperspectral Cubert S185 with spectrometer ASD Handheld 2.	SAE	Train: 99.33%; Validation: 99.7%
Daday et al.[4]	Detection of trees and HLB in citrus trees	Multispectral camera Red-Edge, Multispectral camera Sequoia, Hyperspectral camera Headwall.	SVM	Tree: 95%; HLB: 81.75%
Garcia et al. [9]	Comparison of HLB detection methods	Multispectral MicaSense Altum + Hyperspectral AISA Eagle VNIR. UAV: Husban Goblin Aero Hawk.	SVM, QDA, LDA, SAM	SVM: Aerial: 70%; UAV: 80%. QDA: Aerial: 74%; UAV: 76%. LDA: Aerial: 74%; UAV: 80%. SAM: Aerial: 74%; UAV: 80%
Lan et al. [14]	HLB detection	Multispectral camera ADC- lite. UAV DJI M100.	KNN, SVM, LR, Naive Bayes,	KNN: 81.27%; SVM: 79.76%; LR: 72.20%;

Table 8. Comparison of artificial vision methods for the detection of HLB

under various agricultural conditions, adapting to the needs of both small and large producers.

Furthermore, their ability to integrate with other approaches, such as vegetation indices and machine learning algorithms, strengthens informed and timely decision-making, contributing to more efficient orchard management. However, to maximize their potential, it is crucial to continue investing in research and development to improve accuracy, reduce associated costs, and ensure that these tools are accessible even in regions with limited resources. Only in this way can it be ensured that artificial vision is an inclusive and sustainable solution, protecting the global citrus industry and the livelihood of millions of farmers who depend on it.

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