HortScience 60(4):490–496. 2025. https://doi.org/10.21273/HORTSCI18367-24

Red and White Kaolin Particle Films Enhance Growth and Yield of HLB-infected Sweet Orange Trees

Maryam Khalilzadeh and Myrtho O. Pierre
Citrus Research and Education Center, Department of Horticulture, University of Florida, 700 Experiment Station Road, Lake Alfred, FL 33850, USA

Anirban Guha
Citrus Research and Education Center, Department of Horticulture, University of Florida, 700 Experiment Station Road, Lake Alfred, FL 33850, USA, and Indian Institute of Science Education and Research Thiruvananthapuram, Kerala 695551, India

Juanpablo Salvatierra-Miranda and Christopher I. Vincent
Citrus Research and Education Center, Department of Horticulture, University of Florida, 700 Experiment Station Road, Lake Alfred, FL 33850, USA

Keywords. Candidatus Liberibacter asiaticus, citrus tree growth, huanglongbing, kaolin particle films, yield enhancement

Abstract. **The Florida citrus industry is severely impacted by huanglongbing (HLB), a bacterial disease spread by the Asian citrus psyllid (*Diaphorina citri*), leading to reduced production and extensive management challenges. Additional stresses, such as excessive sunlight, heat, and water deficits, further weaken the affected trees. Kaolin particle films (PFs), including white and recently developed red-dyed types, alleviate the effects of water and heat stress on citrus physiology, help suppress psyllid populations, and delay HLB infection. However, there is limited knowledge about the long-term effects of these PFs, especially red-dyed PF, on production capacity of citrus trees affected by HLB. This study aimed to evaluate the impact of these PFs on both growth and yield of HLB-infected trees. We conducted a field experiment on young 'Hamlin' sweet orange (*Citrus* ×*sinensis*) trees grafted onto 'Kuharske' citrange (*C. sinensis* × *Poncirus trifoliata*) rootstock, treated with foliar applications of white and red-dyed PFs, insecticides, or left untreated. Treatments began before infection and continued after infection with *Candidatus* Liberibacter asiaticus (*C*las), the causal agent of HLB. We assessed tree growth and yield over two years following *C*las infection. Trees treated with either PF had greater yield and growth, including canopy area, volume, density, and height than insecticide-treated and untreated controls. The red-dyed PF increased some growth variables to a greater degree than the white PF. The results suggest that kaolin PFs offer substantial horticultural benefits, including enhanced growth and yield, and may serve as an effective strategy for mitigating the impact of HLB in citrus orchards, even after infection.**

The citrus industry holds tremendous economic and cultural significance. This industry is a pivotal contributor to Florida's economic landscape, creating jobs and generating revenue. Citrus added more than $6.9 billion in 2020–21 to the state's economy and sustained more than 32,000 jobs (Cruz et al. 2024). However, the Florida citrus industry has faced significant challenges, primarily due to citrus greening (huanglongbing; HLB), a bacterial disease caused by the phloem-limited *Candidatus* Liberibacter asiaticus (*C*Las) transmitted by the Asian citrus psyllid (ACP; *Diaphorina citri*) (Hodges and Spreen 2012). This has led to a decline in production and the need for extensive efforts to manage and mitigate the impact of HLB. Significant impacts of HLB on citrus production have also been seen in Brazil, Mexico, China, Nepal, India, and Pakistan.

As of now, no single effective solution has been discovered to control HLB. Historically, the primary approach to manage this disease heavily depends on the use of insecticides to control the insect vector (Blaustein et al. 2018). A few studies endorsed kaolin particle films (PFs) as a viable and effective substitute for detrimental insecticide sprays (Miranda et al. 2018; Saour 2005). PFs act as physical barriers against insect feeding and can make the host plants less recognizable to pests. These films are effective against pests such as *Diaphorina citri* in citrus trees (Hall et al. 2007; McKenzie et al. 2002; Miranda et al. 2018). PFs diminish the capacity of the ACP to land, move, or lay eggs on treated leaves (Hall et al. 2007). Moudgil et al. (2017) introduced the concept of using the commercial kaolin product Surround (TKI Novasource, Phoenix, AZ, USA) mixed with various dyes to mask leaves from insects. Pierre et al. (2021) demonstrated the effectiveness of both white and red-dyed PF treatments in reducing ACP populations and delaying *C*Las infection, with red-dyed PF causing a greater reduction than the standard white PF. However, effects on tree growth and yield were not reported in that study because it was early in the planting establishment period, which motivated the present work.

White PFs had previously been reported to improve horticultural characteristics of trees uninfected by HLB (Hall et al. 2007; Jifon and Syvertsen 2003a). Salvatierra-Miranda et al. (2023) reported growth improvements from white and red-dyed PFs in uninfected trees in pots. However, no study reported the effects of PFs on HLB-affected trees or of red-dyed PFs on trees in the field.

Excessive sunlight, heat, and water deficits on citrus physiology can further weaken trees affected by HLB, exacerbating its impact on growth and yield. Florida's climate, characterized by intense and prolonged sunlight, especially during the peak summer months (Collins et al. 2017), can reduce growth and photosynthesis because trees close their stomata to reduce water loss under the resulting high vapor pressure deficit (VPD) (Jifon and Syvertsen 2003b). Suh et al. (2021) found that shading HLB-affected sweet orange (*Citrus* ×*sinensis*) trees ameliorated prominent HLB symptoms and increased canopy growth and photosynthesis, demonstrating that excessive light conditions augmented disease progression and severity in HLB-infected citrus trees. Applications of PFs have also been used to alleviate the adverse impacts of water deficiency and heat stress on physiology and productivity of horticultural crops through their shading and light redistribution effects (e.g., Chamchaiyaporn et al. 2013; Dinis et al. 2018; Glenn 2009; Rosati et al. 2006). Thus, we hypothesized that applying white or red PF to HLB-affected citrus trees would enhance growth and yield. Building on this hypothesis, the objective of the current study was to assess the horticultural effects of continuous application of red and white PFs on HLB-infected trees.

Materials and Methods

This study was carried out at the University of Florida, Citrus Research and Education Center in Lake Alfred, FL, USA (lat. 28°07′38″N, long. 81°42′57″W), during 2017–20. A planting

Received for publication 3 Dec 2024. Accepted for publication 14 Jan 2025.
Published online 7 Mar 2025.
C.V. developed concepts and designed the study. M.P., J.S., and A.G. implemented the study. M.KH. analyzed and interpretated data and wrote the manuscript. C.V. supervised data analysis and interpretation. C.V., M.P., and A.G. revised the manuscript.
This study was funded by Citrus Research and Development Foundation Grant #16-020.
C.I.V. is the corresponding author. E-mail: civince@ufl.edu.

of 480 'Hamlin' sweet orange (*Citrus ×sinensis* L. Osbeck), grafted onto 'Kuharske' (*C. sinensis* × *Poncirus trifoliata*) rootstock was established on 17 Apr 2017. Trees were planted in a 2.7 m in-row × 6.1 between-rows spacing. Trees were irrigated daily for 1 h each morning using a microsprinkler system with a flow rate of 2 L·h^{-1}. At planting, a slow release of 14–3–11 fertilizer provided 121 kg of nitrogen per hectare. A one-time application of 34 kg of nitrogen per hectare from a 9–2–13 soluble fertilizer was made, followed by quarterly applications of 101 kg of nitrogen per hectare from a 6–3–6 foliar fertilizer. Additionally, 67 kg per hectare of an organic 9.75–2–13 fertilizer was applied three times annually, totaling 323 kg of nitrogen per hectare in the first year and 202 kg per hectare in subsequent years.

Experimental design. A randomized complete block design was used with six blocks and four treatments. The experimental unit consisted of 20 trees, four rows wide and five trees long in each row. The six interior trees from each unit were used to collect measurements, and the remaining exterior trees were considered buffer trees to mitigate overspray or treatment edge effects (Fig. 1). The experiment included four treatments as follows: a control with no foliar insecticide, foliar insecticide with a rotation of applied foliar insecticides, white kaolin (Surround WP), and red kaolin (Surround WP with a red dye). As the PF treatment, the experiment used calcined kaolin clay products, Surround. In the PF treatments, the trees were thoroughly sprayed to cover all the foliage. White and red PF were applied to trees as necessary to keep them covered, depending on rain wash-off, which led to 23 to 26 applications annually. PF applications began immediately after planting in Apr 2017 and continued through Dec 2020, with each being applied at a rate of 56 kg·ha^{-1} at a spray volume of 935 L·ha^{-1}. Reapplication was performed whenever the treatments were no longer visible on the foliage. Detailed information on the production of red-dyed treatment is available in Moudgil et al. (2017), Vincent et al. (2021b), and Salvatierra-Miranda et al. (2023). Briefly, 3.63 kg of Surround was mixed with 60.5 L of water, 168 g of red dye (Pylam Products Company Inc., Tempe, AZ, USA), 19 g of a binding agent (cetylpyridinium chloride monohydrate) (Sigma-Aldrich Inc., St. Louis, MO, USA), 59.5 g of extender/sticker (SKH) (BRANDT Organics, Springfield, IL, USA), and 36 mL of surfactant (GarrCo Products Inc., Converse, IN, USA), then stirred in a cement mixer for 4 h. For insecticide treatment, a range of products was used, including Admire (0.74 mL/tree; Bayer Crop Science, Research Triangle Park, NC, USA), Mustang (0.32 mL/tree; FMC Corporation, Philadelphia, PA, USA), Imidan (1.16 mL/tree; Growan, Yuma, AZ, USA), Delegate (0.30 mL/tree; Corteva AgriScience, Indianapolis, IN, USA), Danitol (1.16 mL/tree; Valent USA, Walnut Creek, CA, USA), Agriflex (0.62 mL/tree; Syngenta LLC, Greensboro, NC, USA), Baythroid (0.22 mL/tree; Bayer Crop Science), Sivanto (1.01 mL/tree; Bayer Crop Science), Voliam Flexi (0.52 mL/tree; Syngenta), and Movento (0.74 mL/tree; Bayer Crop Science). These insecticides were rotated and applied monthly from Apr 2017 to Oct 2020.

Meteorological data. The meteorological data included average, maximum, and minimum monthly temperatures, total rainfall, relative humidity levels, and solar radiation data were obtained from the Florida Automated Weather Network (https://fawn.ifas.ufl.edu/2024) with a weather station located near the study site during the growth measurements periods from Sep 2019 to Oct 2020.

Plant disease status. This experiment was conducted in the same field and involved the same trees as in Pierre et al. (2021). In that research, the authors noted that all trees were infected with *C*Las by Jul 2019, although the PF-treated trees became infected on average later than those without PF treatment (Pierre et al. 2021). Although we do not include those data here, the results were important in evaluating plant health and in understanding how treatments interact with HLB infection in field conditions.

Growth measurements. Seventeen months after planting, from Sep 2019 to Oct 2020, canopy volume, density, height, and area of each tree were measured every 6 months through a geospatial digitization instrument (AGERpoint, Durham, NC, USA). These measurements were conducted using a mobile LiDAR scanner, mounted on a four-wheel-drive vehicle, positioned at a 35° off-nadir angle and 55° from the horizon. The vehicle traversed the experimental grove between rows at a speed of 8 to 11 km·h^{-1}. The LiDAR sensor captured data from trees on both sides of the scanner simultaneously. The LiDAR system employed was a Riegl VUX-SYS integrated mobile LiDAR scanner, equipped with an Inertial Measurement Unit (IMU) and Global Navigation Satellite System (GNSS). The system used a revolving mirror and a 1440-nm laser operating at a pulse repetition rate of 550 kHz, recording up to four returns per pulse. The scanner demonstrated accuracy and precision of 10 and 5 mm, respectively. GNSS and IMU trajectory data underwent post-processing with static base station data to achieve sub-decimeter positional accuracy for the vehicle trajectory. Proprietary algorithms were employed to segment individual trees from the point clouds. Following segmentation, a three-dimensional convex hull was fitted to the tree shape. The canopy volume aboveground was measured as the volume within this convex hull, whereas canopy density was determined as the ratio of points within the convex hull to the total number of laser firings at that location. Tree height was measured as the highest point of the hull (Suh et al. 2021).

Yield and fruit quality. At the harvest time (December 2019 and 2020), all fruits from the trees were handpicked and aggregated by experimental unit (sum of all fruits on the six data trees). The number of fruits from each plot was counted and the total fruit harvested from each plot and the means per tree were presented. A digital weighing balance (SD75L OHAUS, Parsippany, NJ, USA) of ±0.05 g precision was used. The mean fruit weight was calculated from the total fruit number and total fruit weight. Fruits were juiced and °Brix and titrated acidity (TA) of the juice were measured using a refractometer (Atago USA Inc, Pocket Brix-Acidity Meter, Great Northwest, WA, USA). To measure TA, the juice sample was first prepared by dilution. One gram of juice was weighed into a beaker on a scale, and the scale was set to zero. Purified water was then added to the beaker until the total weight reached 50 g, depending on the desired dilution ratio (1:50). For the titration, the beaker with the prepared dilution was placed on the scale, which was reset to zero. Next, 600 μL of the diluted sample were poured onto the sensor and measured using the TA setting. To measure Brix, 600 μL of undiluted juice were applied to the sensor and measured using the Brix setting.

Statistical analysis. The experimental design was a randomized complete block design with six blocks and four treatments. Statistical analyses of data were conducted using R (version 4.3.2; R Core Team 2024). Repeated measures two-way analysis of variance (ANOVA) was performed using the "lme4" package (Bates et al. 2014). Treatment and date were the fixed effects, whereas block was modeled as a random effect. Post hoc analyses were conducted with the "emmeans" package. Visualization of data, including line and bar graphs, was achieved using the "ggplot2" package (Wickham 2016), with

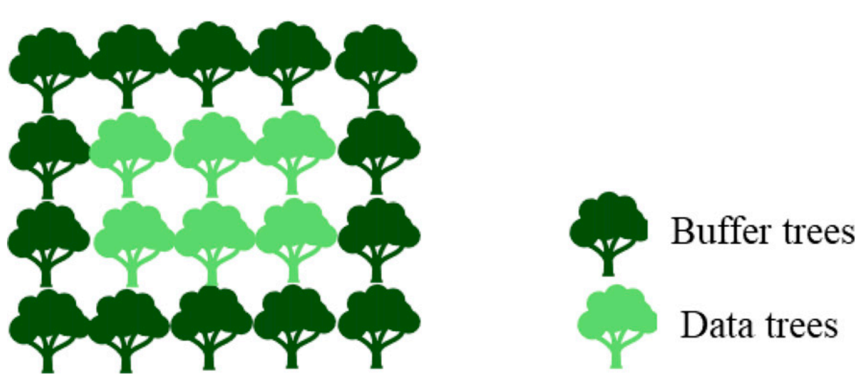

Fig. 1. The schematic illustrates each experimental unit, which comprises 20 trees. Six data trees located in the interior, and 14 buffer trees situated on the exterior.

data manipulation facilitated by the "dplyr" package (Wickham et al. 2023).

Results

Meteorological data. The environmental data during the months of Sep 2019 to Oct 2020 showed fluctuations in temperature, solar radiation, rainfall, and relative humidity (Fig. 2). The greatest contrast in conditions was between warm and rainy conditions in the summer to cooler and drier conditions in the fall and winter seasons, which is generally expected in Florida's climate. These general seasons corresponded to the times between growth measurements, presented subsequently. Particularly, from Sep 2019 to Mar 2020, weather transitioned from warm and sunny days to cooler temperatures along with variations in sunlight, rainfall, and humidity levels as winter approached, which might have posed some challenges for robust plant growth during these months. From Mar 2020 to Oct 2020, temperatures rose again, accompanied by increased sunlight hours. These conditions are typically favorable for citrus trees to thrive. However, we observed peaks in temperature and sunlight from May to August, which could potentially lead to heat stress and photoinhibition in citrus trees. From the first growth measurement period (Sep 2019 to Mar 2020), the total rainfall was 473.5 mm. This amount rose significantly to 1300.5 mm during the second growth measurement period (Mar 2020 to Oct 2020).

Effect of red and white PF application on growth. The repeated-measures ANOVA indicated that both treatment and date factors affected the growth variables of the trees, with a notable interaction effect for plant volume (Table 1). Trees treated with red-dyed PF were taller than white PF-treated trees, which were, in turn, taller than those treated with insecticide or no foliar insecticide. There were no significant differences for plant height between foliar insecticide and no foliar insecticide treatments (Fig. 3A). Red and white PF treatments affected plant volume and plant area, showing enhanced growth compared with foliar insecticide, and no foliar insecticide treatments. The plant volume and area increased over time for all treatments, but the increase was significantly more pronounced for PF-treated plants, and particularly for the red PF treatment, which showed greatest impact on plant area and volume in the later date of the measurement (Fig. 3B and C). These findings indicate that PF applications were more effective in increasing growth during the warmer season than the cooler one.

There were slight differences in canopy density among the treatments. The canopy density of red- and white-PF-treated trees were nearly identical to each other, except for the final date, when white-PF-treated trees had higher canopy density than red-PF-treated trees. Foliar insecticide and untreated control had slightly lower canopy density compared with the PF treatments. The impact of treatment on canopy density was more pronounced in Mar 2020 compared with other dates (Fig. 3D), suggesting that trees with no PF treatment lost more foliage during the cool, dry season of 2019 to 2020.

Effect of red and white PF application on yield. The repeated measures ANOVA indicated that the treatment and date factors and the interaction between treatment and date significantly affected yield (Table 2). In 2020, red- and white-PF-treated trees exhibited higher yield, and the lowest values were recorded in plants that were not sprayed with PFs (Fig. 4). PF-treated trees exhibited a substantial increase in yield from 2019 to 2020. Although trees with no PF showed increased yields in 2020, the yields for these treatments were still less than half of those achieved with PF treatments (Fig. 4). The trees with no PF exhibited extremely low fruit production in 2019, averaging less than one fruit per tree, which was not sufficient to gather fruit quality data (°Brix and TA). In 2019, there were no fruit quality differences between red- and white-PF-treated plants. Similarly, in 2020, no differences were found in fruit quality and Brix/TA ratio among treatments (Table 3).

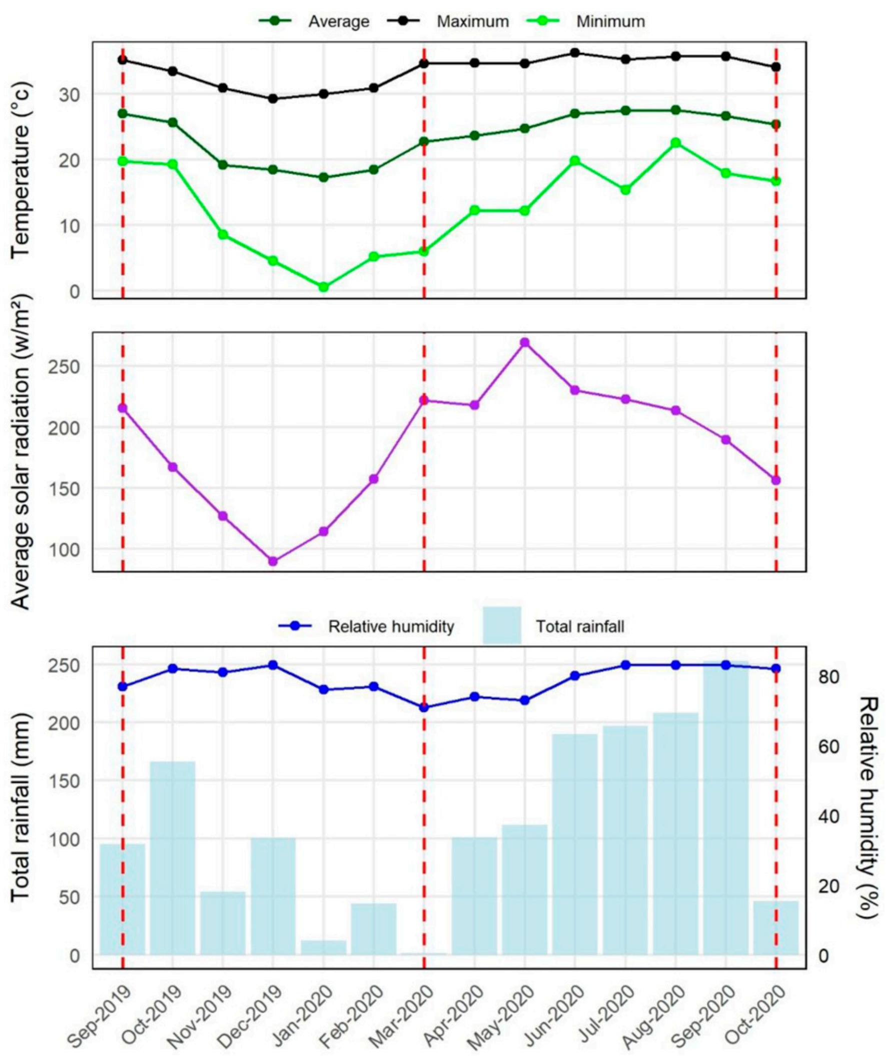

Fig. 2. Seasonal variations in temperature, solar radiation, total rainfall, and relative humidity during the growth measurements period from Sep 2019 to Oct 2020. Temperature measurements represent the averages of the daily maximum, minimum, and mean temperatures. Red dashed lines mark the months when growth measurements were taken.

Discussion

This study is the first to document the long-term effects of red photoselective kaolin PF and the first to report on the impact of any PF on the horticultural performance of HLB-infected citrus trees, from planting through to early yields. PFs had sustained positive effects on growth and yield of infected trees, with improvements ranging from 2 to 4 times greater than the insecticidal control. This may stem from previously demonstrated microenvironmental impacts of PFs on the leaf and canopy, from delaying HLB infection through vector suppression, or from the interaction of the microenvironmental effects with the effects of HLB on tree physiology (Jifon and Syvertsen 2003a; Pierre et al. 2021; Suh et al. 2021).

Kaolin PF effects on HLB-infected citrus growth and yield. The results of the current study are consistent with earlier findings that demonstrated the positive impact of white and red photoselective PFs on potted citrus

Table 1. Repeated-measures analysis of variance for growth variables of 'Hamlin' sweet orange (*Citrus ×sinensis*) trees on 'Kuharske' citrange (*C. sinensis × Poncirus trifoliata*) rootstock treated with red or white kaolin particle films, foliar insecticides, or untreated across 2019 and 2020 with block as a random effect.

Growth variables	Effect	*df*	Sum squares	*F* value	*P* value
Plant height	Treatment	3	13.02	108.46	<0.001
	Date	2	0.43	5.33	0.005
	Treatment × date	6	0.06	0.25	0.960
	Residuals	399	15.77		
Plant volume	Treatment	3	51.81	68.41	<0.001
	Date	2	68.78	136.24	<0.001
	Treatment × date	6	9.31	6.15	<0.001
	Residuals	399	99.54		
Plant area	Treatment	3	45.87	83.40	<0.001
	Date	2	34.99	95.43	<0.001
	Treatment × date	6	1.31	1.19	0.309
	Residuals	399	72.29		
Plant density	Treatment	3	0.42	22.89	<0.001
	Date	2	0.09	6.97	<0.001
	Treatment × date	6	0.01	0.37	0.899
	Residuals	399	2.43		

Table 2. Repeated-measures analysis of variance for yield of 'Hamlin' sweet orange (*Citrus ×sinensis*) trees on 'Kuharske' citrange (*C. sinensis × Poncirus trifoliata*) rootstock treated with red or white kaolin particle films, foliar insecticides, or untreated across 2019 and 2020.

Effect	*df*	Sum squares	*F* value	*P* value
Treatment	3	1628097	8.73	<0.001
Date	1	1270101	20.44	<0.001
Treatment × date	3	754648	4.05	0.014
Residuals	35	2174997		

tree growth (Salvatierra-Miranda et al. 2023), as well as the effects of white PF on citrus growth and yield in field plantings (Ennab et al. 2017; Lapointe et al. 2006). Whereas the referenced studies were performed on HLB-free citrus trees, our study focused on a young citrus planting with 100% HLB infection and strong ACP pressure, introducing a new dimension to the effects of PFs in citrus in the context of disease. Pierre et al. (2021), who reported ACP and HLB-infection results occurring earlier in the same experiment, noted a considerable increase in the trunk cross-sectional area of sweet orange trees after 17 months of applying both red and white PFs, despite HLB pressure. However, their study did not address long-term growth or yield. The current study examines the long-term horticultural impacts of using kaolin PFs on citrus, specifically focusing on performance following HLB infection. Our findings indicate that growth advantages persist even in the presence of existing infections.

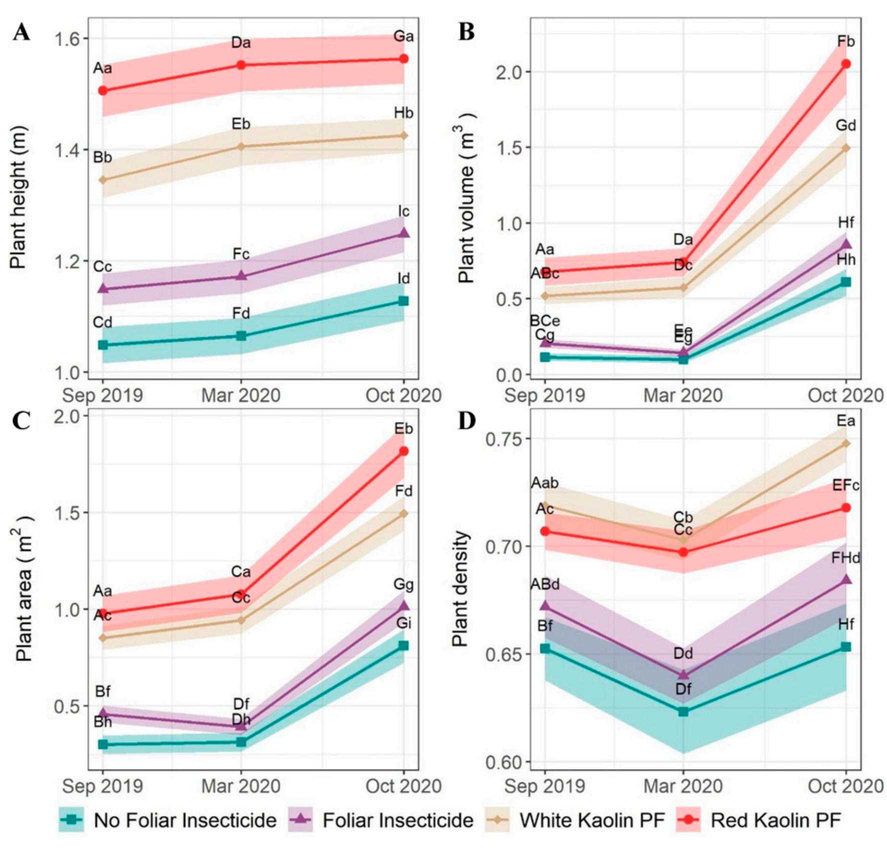

Fig. 3. The growth variables of 'Hamlin' sweet orange (*Citrus ×sinensis*) trees on 'Kuharske' citrange (*C. sinensis × Poncirus trifoliata*) rootstock treated with red or white kaolin particle films, foliar insecticides or untreated across 2019 and 2020. The shaded area surrounding each line graph represents the standard error about the mean. Different uppercase letters at each time point indicate differences between treatments at that specific time and different lowercase letters within one treatment designate differences over time for that particular treatment.

Red-colored PF generally resulted in higher growth-related variables compared with white PF, although these differences were not always statistically significant. The exception was canopy density, which was greater in trees treated with white PF. Lower canopy density of red PF-treated trees compared with white PF-treated trees may be attributed to lesser reflectance of red PF causing more shading within the canopy, which we discuss below.

Altered microenvironmental effects on physiology in the context of HLB. PFs consistently improved the growth and yield of infected trees, likely due to their known physiological effects on leaves by altering microenvironmental conditions. Kaolin PFs impact light intensity, leaf temperature, and leaf-air VPD, which positively impact photosynthesis and stomatal conductance (Jifon and Syvertsen 2003a; Salvatierra-Miranda et al. 2023). High temperatures and excessive light cause photoinhibition, stomatal closure, and reduced CO_2 assimilation, lowering growth and yield (Blanke 2000; Jifon and Syvertsen 2003b). High leaf temperatures also increase nonphotochemical quenching, further diminishing photosynthesis (Guha et al. 2022). Shading can mitigate these effects by reducing irradiance and leaf temperatures, enhancing photosynthesis and growth, including in the context of HLB-affected trees (Alarcón et al. 2006; Suh et al. 2021). Both red and white PFs provide shading, with red PFs offering a greater degree of shading. Salvatierra-Miranda et al. (2023) found that whereas white PF reduced irradiance by 56%, red PF achieved 74% shading at similar rates to those applied in this study. However, in the field, wind and rain remove the PF over time, reducing the degree of shading. Thus, the actual shading effect over time is likely to be much less than 50%.

Additionally, PFs alter the distribution of irradiance throughout the canopy. Leaves in the outer canopy face the challenge of excessive light exposure and frequent photoinhibition, requiring them to spend energy to protect against potential damage. Meanwhile interior leaves may undergo suboptimal light levels, reducing photosynthesis through insufficient light. PFs play a beneficial role by redirecting and reflecting light away

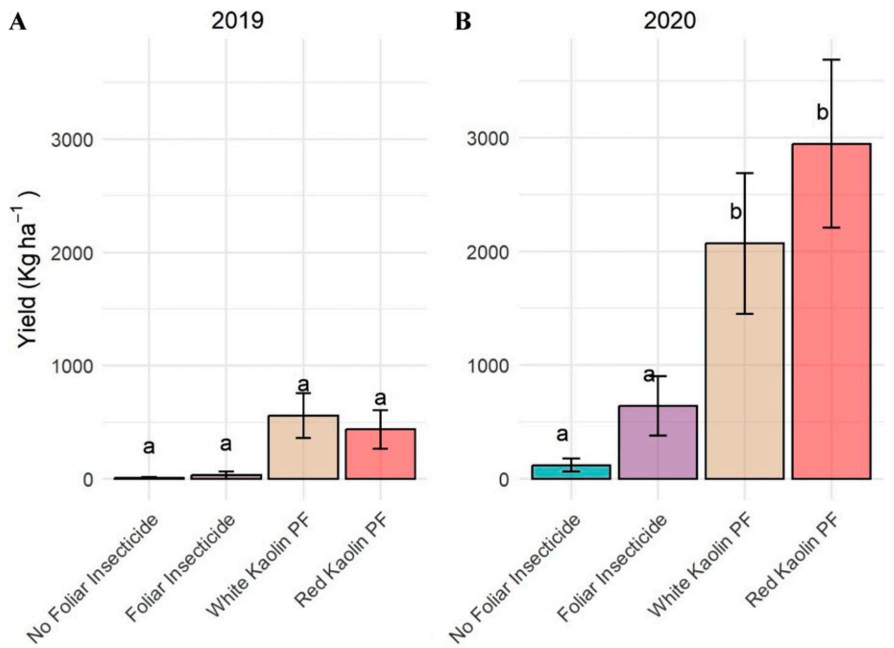

Fig. 4. Fruit yield of 'Hamlin' sweet orange (*Citrus* ×*sinensis*) trees on 'Kuharske' citrange (*C. sinensis* × *Poncirus trifoliata*) rootstock treated with red or white kaolin particle films, foliar insecticides, or untreated across 2019 (**A**) and 2020 (**B**). Different letters at each time point indicate differences between treatments at that specific time.

from and into the canopy, thereby alleviating excessive irradiance in the outer canopy and excessive shading in the inner canopy, increasing total canopy photosynthesis (Rosati et al. 2007).

In the present work, the lower canopy density to the red-PF-treated trees compared with the white-PF-treated trees indicates a possible shade-avoidance response, which may be due to both increased direct shading and decreased reflectance into the canopy. Salvatierra-Miranda et al. (2023) found that white and red photoselective PFs have different shading and reflectance characteristics. Red PF provides more shade and reflects less photosynthetically active radiation. However, that study did not observe an increase in shoot length or internode length, which would indicate a shade avoidance response. Nevertheless, the greater shading from the red PF might explain the lower canopy density seen in red-PF-treated trees. In a related study, Suh et al. (2021) discovered that shade netting reduced the canopy density of trees affected by HLB, even though it led to an overall increase in growth. The current study indicates that both PF treatments improved growth of HLB-infected trees, while the reduced canopy density in response to red PF may indicate a shade avoidance response due to supra-optimal shading, particularly due to reduced inner-canopy reflectance. The possible shading effects suggest that better understanding of rates and dyes could improve the efficacy of this tool. For example, a lower rate of red PF than that used in this study could be optimal.

Interaction of PFs physiological effects with HLB. Kaolin PFs appear to mitigate some of the physiological impacts of HLB on citrus trees by improving canopy density and reducing water stress. HLB infection leads to reduced photosynthesis and altered carbohydrate dynamics within citrus trees, ultimately resulting in the formation of sparse canopies (Achor et al. 2020; Bové 2006; Kim et al. 2009). It also decreases CO_2 assimilation by reducing photosynthetic surface area (Keeley et al. 2022). HLB impact on sugar transport leads to poorly developed roots (Johnson et al. 2012; Kumar et al. 2018) with reduced capacity for water and nutrient uptake (Kadyampakeni et al. 2014; Shahzad et al. 2020), increasing water deficit and reducing stomatal conductance (Keeley et al. 2022). The shading effect of PFs can help balance water demand and carbohydrate supply, improving citrus photosynthesis. As highlighted by Vincent et al. (2021a), natural shade improves citrus photosystem II performance and reduces evidence of HLB symptoms. Suh et al. (2021) showed that moderate shading from shade nets alleviated sink limitation of HLB-infected trees in the field and boosted photosystem efficiency and leaf carbon fixation, leading to better growth and yield despite HLB. Kaolin PFs, by lowering canopy temperature, help retain water without reducing stomatal conductance (Jifon and Syvertsen 2003a; Salvatierra-Miranda et al. 2023). Thus, PFs may benefit HLB-affected trees by alleviating HLB-induced leaf water deficits. In the present work, the maintenance of canopy density with PFs during the low-rainfall period between 2019 and 2020 supports this hypothesis.

PF effects on pest and disease. The results in terms of total growth and yield may also be attributed to PFs impacts on ACP populations. Pierre et al. (2021) reported that in the first 2 years of this experiment, ACP populations were reduced by PF treatments. This resulted in delayed infection with *C*Las, resulting in a temporary growth rate benefit to disease-free trees in PF treatments. Additionally, ACP feeding on citrus leaves or reproduction negatively impacts health and yield, even in already-infected trees (Tansey et al. 2017); thus, the PFs could improve growth of trees before and after *C*Las infection in the present study due to reduced pest populations, as reported in Pierre et al. (2021). The lower yield and fruit numbers in non-PF treatments may therefore be partially due to the earlier *C*Las infection, along with the negative effects of ongoing ACP feeding and reproduction. Johnson et al. (2012) noted that the symptoms on infected trees are influenced by tree age, as well as the timing and phase of infection. If this hypothesis is correct, our findings suggest that implementing kaolin PFs immediately after planting citrus trees could enhance growth directly and help delay *C*Las infection. However, the effects of PFs on ACP infestation and *C*Las infection do not fully account for the results of this study. Despite a 100% *C*Las infection rate, we observed that PF-treated plants exhibited greater growth and yield compared with those without PFs, including improved foliar retention during the spring of 2020. Although we

Table 3. Fruit number (number/tree), average fruit weight (g), and fruit quality (°Brix, TA, and Brix/TA ratio) measurements of 'Hamlin' sweet orange (*Citrus* ×*sinensis*) trees on 'Kuharske' citrange (*C. sinensis* × *Poncirus trifoliata*) rootstock treated with kaolin particle films, foliar insecticides, and no foliar insecticides across 2019 and 2020.

	Fruit (number/tree)		Avg fruit wt (g)		°Brix		TA		Brix/TA
Treatment	2019	2020	2019	2020	2019	2020	2019	2020	2020
Red Kaolin PF	6.50 a	40.50 a	102.3 a	120.98 a	7.64 a	7.85 a	2.83 a	3.63 a	2.16 a
White Kaolin PF	7.67 a	27.50 ab	118.62 a	114.64 a	7.55 a	8.38 a	3.48 a	3.93 a	2.13 a
Foliar insecticides	0.67 a	9.33 bc	80.00 ab	101.05 b	NA	6.86 a	NA	3.10 a	2.21 a
No foliar insecticides	0.33 a	2.00 c	45.50 b	105.00 ab	NA	7.03 a	NA	3.26 a	2.16 a

NA = not available data; PF = particle films; TA = titrated acidity.

Different letters within each column indicate significant differences at $P \leq 0.05$.

did not measure ACP populations at that time, it is important to note that ACP numbers are generally low during the preceding months due to cooler temperatures and limited new shoots for ACP reproduction (Pierre et al. 2021).

Conclusion

Kaolin PFs promote the growth of trees affected by HLB and result in increased yields. This is due to their beneficial effects on plant physiology and pest management, resulting in growth or yield improvements that are 2 to 4 times greater than those achieved with insecticidal control. PFs is a shade treatment that decreases leaf temperature, increases water use efficiency, and facilitates better photosynthesis in citrus canopies. It further improves growth, protects citrus against the spread of HLB, and reduces water demand of trees already infected with HLB. The present study suggests that the use of PF treatments, especially red-dyed PF, can be a valuable strategy for citrus growers aiming to mitigate the impact of HLB and enhance the overall health and productivity of their orchards. The sustained positive effects observed from years 2 to 4 after planting highlight the efficacy of PF treatments in promoting the health of sweet orange trees. However, further research and field trials may be needed to validate these findings across different environmental conditions and citrus varieties, assess whether the positive impacts of PFs under HLB differ from those of uninfected trees, and determine what rates of PFs confer the maximum benefit. Considering the physiological effects, we can hypothesize that the advantages or disadvantages may vary depending on the season and rate of application. For instance, low rainfall may enhance the benefits, whereas cool temperatures may attenuate the benefits of PF applications. The benefits, however, are strong, ultimately resulting in strong increases in yield of sweet orange plantings under high HLB pressure.

References Cited

Achor D, Welker S, Ben-Mahmoud S, Wang C, Folimonova SY, Dutt M, Gowda S, Levy A. 2020. Dynamics of *Candidatus* Liberibacter asiaticus movement and sieve-pore plugging in citrus sink cells. Plant Physiol. 182(2):882–891. https://doi.org/10.1104/pp.19.01391.

Alarcón JJ, Ortuno MF, Nicolás E, Navarro A, Torrecillas A. 2006. Improving water-use efficiency of young lemon trees by shading with aluminised-plastic nets. Agric Water Mgmt. 82(3):387–398. https://doi.org/10.1016/j.agwat.2005.08.003.

Bates D, Mächler M, Bolker B, Walker S. 2014. Fitting linear mixed-effects models using lme4. arXiv preprint 1406.5823. https://doi.org/10.48550/arXiv.1406.5823.

Blanke MM. 2000. Photoinhibition in citrus. Proc Intl Soc Citriculture. 1:619–622.

Blaustein RA, Lorca GL, Teplitski M. 2018. Challenges for managing *Candidatus* Liberibacter spp. (huanglongbing disease pathogen): Current control measures and future directions. Phytopath. 108(4):424–435. https://doi.org/10.1094/PHYTO-07-17-0260-RVW.

Bové JM. 2006. Huanglongbing: A destructive, newly-emerging, century-old disease of citrus. J Plant Path. 88(1):7–37. https://www.jstor.org/stable/41998278.

Chamchaiyaporn T, Jutamanee K, Kasemsap P, Vaithanomsat P, Henpitak C. 2013. Effects of kaolin clay coating on mango leaf gas exchange, fruit yield and quality. Agric Nat Resources. 47(4):479–491. https://li01.tci-thaijo.org/index.php/anres/article/view/243088.

Cruz J, Ferreira JP, Court C, McDaid K. 2024. 2020–2021 Economic Contributions of the Florida Citrus Industry: FE1155, 8/2024. EDIS. 2024(4). https://doi.org/10.32473/edis-fe1155-2024.

Collins JM, Rohli RV, Paxton CH. 2017. Florida weather and climate: More than just sunshine. University Press of Florida, Gainesville, FL, USA. https://doi.org/10.2307/j.ctvx06wfz.

Dinis LT, Malheiro AC, Luzio A, Fraga H, Ferreira H, Gonçalves I, Pinto G, Correia CM, Moutinho-Pereira J. 2018. Improvement of grapevine physiology and yield under summer stress by kaolin-foliar application: Water relations, photosynthesis and oxidative damage. Photosynthetica. 56(2):641–651. https://doi.org/10.1007/s11099-017-0714-3.

Ennab HA, El-Sayed SA, El-Enin MM. 2017. Effect of kaolin applications on fruit sunburn, yield and fruit quality of Balady mandarin (*Citrus reticulata*, Blanco). Menoufia J Plant Prod. 2(2):129–138. https://doi.org/10.21608/mjppf.2017.176024.

Glenn DM. 2009. Particle film mechanisms of action that reduce the effect of environmental stress in 'Empire' apple. J Am Soc Hortic Sci. 134(3):314–321. https://doi.org/10.21273/JASHS.134.3.314.

Guha A, Vharachumu T, Khalid MF, Keeley M, Avenson TJ, Vincent C. 2022. Short-term warming does not affect intrinsic thermotolerance but induces strong sustaining photoprotection in tropical evergreen citrus genotypes. Plant Cell Environ. 45(1):105–120. https://doi.org/10.1111/pce.14215.

Hall DG, Lapointe SL, Wenninger EJ. 2007. Effects of a particle film on biology and behavior of *Diaphorina citri* (Hemiptera: Psyllidae) and its infestations in citrus. J Econ Entomol. 100(3):847–854. https://doi.org/10.1093/jee/100.3.847.

Hodges AW, Spreen TH. 2012. Economic impacts of citrus greening (HLB) in Florida, 2006/07–2010/11: FE903/FE903, 1/2012. EDIS. 2012(1). https://doi.org/10.32473/edis-fe903-2012.

Jifon JL, Syvertsen JP. 2003a. Kaolin particle film applications can increase photosynthesis and water use efficiency of 'Ruby Red' grapefruit leaves. J Am Soc Hortic Sci. 128(1):107–112. https://doi.org/10.21273/JASHS.128.1.0107.

Jifon JL, Syvertsen JP. 2003b. Moderate shade can increase net gas exchange and reduce photoinhibition in citrus leaves. Tree Physiol. 23(2):119–127. https://doi.org/10.1093/treephys/23.2.119.

Johnson E, Bright DB, Graham JH. 2012. Early root infection and damage in citrus huanglongbing disease development. Phytopathology. 102(7):54–59. https://doi.org/10.5070/C411025181.

Kadyampakeni DM, Morgan KT, Schumann AW. 2014. Root density distribution and water uptake of citrus trees infected with huanglongbing. Proc Florida State Hortic Soc. 127:37–41.

Keeley M, Rowland D, Vincent C. 2022. Citrus photosynthesis and morphology acclimate to phloem-affecting huanglongbing disease at the leaf and shoot levels. Physiol Plantarum. 174(2):e13662. https://doi.org/10.1111/ppl.13662.

Kim JS, Sagaram US, Burns JK, Li JL, Wang N. 2009. Response of sweet orange (*Citrus sinensis*) to '*Candidatus* Liberibacter asiaticus' infection: Microscopy and microarray analyses. Phytopathology. 99(1):50–57. https://doi.org/10.1094/PHYTO-99-1-0050.

Kumar N, Kiran F, Etxeberria E. 2018. Huanglongbing-induced anatomical changes in citrus fibrous root orders. HortScience. 53(6):829–837. https://doi.org/10.21273/HORTSCI12390-17.

Lapointe SL, McKenzie CL, Hall DG. 2006. Reduced oviposition by *Diaprepes abbreviatus* (Coleoptera: Curculionidae) and growth enhancement of citrus by Surround particle film. J Econ Entomol. 99(1):109–116. https://doi.org/10.1093/jee/99.1.109.

McKenzie CL, Lapointe SL, Hunter WB, Puterka GJ. 2002. Efficacy of Surround® for control of Asian citrus psyllid on citrus, 2000. Arthropod Mgmt Tests. 27(1):D8. https://doi.org/10.1093/amt/27.1.D8.

Miranda MP, Zanardi OZ, Tomaseto AF, Volpe HX, Garcia RB, Prado E. 2018. Processed kaolin affects the probing and settling behavior of *Diaphorina citri* (Hemiptera: Lividae). Pest Manag Sci. 74(8):1964–1972. https://doi.org/10.1002/ps.4901.

Moudgil BM, Musella SC, Etxeberria E, Rogers ME, Brodersen CR, Sharma P, University of Florida Research Foundation Inc. 2017. Colored clays for agricultural and other industrial applications. U.S. Patent 9,763,440.

Pierre MO, Salvatierra-Miranda J, Rivera MJ, Etxeberria E, Gonzalez P, Vincent CI. 2021. White and red-dyed kaolin particle films reduce Asian citrus psyllid populations, delay huanglongbing infection, and increase citrus growth. Crop Prot. 150:105792. https://doi.org/10.1016/j.cropro.2021.105792.

R Core Team. 2024. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.r-project.org/.

Rosati A, Metcalf SG, Buchner RP, Fulton AE, Lampinen BD. 2006. Physiological effects of kaolin applications in well-irrigated and water-stressed walnut and almond trees. Ann Bot. 98(1):267–275. https://doi.org/10.1093/aob/mcl100.

Rosati A, Metcalf SG, Buchner RP, Fulton AE, Lampinen BD. 2007. Effects of kaolin application on light absorption and distribution, radiation use efficiency and photosynthesis of almond and walnut canopies. Ann Bot. 99(2):255–263. https://doi.org/10.1093/aob/mcl252.

Salvatierra-Miranda J, Toussaint SB, Pierre MO, Vincent CI. 2023. Photoselective particle films influence physiology and growth of citrus. Sci Hortic. 315:111973. https://doi.org/10.1016/j.scienta.2023.111973.

Saour G. 2005. Efficacy of kaolin particle film and selected synthetic insecticides against pistachio psyllid *Agonoscena targionii* (Homoptera: Psyllidae) infestation. Crop Prot. 24(8):711–717. https://doi.org/10.1016/j.cropro.2004.12.007.

Shahzad F, Chun C, Schumann A, Vashisth T. 2020. Nutrient uptake in huanglongbing-affected sweet orange: Transcriptomic and physiological analysis. J Am Soc Hortic Sci. 145(6):349–362. https://doi.org/10.21273/JASHS04929-20.

Suh JH, Guha A, Wang Z, Li SY, Killiny N, Vincent C, Wang Y. 2021. Metabolomic analysis elucidates how shade conditions ameliorate the deleterious effects of greening (huanglongbing) disease in citrus. Plant J. 108(6):1798–1814. https://doi.org/10.1111/tpj.15546.

Tansey JA, Vanaclocha P, Monzo C, Jones M, Stansly PA. 2017. Costs and benefits of insecticide and foliar nutrient applications to huanglongbing-infected citrus trees. Pest Manag Sci. 73(5):904–916. https://doi.org/10.1002/ps.4362.

Vincent C, Guha A, Killiny N, Diepenbrock L. 2021a. Understory environment promotes photosynthetic efficiency and mitigates severity and function of an introduced, vectored pathosystem: A study of a feral citrus population in central Florida. Trees. 35(5):1711–1725. https://doi.org/10.1007/s00468-021-02147-2.

Vincent CI, Pierre M, Miranda JS, Etxeberria EJ, University of Florida Research Foundation Inc. 2021b. Dye-containing kaolin compositions for crop protection and improving plant physiology. U.S. Patent Application 17/279,786.

Wickham H. 2016 ggplot2: Elegant graphics for data analysis. Springer, Cham, Switzerland. https://doi.org/10.1007/978-3-319-24277-4_9.

Wickham H, François R, Henry L, Müller K, Vaughan D. 2023. dplyr: A grammar of data manipulation. R package version 1.1. 2. Computer software. https://doi.org/10.32614/CRAN.package.dplyr.