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Case Report

Achievements and Challenges in Controlling Coffee Leaf Rust (*Hemileia vastatrix*) in Hawaii

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Abstract: In this case study, the current situation faced by coffee growers attempting to control coffee leaf rust (*Hemileia vastatrix*) in Hawaii is reported. CLR is considered the most devastating disease affecting coffee crops worldwide and was detected in Hawaii in 2020. Three small coffee farms from the South Kona district of Hawaii Island were selected. The goals of this case study were to: (1) assist coffee growers in the early detection of CLR incidence, and consequently support farmers with recommendations for control, (2) record agronomic information and management practices, and (3) estimate the cost to control CLR during 2021 and 2022 seasons. Low CLR incidence (<4%) was initially observed at all farms (January–June 2021), but increased as the harvest began, ending the season (December 2021) at 77%, 21% and 6% incidence at farms 1, 2 and 3, respectively. At the end of 2022 season (December), CLR incidence reached 43%, 20% and 3% at farms 1, 2 and 3, respectively. The number of sprays per season (5–10), the type of fungicides applied (preventive, curative), the timing of sprays, the efficacy of applications and weather conditions all played a role in determining the infection rates at each farm. Effective control of CLR is possible in Hawaii if the sprays of fungicides are carried out with the right products, appropriate timing and good coverage.

Keywords: agroecosystems; coffee farms; *Coffea arabica*; plant pathogen; disease incidence; fungicides; integrated pest management; control cost

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1. Introduction

After coffee leaf rust (CLR), *Hemileia vastatrix* Berk and Broome (Basidiomycota, Pucciniales) was detected and reported on Maui, Hawaii in late 2020 [1], coffee growers have suffered the ravages of this devastating plant-pathogenic fungus, which spread very quickly throughout the coffee-producing islands of the Hawaiian archipelago in just 12 months [2]. Efforts by state and federal agencies, non-governmental organizations, coffee growers associations and the whole Hawaii coffee industry are aimed at preventive management and control of CLR in the short, medium and long term. CLR is the most damaging airborne pathogen fungus affecting commercial coffee crops in Brazil, Colombia, Central America and worldwide [3–6]. Trees affected by CLR showed a reduction in photosynthesis and a decrease in yield (10–80%), due to the increase in infection and severity on leaves and the consequent defoliation [5]. Originally from Africa, *H. vastatrix* is an obligate pathogen that only targets species from the genus *Coffea* [5–8]. Spores of the fungus known as uredospores are deposited on coffee leaves by wind, rainfall, animals, insects and human activities [4–6]. Favorable conditions for uredospores to start the germination process include temperatures of 20–25 °C, water available during 6 h on coffee leaf surfaces and absence or low luminosity [4,6]. After germination has started, the structures of the fungus start to take nutrients for its development and reproduction [4,6]. Small yellow spots, which are the initial symptom of the disease, appear on the upper leaf surface. After 25–35 days, lesions with yellow-orange pustules appear on the lower leaf surface and produce the sporulation of the fungus [4,6]. Dissemination of the uredospores occurs and the cycle of the disease starts again. During the season, the fungus develops polycyclic epidemics causing a permanent infection on susceptible coffee tree varieties [4,8].

Experiences from other coffee producing regions have shown that the best long-term solution is the establishment of CLR resistant varieties [7–12]. In the short and medium term, control is primarily through the use of fungicides and the implementation of agronomic practices that affect the survival of the fungus, but improve the health of coffee trees [13–16]. Those agronomic practices include sanitation, pruning, weed control, fertilization and regulation of shade.

Unfortunately, 99% of commercial coffee crops in Hawaii are planted with susceptible varieties to CLR and the coffee industry was not prepared for the arrival of *H. vastatrix*. Management of CLR in Hawaii is currently focused on the improvement of agronomic practices and sprays of preventive and curative fungicides, while the introduction and establishment of CLR resistant varieties is carefully and safety conducted.

The unique location of the Hawaiian Islands in the middle of the Pacific Ocean, the volcanic soils and the high variety of microclimates result in one of the best coffees around the world. Coffee produced in the Kona and Ka'u districts are recognized for their high quality, receiving premium value in the specialty market. *Coffea arabica* L. (Gentianales: Rubiaceae) is the most common species of coffee grown in Hawaii with commercial varieties such as Typica, Caturra, Bourbon, Yellow Catuai, Red Catuai, Mondo Novo [17] and Geisha. However, all of these are susceptible to CLR. The Hawaii coffee industry is socio-economically important for the state. There are around 1000 coffee growers, who cultivate approximately 3000 ha of commercial coffee across the islands. The value of coffee produced in Hawaii was estimated at USD 113 million during the 2021 season [18].

CLR monitoring was initiated in January 2021 at 30 coffee lots from Kona, West Hawaii Island and results for the first year of CLR incursion were reported by Aristizábal & Johnson [2]. Evaluations are still in progress at coffee farms in Kona, Ka'u and Hilo districts of Hawaii Island. This article documents the management of CLR at coffee farms in South Kona during coffee seasons 2021 and 2022. The initial goal of this field study was to assist coffee growers in the early detection of CLR (2021 coffee season) through monitoring the disease incidence and collecting information about agronomic practices conducted by coffee farmers to suppress CLR. The second goal was to compare the CLR incidence and management of the disease during 2021 and 2022 coffee seasons at three contrasting coffee farms in South Kona. Finally, the third goal was to estimate the cost to control the disease based on sprays of fungicides (products plus labor) and monitoring. The total cost to control CLR was estimated as the percentage or profit per acre (sold coffee yield) spent each year (2021 and 2022) controlling the disease. Since the CLR was recently detected in Hawaii, there are limited field studies that show the best practices for managing the disease in Hawaiian coffee agroecosystems. Therefore, this case study addresses the lack of information that applies directly to coffee farmers in Hawaii and strengthens the management of CLR in other places where coffee is grown.

2. Materials and Methods

2.1. Location

This study was conducted at three small coffee farms (0.5–3 ha) located in the South Kona district of Hawaii Island. Characteristics of coffee farms are shown in Table 1 and Figure 1A–C. The temperature on average was 21.1 ± 0.3 °C, the relative humidity on average was 84.5 ± 0.6% and the annual precipitation was 1159 mm. Data from a manual weather station consisting of a Hobo Pro V2 temperature/RH data logger (Onset Computer Corporation, Bourne, MA, USA) and rain gauge equipment with a manual data logger (Rain Wise Inc., Boothway, PA, USA) installed at farm 1.

Table 1. Characteristics of three coffee farms in this case study, located in the South Kona district of Hawaii Island, Hawaii, USA.

Farm	Location	Elevation (m)	Area (ha) planted	Coffee varieties	Density (Trees/ha)	Age (yrs)	Shade Trees *	Management **	Terrain (Inclination)
1	Captain Cook	610	2	Typica	1625	100	Yes	C-O	Rocky (15%)
2	Honaunau	454	1.5	Typica	2250	25	No	C	Rocky (18%)
3	Milolli	457	0.5	Typica	2000	50	Yes	C	Rocky (5%)

* Shade trees include avocado, macadamia nut, cocoa, citrus, guava, native tropical trees and banana plants. ** Management: C = conventional and O = organic.

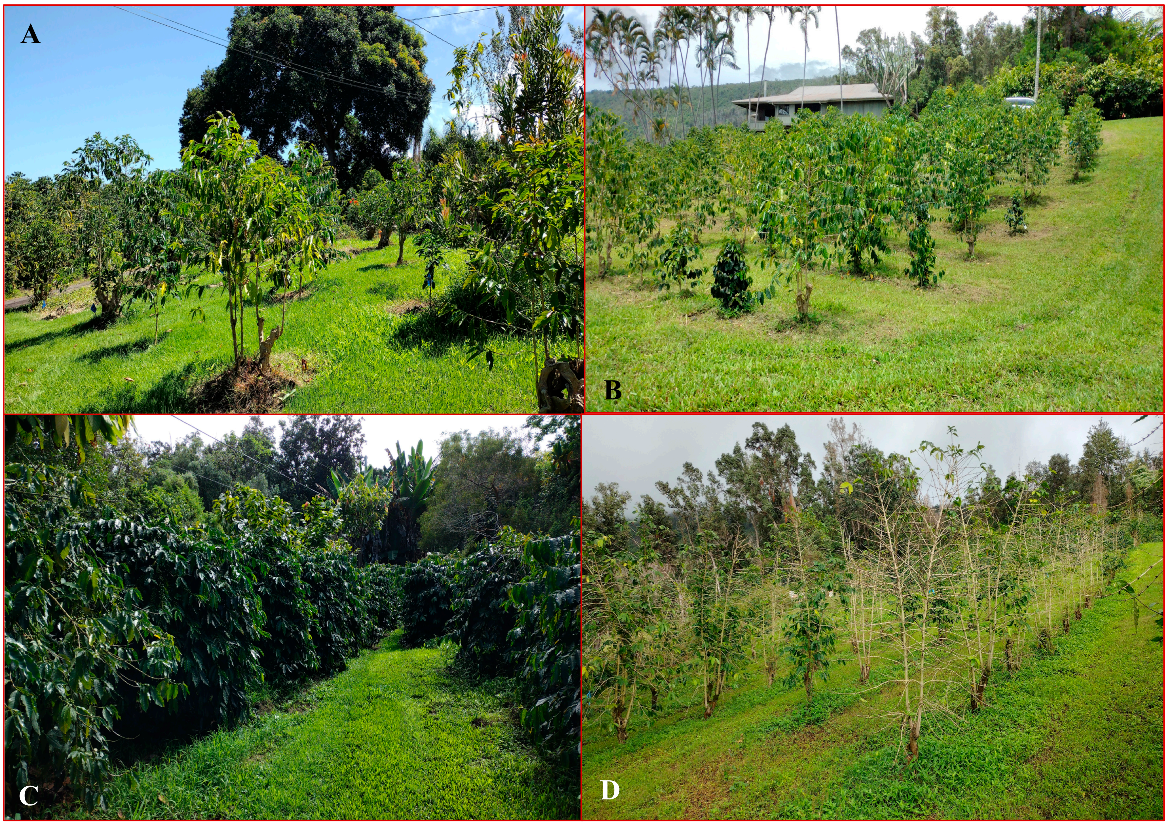

Figure 1. Coffee farms located in South Kona district of Hawaii Island, Hawaii, USA: farm 1, located in Captain Cook (**A**), farm 2, located in Honaunau (**B**), and farm 3, located in Milolli (**C**) villages, respectively. Coffee trees at the end of harvesting season (December) with high defoliation caused by CLR infection (**D**).

2.2. Monitoring CLR Incidence

The identification of CLR and the determination of CLR incidence (%) plus severity of the infection was conducted through a standardized methodology previously reported in Hawaii by Aristizábal & Johnson [2,19]. According to Rivillas et al. [4], a similar methodology for monitoring CLR incidence was conducted in Colombia on 60 trees per ha and on three branches per tree (total 180 branches) with densities of 5000–10,000 trees per ha. However, since the density of trees planted in Hawaii is low (1200–2500 trees per ha), the sampling plan was conducted on 25 trees per ha and two branches per tree (total 50 branches). For monitoring the CLR incidence, in each coffee lot, 25 coffee trees were randomly selected following a zig-zag path across the field. Two branches were randomly selected per tree: one located in the mid-canopy of the tree and the second one in the lower canopy. All fully developed leaves per branch were counted and recorded. Then, all coffee leaves showing active sporulation of CLR (yellowish-orangish powdery lesions) on the underside of leaves were counted and recorded as positive for infection (Figure 2A,B). The incidence of CLR infection (%) was estimated as the total number of infected leaves divided by the total number of leaves counted and then multiplied by 100.

Figure 2. Monitoring CLR infection with the participation of coffee growers (**A**), and detecting the initial infection and sporulation of CLR on a coffee leaf (**B**). Spraying a fungicide using a backpack mist blower sprayer and wearing all personal protection equipment (PPE) (**C**).

A strong positive correlation between CLR incidence and severity was reported in other coffee producing regions [20–23] and a similar correlation was found in the first survey of CLR in Hawaii [2]. Therefore, no assessments of CLR severity were conducted in this study.

The total number of coffee leaves per branch was used to estimate defoliation. In each coffee lot, the average of the total number of coffee leaves per branch recorded during each coffee season (2021 and 2022) was compared to estimate foliage reduction. During the 2021 coffee season, the survey for monitoring CLR was conducted every two months, while during the 2022 coffee season monthly evaluations were conducted. Field evaluations for monitoring CLR incidence were conducted with the collaboration of growers, with whom the findings, observations and recommendations were discussed. However, the spray of fungicides to control CLR and the implementation of agronomic practices recommended for improving the health of trees were conducted at the discretion of the growers.

2.3. CLR Management

The management of CLR relied on the application of fungicides and the implementation of appropriate agronomic practices [4,9,11] such as weed control, fertilization, pruning, regulation of shade (trees associated with coffee crops), etc. When CLR was detected in Hawaii (2020), several preventive copper-based fungicides (copper hydroxide and copper oxychloride) and *Bacillus* fungicides (*B. subtilis* and *B. amyloliquefaciens*) were registered to be used in coffee crops to control *H. vastatrix* (CLR) and other plant pathogens such as *Cercospora coffeicola* (brown eyespot) (Table 2). In addition, a translaminar fungicide (Priaxor® Xemiun®) was approved for use through an emergency declaration by the Hawaii Department of Agriculture (HDOA) in 2021 (Table 2).

Table 2. List of fungicides and foliar fertilizers used by coffee growers during the 2021 and 2022 coffee seasons. Additional fungicides are approved in Hawaii by the HDOA, but not listed in this table.

Brand Name	Manufacturer/Location	Active Ingredient	Dose /Acre	Maximun Annual Rate/Acre	Restricted Entry Interval (REI)
Serenede ASO	Bayer CropScience St. Louis, Missouri, USA	QST 713 strain *Bacillus subtilis*	64–128 Fl oz	NA	4 h
Double Nickel 55	Certis Biologicals Columbia, Missouri, USA	*Bacillus amyloliquefaciens* strain D747	0.25–3 lb	NA	4 h
Badge X2	Isagro USA Inc. Morrisville, North Caroline, USA	Copper Oxychloride 23.83% Copper Hydroxide 21.49%	1–3 lb	45 lb	24 h
Kocide 3000	Certis Biologicals Columbia, Missouri, USA	Copper Hydroxide 46.1%	0.75–1.75 lb	42 lb	48 h
OxiDate 2	BioSafe Systems Hartford, Connecticut, USA	Hydrogen Dioxide 27.1% Peroxyacetic Acid 2%	32 Fl oz	NA	1 h
Priaxor Xemium	BASF Research Triangle Park, North Caroline, USA	Fluxapyroxad 14.33% Pyraclostrobin 28.58%	7.14 Fl oz	14.28 Fl oz	12 h
* Cafedak	Sustainable Agro Solutions S.A. Almacelles-Lleid, Spain	Micronutrients: B (0.4%), Fe (2%), Mn (0.5%), Mo (0.2%), Zn (2%)	64–160 Fl oz	NA	NA
* Tropical TM Metalosate	Abion Laboratories, Inc. Clearfield, Utah, USA	Nutrients: N (1.5%), Mg (0.5%), B (1%), Fe (0.66%), Mo (0.1%), Zn (2%)	16–32 Fl oz	NA	NA

* Foliar fertilizers, used to support nutrition of coffee trees, were mixed with fungicides applied to control CLR in Hawaii. Conversions: 1 acre = 0.4 ha; 1 fluid ounce = 29.54 mm; and 1 lb = 0.454 kg.

At all three coffee farms, the application of fungicides and foliar fertilizers was conducted with the use of a mist blower backpack sprayer (3.75 gallon capacity), STIHL SR 450, (STIHL Incorporated, Virginia Beach, VA, USA). Around 8–10 tank sprayers were used to cover 1 acre, which correspond to 30–38 gallons (114–144 L) of water per acre or 75–95 gallons (284–360 L) of water per ha (Figure 2C). Doses of fungicides were applied in concordance with the label of each product (Table 2). Coffee farmers and field workers used personal protection equipment (PPE) during the sprays of products and a restricted entry interval (REI) was followed according to the regulations (Table 2, Figure 2C).

2.4. Cost to Control CLR with Fungicides

During both coffee seasons (2021 and 2022), records for the control of CLR through the use of fungicides were analyzed. Those records include cost for the management of CLR, the number of sprays, amount of products used per acre (fungicides and foliar fertilizers), labor cost and fuel use for the sprayer. The use of insecticides to control the coffee berry borer (CBB, *Hypothenemus hampei*) that were mixed with fungicides were not included in the economic analysis. The cost for monitoring CLR was estimated as $25 per survey, which was conducted every two months (2021) or monthly (2022). Coffee yield (cherries produced per acre) was recorded for each coffee season. The prices for selling coffee cherries were USD 2.40 per lb in 2021 and USD 2.55 per lb in 2022, respectively (prices from Greenwell Farms, a major buyer in Kona). The proportion of cost to control CLR was estimated on coffee production per acre per season, value of coffee cherries per lb in each coffee season and the cost of sprays during the entire season. In other words, the number of coffee cherry pounds needed to pay for the total cost of sprays (fungicides and foliar fertilizers) was used to estimate the proportion of coffee yield that is equivalent to the CLR control cost during each coffee season. This was the real proportion cost to control CLR based on coffee production per acre and per season.

2.5. Data Analysis

For each coffee farm, descriptive analysis was conducted to estimate the mean of CLR incidence and the mean number of leaves per branch and the standard error of the means (SEM) for each coffee season (2021 and 2022). A comparison of mean CLR incidence and the mean number of coffee leaves per branch among the coffee farms was conducted using a Kruskal–Wallis test for non-parametric data. The Dunn's multiple comparison test was then conducted to determine differences among coffee farms. A formal statistical test was not conducted since no control group was available due to the high risk of CLR infection and potential yield losses. Funds were not available to compensate farmers for economic losses. All statistical analyses were conducted with the stats package in R v. 3.5.2 [24].

3. Results

3.1. CLR Incidence

During the first survey for monitoring CLR incidence conducted in January–February 2021, the pathogen was detected at farms 1 and 2, while it was detected during March–April at farm 3. In all three farms the CLR was relatively low (<4%) until July–August (Figure 3 and Supplementary Data S1). However, CLR incidence rapidly increased during the harvest season (second half of 2021) reaching a maximum peak during November–December (end of harvest season). The CLR incidence reached 77% at coffee farm 1, while it was 21% at farm 2 and 6% at farm 3 (Figure 3). According to the Kruskal–Wallis test, there was a significant difference in CLR incidence among coffee farms (X^2 = 21.88, df = 5, p < 0.001) during both seasons. The Dunn's test for multiple comparisons showed significant differences in CLR incidence between farm 1 and farms 2 (p < 0.001) and 3 (p < 0.0001), but no difference was found between farms 2 and 3 (p < 1) (Figure 4). At the beginning of 2022, the CLR incidence remained high at all three coffee farms, and was similar to the peak from the previous season. However, a quick decline of the disease was observed at coffee farms 2 and 3 during the early season (February–July), as a result of preventive and translaminar fungicide sprays. In contrast, a slow decline of CLR incidence at coffee farm 1 was observed, which was the result of high defoliation caused by the pathogen as well as what appeared to be the natural decline of CLR across Kona during the first half of 2022 (Figure 1D). An increase in CLR incidence was observed during the second half of 2022 on farms 1 and 2, and especially at the end of harvest season (November–December) reaching 43% and 20% incidence, respectively. In contrast, the increase in CLR incidence on coffee farm 3 was low, reaching only 3% in December 2022.

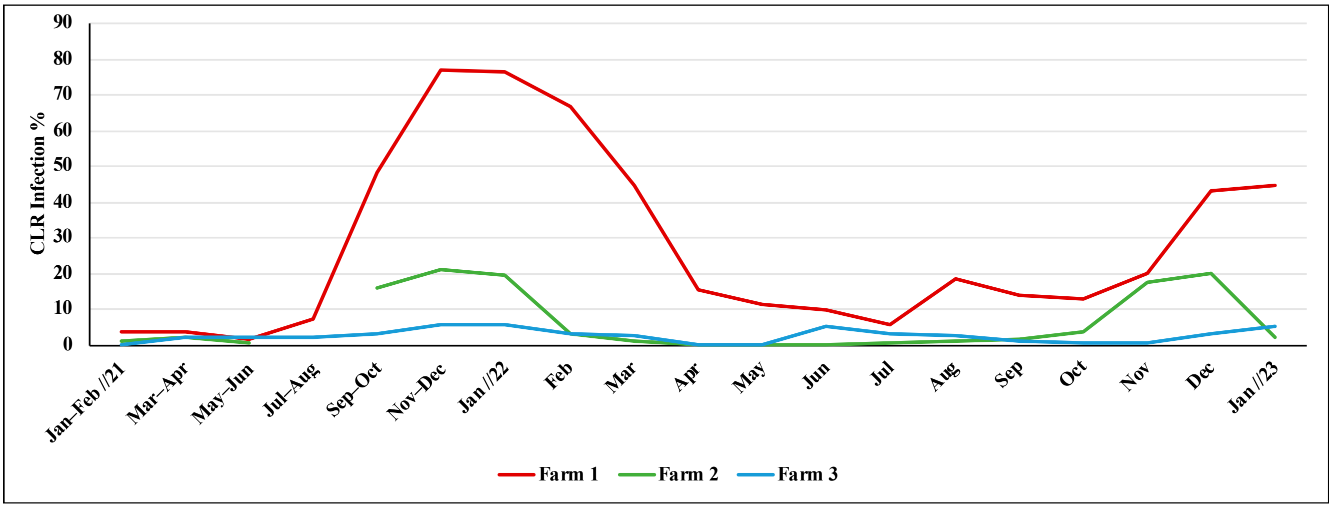

Figure 3. Coffee leaf rust incidence at three coffee farms from the South Kona district of Hawaii Island. Data correspond to coffee seasons 2021 and 2022.

The CLR incidence (mean ± SEM) for each coffee farm during both coffee seasons surveyed (2021 and 2022) is shown in Figure 4. In coffee farms 2 and 3, the CLR incidence on average was significantly lower in comparison with farm 1.

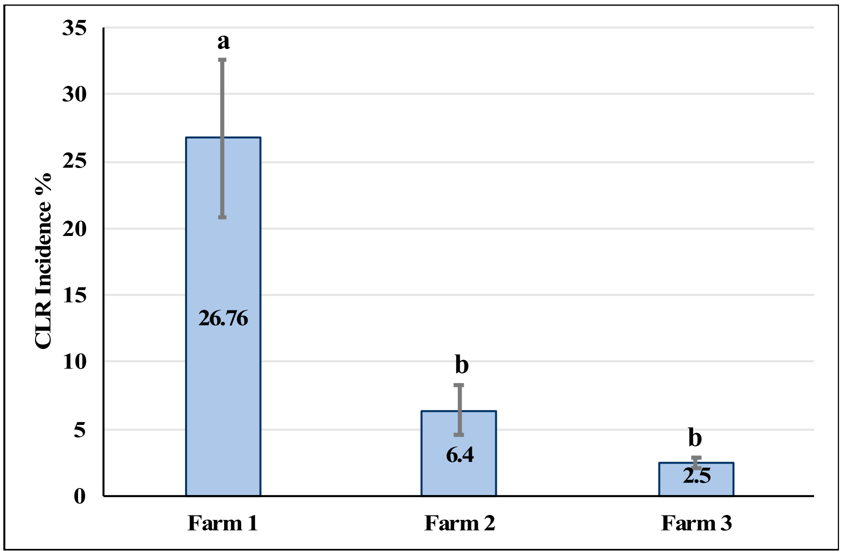

Figure 4. Coffee leaf rust incidence (mean ± SEM) for three farms during from South Kona district of Hawaii Island. Data correspond to coffee seasons 2021 and 2022. Means marked with the same letters are not significantly different (Dunn's test, $p = 0.05$).

3.2. Number of Coffee Leaves per Branch

The defoliation of coffee trees was not measured directly, but the number of coffee leaves per branch counted during the survey can give an idea about the impact of CLR infection and severity on reduction of foliage (Figure 5 and Supplementary Data S2). According to the Kruskal–Wallis test, significant differences in the mean number of leaves per branch was found among farms during both seasons ($X^2 = -36.87$, $df = 5$, $p < 0.001$). The Dunn's test for multiple comparisons revealed significant differences in the mean number of coffee leaves per branch between farm 1 vs. farm 2 ($p < 0.007$) and 3 ($p < 0.0001$), and between farm 2 vs. farm 3 ($p < 0.0047$) (Figure 6).

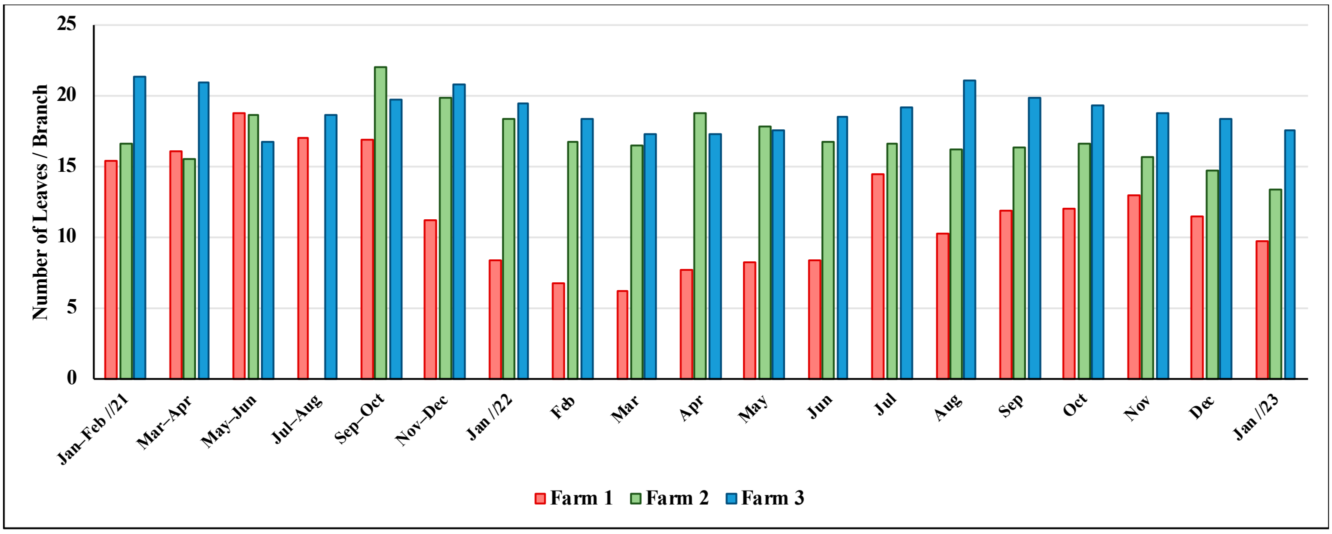

Figure 5. Number of coffee leaves per branch on average for three coffee farms from South Kona district of Hawaii Island. Data correspond to coffee seasons 2021 and 2022.

At the beginning of the CLR survey (January 2021), the average number of coffee leaves per branch was similar at coffee farms 1 and 2, while it was higher at farm 3 (Figure 5). Over the course of two years, the number of coffee leaves per branch was relatively stable at all three farms until the end of harvest season (December–January), in which a high reduction of leaves was observed at farm 1 (Figure 5). In contrast, at coffee farms 2 and 3, a slight reduction in the number of coffee leaves per branch was observed.

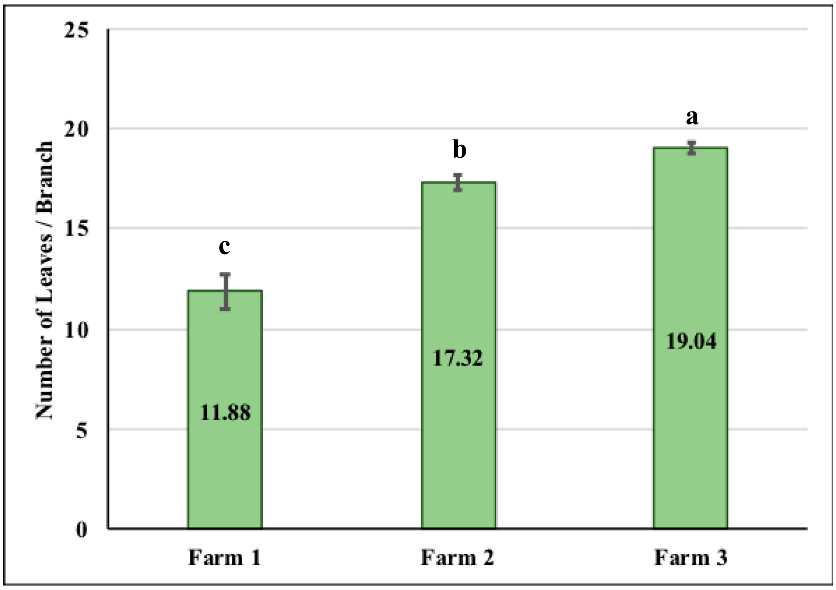

Figure 6. Number of coffee leaves per branch (mean ± SEM) during the coffee seasons (2021 and 2022) at three coffee farms in South Kona district of Hawaii Island. Means marked with the same letters are not significantly different (Dunn's test, p = 0.05).

During the early coffee season 2022, a lower number of coffee leaves per branch was observed at all farms in comparison with evaluations conducted at the end of the 2021 season. However, the reduction was higher at farm 1 in comparison with farms 2 and 3 (Figure 5). A gradual increase in the number of coffee leaves per branch was observed in all farms after March 2022 and until July–August (at the beginning of harvesting season). Then, a decline in the number of coffee leaves per branch was observed toward the end of harvest season (November–December) and during post-harvest season (January 2023), which may be attributed to the increased CLR infection and severity that occurred during the same period. When comparing the number of coffee leaves per branch on average between the two seasons (2021 and 2022), a reduction in foliage was observed at all three farms, but it was higher at farm 1. In fact, 38% on reduction of leaves was observed at farm 1, while this reduction was 10% at farm 2 and only 5% at farm 3.

3.3. Cost for Control CLR

During the 2021 coffee season, farms 1 and 2 conducted six and ten sprays of preventive fungicides, respectively, while at farm 3, ten sprays of preventive and curative (translaminar) fungicides were applied (Table 3). During the 2022 coffee season, five sprays were applied at farm 1, which was relatively similar in comparison with the previous season, while a slight reduction in the number of sprays was observed at farms 2 and 3, in which eight and seven sprays were conducted during the same season, respectively (Table 3). Differences in the total cost to apply fungicides during an entire season are related to the number of sprays, value of products applied (fungicides and foliar fertilizers) and labor cost, which ranged between (USD 15 and 25/h. At all three coffee farms, the total cost to control CLR was relatively similar (9–11% based on coffee yield) during the 2021 coffee season, but this cost was slightly lower during the 2022 coffee season at farms 2 and 3 (Table 4). Coffee yields (lb of cherries per acre) were relatively similar between coffee farms 1 and 3, but higher at coffee farm 2 during the 2021 season (Table 4). In the following season (2022), a high reduction in coffee yield (45%) was reported at farm 1 in comparison with the previous season. This reduction was due in part to the high CLR incidence (77%) recorded at the end of harvest season in 2021, which caused a significant reduction in the number of coffee leaves per branch (defoliation) during the early coffee season 2022 (Figure 5). In addition, about 50% of coffee trees were pruned or stumped due to the disease. At coffee farms 2 and 3 there was no reduction in coffee production during the same period (Table 4).

Table 3. Number of sprays, products (fungicides and foliar fertilizers) and timing of applications conducted by coffee growers during 2021 and 2022 seasons at three farms in the South Kona district of Hawaii Island. Top line shows coffee tree phenology during the season.

Season	Farm (Sprays)	Post-Harvest	Flowering			Developing Berries			Pre-Harvest	Harvest Season			
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2021	1 (6)		O		K			S			B	S	B
	2 (10)	B	O	S	S + C	S + C	O	S + C		B		S + C	S + C
	2 (10		S	S + C	C	S + C	P	C	K + C	S + C	O	S + C	
2022	1 (5)	S		O				B + C			S + C	P	
	2 (8)		P	S + C	S + C	S + C	S + C		C	K + C			P + C
	3 (7)	K + C		P + T		S + C	K + C	P + C		S + C		K + T	

Products: copper-based fungicides (B = Badge® X2; K = Kocide® 3000), biofungicide (S = Serenede ASO), O = OxiDate® 2; translaminar (P = Priaxor® Xemium®) and foliar fertilizers (C = Cafedak; T = Tropical Metasolate).

Table 4. Number of sprays of fungicides applied per season, total cost per acre (products + labor), average of a single spray per acre, yield (coffee cherry), profit, lb of coffee cherry needed to compensate the CLR cost per acre and proportion of CLR control cost, at three coffee farms located in the Kona district of Hawaii Island. Data form 2021 and 2022 coffee seasons.

Season	Farm	Fungicide * (P + TS) = Total Sprays	Total Cost/Acre (USD)	Average Cost/Acre (USD)	Yield/Acre (Lbs)	Profit/Acre (USD)	CLR Cost/Acre (%)
2021	1	(6 P + 0 TS) = 6	850	142	3888	9331	9
	2	(10 P + 0 TS) = 10	1167	117	5033	12,079	10
	3	(9 P + 1 TS) = 10	1062	106	4183	10,039	11
2022	1	(4 P + 1 TS) = 5	959	191	2151	5485	17
	2	(6 P + 2 TS) = 8	1330	166.00	6159	15,705	9
	3	(5 P + 2 TS) = 7	991	142	4684	11,942	8

* P = preventive, T S = translaminar systemic, (P + TS) = total number of sprays per season. 1 acre = 0.4 ha. Coffee season 2021 data from Aristizábal & Johnson [2].

4. Discussion

With the detection of CLR in Hawaii in late 2020 [1], coffee growers are facing the most devastating pathogenic fungus affecting coffee crops worldwide [2]. *H. vastatrix* is an airborne plant pathogen, which is dispersed by the wind among other factors [11,25]. *H. vastatrix* is a multiple cycle plant pathogenic fungus, which may increase its infection exponentially and cause high defoliation and consequently yield losses [4,5,26]. The management of susceptible coffee varieties is focused on sprays of preventive and curative fungicides and through the implementation of appropriate agronomic practices [4,9,11].

The three commercial coffee farms surveyed in this study showed significant differences in CLR incidence (mean = 2–28%) during the 2021 and 2022 seasons. At all three farms, growers conducted good agronomic practices (weed control, fertilization, pruning) and sprayed fungicides. Differences in microclimate and farm management resulted in high variation in infection among these farms and is discussed in the following paragraphs.

4.1. Initial Situation Facing by Coffee Growers in Hawaii

Due to the susceptible coffee varieties (Typica, Caturra, Bourbon, Catuai and Geisha) planted, the advanced age of coffee trees (20–100 years old), the fast dispersal of CLR across the Hawaii islands (12 months), the high aggressiveness of the pathogen *H. vastatrix* race XXIV [27–29], the high cost of fungicides, the limitation of field workers, the high cost of labor [2] and the lack of knowledge and experience with management of this pathogen, coffee growers began to live one of the worst nightmares of the coffee industry in Hawaii. Similar to coffee growers, agricultural technicians from Hawaii's state and federal agencies had never worked with this plant pathogen before. Therefore, the initial recommendations given to coffee growers to address CLR were supported by the previous literature published from coffee producer countries in South and Central America, Africa regions and in India [4–6,16,30–32].

Sanitation practices that included pruning were recommended in the early detection of the CLR. In some cases, in which CLR infection was high "hot spots", stump-pruning of the trees was recommended. Regulation of shaded trees associated with coffee crops also was conducted to allow additional sun radiation and wind flow, which can help to suppress the survival of CLR spores and germination [15,33]. The improvement of agronomic practices (weed control, fertilization and pruning) was a key factor to improve the health of coffee trees and give them the best conditions that help them fight against this pathogenic fungus [4,15,34] and other pests such as the coffee berry borer [35,36]. Finally, severe defoliation caused by CLR infection is expected to affect the coffee yield for the next season, debilitating the trees and causing branch dieback [9,11,37], which could represent a high loss of profit affecting the coffee industry in Hawaii.

4.2. CLR Incidence and Defoliation

During both coffee seasons, the pattern of CLR incidence was similar at all three farms: low during the first semester (flowering and berry development) and high during the second semester (fruit maturation and harvest). However, CLR incidence levels were different among farms reaching 77%, 22% and 6% at the end of 2021 and 43%, 20% and 3% at the end of 2022 at farms 1, 2 and 3, respectively. Higher CLR incidence was observed at farm 1, which showed significant differences in comparison with farms 2 and 3. High CLR incidence occurred during the harvest season. This may be due to the physiological response of the coffee plants, which were focused on fruit filling rather than supporting the defense system against the pathogen [4,11,33,38]. In addition, years with high intensity of flowering and fruit production have been associated with high levels of CLR infection [11,34,39,40]. In Kona coffee farms, production was 17% higher during the 2021 coffee season in comparison with 2020 [2]. Other aspects such as weather conditions (temperature, rainfall, humidity, solar radiation), age of trees (20–100 years), planting density (1600–2250 trees per ha) and the type and method of fungicide spray application may all play relevant roles in CLR infection and the effectiveness of the fungicides applied. At farm 1 the combination of older trees (100 years old), shade from associated trees (avocado, citrus, macadamia nut, palms and banana), high rainfall and humidity, lower solar radiation and ineffective sprays of fungicides, all could have contributed to the high increase in CLR at the end of the harvest season.

The reduction in CLR incidence, which was observed during the first half of 2022 at all coffee farms, was attributed to several factors including finalization of harvest season (December–January), defoliation, cooler temperatures (December–February) and drier conditions [2]. In addition, the management practices conducted by growers, which included sprays of fungicides and improvement of agronomic practices (weed control, fertilization, pruning) contributed to the reduction of the disease. The addition of foliar fertilizers in each spray (Farm 3) may have improved the nutrition of coffee trees by strengthening the defense system against CLR. Coffee tree nutritional imbalance influences CLR infection and severity, which facilitate the fall of infected leaves [4,11].

The number of coffee leaves per branch was significantly lower at farm 1 in comparison to farms 2 and 3 (Figures 5 and 6). Because of high CLR incidence and severity, defoliation occurred in the 2021 season, resulting in a 45% reduction in coffee production during 2022 season at farm 1. According to Jong et al. [41] and Rivillas et al. [4], the progress of the CLR epidemic (which was the result of a polycyclic pathogen) passes through three phases (slow, fast and maximum) during the coffee season. During the maximum phase, which coincides with the end of harvest season, highly infected coffee leaves fall off because of high severity of infection [4]. Reduction in the number of coffee leaves per branch was observed at all three farms (38%, 10% and 5%) when comparing the 2021 and 2022 seasons at farms 1, 2 and 3, respectively. Those results suggest that despite the fact that fungicides (preventive and curative) were applied, there is a defoliation that can affect coffee production and quality of green beans (processed coffee). Defoliation directly affects coffee production during the next season. The impact of high infection and high defoliation observed on coffee crops in South and Central America was associated with a reduction in coffee production between 10–30% [4,8–15].

4.3. Spraying Preventive and Curative Fungicides

Overall, six sprays of fungicides were conducted at farm 1 during 2021 and five during 2022, while ten sprays were conducted at farms 2 and 3 during 2021 and 7–8 sprays during 2022 at the same two farms, respectively. It is likely that the lower number of sprays at farm 1 resulted in high CLR incidence during both seasons compared to farms 2 and 3. In addition, the use of only preventive fungicides (Figure 7A,B) did not contain the disease when applied at high levels of infection (>10%), as observed at farms 1 and 2 during the 2021 season. However, when preventive fungicides (copper-based) were applied properly and with relatively low incidence (<5%), the active sporulation was suppressed and coffee trees were protected for 5–8 weeks. When a curative translaminar fungicide was applied, CLR was contained for 2–3 months, as observed at farm 3 during both seasons and at farm 2 during the second season (Figure 7A,C). The timing of application was critical, since two sprays of the translaminar during the development of berries (March and July) followed by two sprays of preventive fungicides, resulted in low CLR incidence (<3%) during harvest season, as observed at farm 3 during 2022. However, two sprays of the translaminar (February and December) followed by several sprays of preventive fungicides did not contain the CLR infection below 5% at the end of harvest season as observed at farm 2 during the 2022 season.

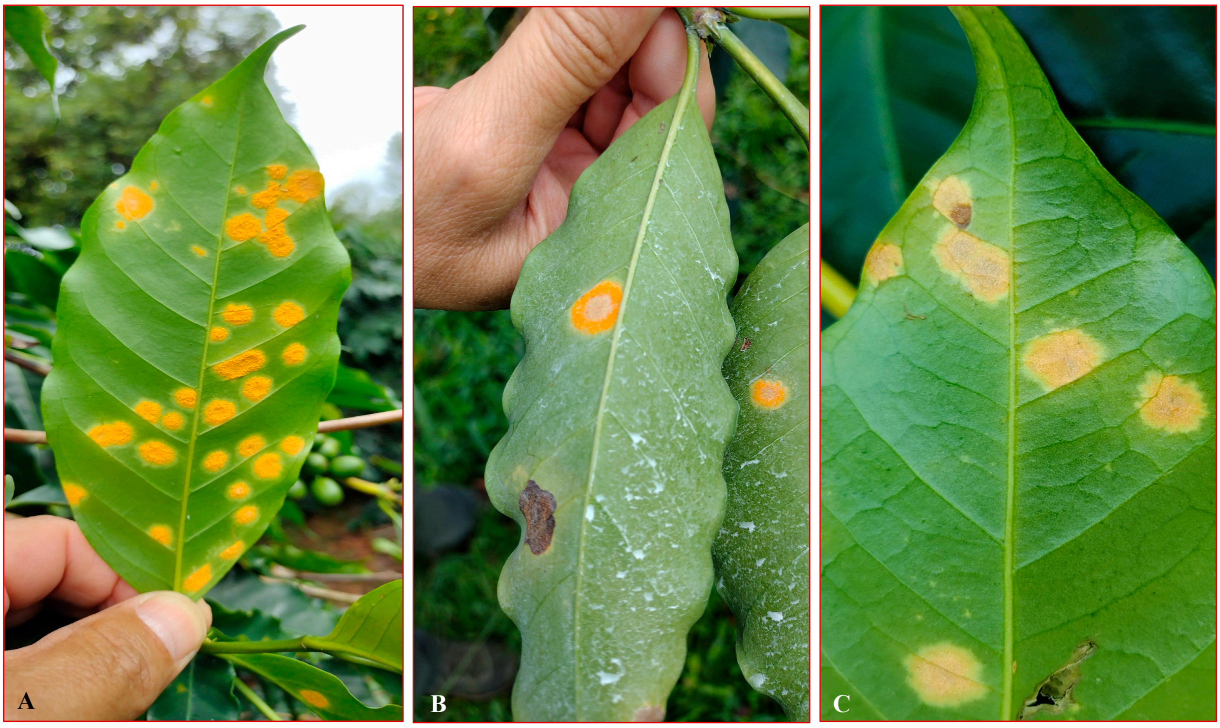

Figure 7. Coffee leaf showing CLR infection with active sporulation before sprays of fungicides (**A**). Infected coffee leaf ten days after a copper-based fungicide was applied. Notice a halo around the infected spot, which is the appearance of spores after the spray (**B**). Infected coffee leaf showing dry spots without active sporulation, which is the effect of a translaminar fungicide applied ten days previously (**C**).

According to Sera et al. [9], in Brazil, chemical control for CLR has been used for over 50 years. However, over the years, the use of fungicides has been rationally reduced, which has resulted in an economic benefit [9]. The use of fungicides in Brazil is based on monitoring, and decision support to help coffee growers select the correct fungicide, dosage and timing for spraying, which interrupts the CLR cycle and suppresses the disease during the coffee season [9,42,43]. Three types of fungicides are currently used in Brazil: contact, mesostemic and systemic for the chemical control of CLR [15]. In Colombia, the chemical control of CLR includes copper products (contact-preventive), systemic triazoles (preventive–curative) and systemic strobilurins (rust spore eradicator) [4,44,45]. In Brazil, the first sprays of fungicides normally occur in December, when symptoms of CLR begin to appear, and the number of sprays per season ranges from two to four sprays applied at 45–60 day intervals [9]. Most fungicides applied in Brazil are systemic products [9].

In Colombia, the first spray of fungicides starts 60 days after flowering and it is continued at 90, 120 and 180 days after flowering for the control of CLR based on the occurrence of the major coffee bloom [4]. This is the period for development of berries and pre-harvest period, in which the function of coffee leaves is focused on nutrition and fruit filling [4]; therefore, leaves are more susceptible to be infected by CLR. In Colombia, on average four sprays of fungicides are applied, in some cases a minimum of two sprays of systemic and maximum of six sprays including copper-based preventives and systemic products [4]. In Hawaii, the number of sprays that are needed to suppress the disease at low levels (<5% infection threshold) has not been estimated, since field trials are in progress with the products that are authorized by the HDOA. The only recommendation related to frequency of sprays is based on product labels [46], which is due to the recent detection of CLR and lack of field research in Hawaiian coffee agroecosystems. It is possible that in the future with two effective sprays of the translaminar or other systemic and two to four additional effective sprays of the preventive fungicides (copper or *Bacillus* strains), CLR may be controlled in Hawaii making the management more economical and environmentally feasible.

The proper use of fungicides (preventive and curative) may result in effective CLR control. However, the selection of the fungicide, doses, timing and coverage are critical for the efficient management of CLR infection [2,4,9,11,44]. The use of only preventive fungicides did not control the disease when few sprays were conducted (farm 1). However, when higher numbers of sprays were conducted the control of disease was more effective (farm 2), but not enough to obtain an optimal control (<5%), which only was achieved with the use of a translaminar (farm 3). Other factors (biotic and abiotic) may affect the efficacy of those fungicides. This means that even sprays of a systemic curative fungicide do not necessarily guarantee the control of CLR if weather conditions are not favorable (frequent rain), the infection and severity of the disease are high (>20%) and late sprays are conducted. According to Souza et al. [47], the efficacy of systemic-curative fungicides is reduced if incidence of CLR is higher than 10% and high production (fruit load) is expected. The pathogen *H. vastatrix* needs optimum conditions to infect the coffee leaves, reproduce and disperse, which includes frequent rain, low sun radiation and temperatures of 16–28 °C [4,37,48–51]. If rainfall periods coincide with development of berries (60–180 days old), the CLR infection increases since plant energy is directed at filling the fruits [4]. Therefore, fungicides must be applied when CLR infection levels are low to prevent an exponential increase in CLR [4]. In addition, the timing of fungicide applications played a relevant role in the efficacy of products [4,9,11,31]. At coffee farms 2 and 3, the translaminar was used in 2022, but it was more effective at farm 3, presumably because this product was applied during the coffee berry development period (March–July) resulting in low CLR infection at the start of the harvest season.

The sprays of preventive fungicides and even the translaminar fungicide need good coverage on both sides of the leaf to obtain effective control. This is difficult to achieve with the use of backpack sprayers, which are primarily used at Kona farms due to the rough terrain [2]. The rocky and sloping terrain common at Kona coffee farms plus the height of typica coffee trees (8–12 feet) limit the effective application of fungicides using backpack sprayers. This situation was seen at farm 1, in which CLR incidence reached 77%. Similar terrain conditions are seen at farm 2, but the sprays were more effective, since CLR was lower than 22% during both seasons. Rocky terrain, but with less inclination facilitated sprays at farm 3, in which CLR incidence was lower than 6% during both seasons. Weather conditions play an important role not just in the development, progress and dispersal of the CLR infection, but also in the efficacy of fungicides applied. When copper-based fungicides are sprayed, 50% of the particles of product attached to leaves are washed off after the first rainfall occurs [4,52]. Therefore, additional preventive sprays and the use of surfactants are needed during the wet season for the improvement of fungicide efficacy.

Monitoring CLR infection is important not just to know the pattern of the disease during the coffee season, but also to determine control measures such as the spray of fungicides with high precision. In addition, the effectiveness of fungicide application is determined by monitoring CLR infection and examining sporulation activity on lesions, which should appear dry if a systemic-curative fungicide was applied properly (Figure 7C). In Colombia, the management of CLR is more effective and economically feasible when the infection is monitored [4,53]. Similarly, in Brazil, a reduction of 75% in the use of fungicides for the control of CLR was reached when monitoring was conducted and a threshold of 5% infection was used for spraying systemic fungicides [43].

4.4. Cost of Spraying Fungicides

At all three coffee farms, the cost to control CLR was similar (9–11%) based on coffee production during the 2021 season. At farms 2 and 3, a slight reduction in costs to control the disease (8–9%) was observed in 2022. However, at farm 1 the situation was totally different. Since coffee production was reduced during the 2022 season in comparison with 2021 due to high defoliation caused by CLR, a 45% loss in coffee yield was reported. Moreover, a loss in profit was observed since coffee production was low and the cost to control CLR increased to 17%. For the first coffee season with CLR at commercial coffee farms in Hawaii (2021), the cost to control the disease ranged 2–11%, estimated as percentage of total profit per acre spent to control CLR [2]. Coffee farms that used tractors for spraying fungicides spent 2–3%, while farms that used backpack sprayers spent 4–11% of profit per acre [2]. In Colombia the economic viability of chemical control against CLR was estimated as the equilibrium point of volume production [4]. The equilibrium point determines the number of arrobas (1 arroba = 25 lb) of parchment coffee (processed dried coffee) needed to cover the cost to control CLR, and it is estimated based on control cost per hectare, production and price for selling parchment coffee [4]. The equilibrium point ranged between 5.2 arrobas (130 lb) and 13.1 arrobas (327.5 lb) of parchment coffee when different backpack sprayers were used to apply fungicides. Assuming a production average of 145 arrobas (3625 lb) of parchment coffee per ha (annual coffee production in Colombia), the cost to control CLR based on the equilibrium point would represent between 4% and 9%. However, if coffee production is high (200–400 arrobas of parchment coffee per ha or 5000–10,000 lb), which is common in the central coffee region of Colombia, the cost to control CLR would be lower.

The use of tractors for spraying fungicides is highly limited at coffee farms located in the Kona district due to the rocky steep terrain. Therefore, backpack sprayers are mostly used to apply fungicides, which not only increase the cost to control CLR, but also the effectiveness of fungicides is reduced due to the difficulty of walking on rocky sloping terrain. In addition to the cost to control CLR, coffee farmers spend about 11% of their net profit controlling the coffee berry borer, which is an invasive pest reported in Hawaii in 2010 [35,36]. The mixture of compatible fungicides, insecticides and foliar fertilizers may reduce the cost of labor, since a smaller number of sprays are needed to target CLR and CBB and supply foliar nutrition (microelements) simultaneously. Before spraying fungicides, it is important to consider weather conditions (rainfall) to prevent the repetition of a spray that is washed off by the rain. The use of surfactants is recommended when fungicides are applied.

4.5. Achievements and Challenges in Controlling CLR in Hawaii

Although CLR was detected recently in Hawaii (2020) [1], progress has been made by farmers and technicians in treating the disease. The entire coffee industry in Hawaii is working in conjunction with federal and state agencies to address the CLR issue and support coffee growers. Basic and applied research conducted by USDA-ARS PBARC, the University of Hawaii and the Synergistic Hawaii Agriculture Council is in progress in laboratories and commercial coffee farms. Ongoing studies include evaluation of fungicide efficacy, a rotation program with fungicides, the impact of agronomic practices and the introduction of resistant CLR varieties. A standardized sample plan for early detection and monitoring of CLR incidence was proposed and it is currently used to collect information across coffee farms on Hawaii Island [2,19]. Evaluations of CLR incidence at more than 30 coffee farms has provided insight into patterns of CLR in Hawaii, which is relevant to establish an IPM adapted to Hawaiian coffee agroecosystems. Passive and active samplers were installed across Hawaii Island to capture CLR spores and determine months with high dispersal, which is important to link with coffee plant phenology, weather conditions and management of CLR. The race of CLR was identified as race XXIV, which previously was reported in Brazil and Central America and it is considered highly aggressive [27,28,54]. This information is relevant to select potential coffee plants that are resistant to *H. vastatrix* race XXIV.

The introduction of varieties resistant to CLR is in the early stages. Coffee seeds from several resistant varieties have been obtained and established in quarantine facilities to later be planted and used to conduct studies related to adaptation, production, resistance and coffee quality. Field evaluations of preventive and curative fungicides are in progress with authorized products and potential products expected to be registered soon. Information and recommendations related to CLR control have been delivered to coffee farmers through different media, documents, conferences, webinars, etc. Economic resources to reduce the cost of fungicides were approved by Hawaii congress to subsidize (50%) this cost.

From this study, the most relevant observation is related to the sprays of fungicides used to control CLR. The number of fungicide sprays, products applied (preventive and curative), timing of application and spray efficacy (coverage of foliage) were key aspects that resulted in effective control of CLR as observed at farm 3. The use of the translaminar fungicide (Priaxor® Xemiun®) in combination with preventive fungicides applied during the early coffee season (February–July) are critical to start the harvest season with a low CLR incidence (<3%). Implementation of timely agronomic practices (weed control, fertilization, pruning) and the addition of micronutrients with foliar fertilizers will improve plant health and the plant defense system against a CLR attack.

According to Koutouleas et al. [55], CLR is still a serious plant pathogen affecting global coffee production despite efforts to control the disease in many other countries for more than 50 years. Moreover, the CLR situation in Hawaii is highly relevant due to its recent detection, the lack of studies in the islands and the lack of experience controlling this disease. Many aspects remain challenging for coffee farmers in Hawaii facing the CLR epidemic. The limited number of field workers and high cost of labor are two major aspects that affect normal agronomic activities at commercial farms from Hawaii including the control of insect pests and diseases and harvesting practices. Coffee varieties susceptible to CLR (99%) planted in Hawaii and old coffee trees (20–100 years old, about 50% of what is currently planted on Hawaii Island) are two other aspects that favor the development of CLR. The lack of knowledge and experience managing coffee leaf rust are challenges not just to coffee growers, but to technicians working in Hawaiian coffee agroecosystems. However, the last three years have been important for learning about CLR biology and its relationship with coffee plant phenology, weather conditions and the use of different alternatives of control. Several aspects of control (appropriate and efficient use of fungicides, establishment of resistant CLR varieties, cultural practices, etc.) still need to be adjusted to develop an economically feasible integrated pest management plan for CLR that is adapted to Hawaii coffee agroecosystems.

5. Conclusions

CLR continues to be a major challenge for coffee growers in Hawaii. The initial impact of the CLR epidemic observed in Hawaii during the 2021 and 2022 seasons is still being felt by many coffee growers that have seen significant reductions in coffee yields. In the present study, three coffee farms serving as case studies from the South Kona district relied on improvement of agronomic practices and the use of fungicides to control CLR during the 2021 and 2022 seasons. CLR incidence levels were highly variable among these farms and these differences were attributed to multiple biotic and abiotic factors. Appropriate and efficient use of the translaminar-systemic (two sprays of Priaxor® Xemium®) during the early season (February–July) in combination with preventive fungicides (five sprays) resulted in low CLR incidence (<3% on average). The results observed at coffee farm 3 during the 2022 season suggest that it is possible to keep CLR under control if agronomic practices are conducted properly and sprays of fungicides are appropriately timed. This suggests that it will be possible to reduce fungicide applications to 3–6 sprays in the future, if the right fungicide is used at the right moment (early coffee season) and good coverage is achieved. Finally, fewer sprays to control CLR will reduce the costs and minimize risks for field workers and the environment. However, additional field studies are needed to develop an economical and environmentally feasible management plan for CLR in Hawaiian coffee agroecosystems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agrochemicals3020011/s1, Supplementary data S1: Coffee leaf rust incidence (%) at three coffee farms from South Kona district of Hawaii Island. Data correspond to coffee seasons 2021 and 2022; Supplementary data S2: Average number of leaves per branch at three coffee farms from the South Kona district of Hawaii Island. Data correspond to coffee seasons 2021 and 2022.

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