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Integrated management reduces Frosty Pod Rot in cacao (*Theobroma cacao* L.) pods in Huila, Colombia

El manejo integrado reduce la moniliasis en mazorcas de *Theobroma cacao* L. en Huila, Colombia

Eleonora Rodriguez Polanco[1]*, Edinson Bayardo Parra Alferes[1], Felipe López-Hernández[2], Paula Bermeo-Fúquene[1], Diego Alberto Navarro[1], Edgar Mauricio Rico[1] and Jhon Jairo Zuluaga[1]

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ABSTRACT
Frosty Pod Rot (FPR) caused by *Moniliophthora roreri* is the most devastating disease affecting cacao production in Colombia. This study evaluated the efficacy of different management strategies against FPR in commercial cacao plantations (clone ICS-39) located in Huila, Colombia. Traditional Crop Management (TCM), which involved diseased fruit removal, was compared with Integrated Crop Management (ICM), which additionally included biweekly or weekly applications of chemical and biological fungicides. These management techniques were tested across three frequencies of diseased fruit removal: every 7, 14, and 21 days. Disease incidence (evaluated in immature and mature cacao pods) was quantified using the area under the disease progress curve (AUDPC). Yield and a differential management index were also calculated. For immature cacao pods under natural infection conditions, ICM strategies significantly decreased disease incidence. In particular, ICM combined with diseased fruit removal every 7 days reduced AUDPC by 70% when compared to traditional management (TCM-7). In contrast, fruit removal every 21 days, even with ICM, proved less effective. These findings demonstrate the critical role of frequent removal of diseased cacao pods in combination with chemical and biological products. Integrated management represents an effective and valuable approach for FPR control, contributing to improved cacao productivity in commercial plantations in the Huila region.

KEYWORDS: Crop management, Cultural practices, Epidemiology, Fungicide, *Moniliophthora roreri*

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RESUMEN
La moniliasis de la mazorca del cacao causada por *Moniliophthora roreri*, es la enfermedad más devastadora para la producción de cacao en Colombia. En este estudio se evaluó la eficiencia de diferentes estrategias de manejo para esta enfermedad en plantaciones comerciales de cacao (clon ICS-39) en el departamento de Huila en Colombia. Se comparó el manejo tradicional del cultivo (TCM), que consistió en la eliminación de frutos enfermos, con el manejo integrado de cultivo (ICM), que además incluyó aplicaciones semanales o quincenales de fungicidas químicos y biológicos. Estas técnicas de manejo se probaron en tres frecuencias

[1]Centro de Investigación Nataima, Corporación Colombiana de Investigación Agropecuaria – AGROSAVIA. Espinal, Tolima, Colombia. lrodriguezp@agrosavia.co, ebayardo@agrosavia.co, pbermeo@agrosavia.co, dnavarro@agrosavia.co, emrico@agrosavia.co, jzuluaga@agrosavia.co
[2]Centro de Investigación La Selva, Corporación Colombiana de Investigación Agropecuaria – AGROSAVIA. Rionegro, Antioquia, Colombia. llopez@agrosavia.co

*Corresponding author

de eliminación de frutos enfermos: 7, 14 y 21 días. La incidencia de la enfermedad en frutos de cacao inmaduros y maduros fue cuantificada usando el área bajo la curva del progreso de la enfermedad (AUDPC). También se calcularon el rendimiento y un índice de manejo diferencial. Los resultados mostraron que, para las mazorcas de cacao inmaduras en condiciones naturales de infección, la estrategia del ICM disminuye la incidencia de la enfermedad. Especialmente, el ICM combinado con la eliminación de la mazorca cada 7 días redujo el AUDPC en un 70% comparado con el control tradicional (TCM-7). Por el contrario, la eliminación de los frutos cada 21 días, incluso con ICM, tiene menor efectividad. Estos resultados muestran la importancia de la frecuencia de eliminación de mazorcas enfermas de cacao y la combinación con la aplicación de productos químicos y biológicos. El manejo integrado constituye una estrategia eficaz y útil para el control de la moniliasis, mejorando la productividad del cultivo de cacao en plantaciones comerciales del departamento del Huila.

PALABRAS CLAVE: Manejo del cultivo, Prácticas culturales, Epidemiología, Fungicida, *Moniliophthora roreri*

INTRODUCTION

Cacao (*Theobroma cacao* L.) is a tropical crop used as the primary raw material for the chocolate industry, with essential applications in the cosmetics and pharmaceutical industries (FAOSTAT 2022). The leading producer is the African continent, which currently accounts for a substantial 69.85% of worldwide cocoa output (FAOSTAT 2022). However, cacao production is severely threatened by various plant pathogens, particularly Frosty Pod Rot (hereafter, FPR), caused by the aggressive basidiomycete *Moniliophthora roreri* (Cif. & Par.) H.C. Evans, Stalpers, Samson & Benny. This pathogen is widespread across the Americas (McElroy et al. 2018). (McElroy et al. 2018), and is one of the most devastating diseases affecting global cacao production (Bailey and Meinhardt 2016; Kongor et al. 2024). The high aggressiveness, the efficient dispersal of *Moniliophthora roreri*, coupled with favorable environmental conditions and limited effective control strategies, are responsible for its devastating impact on commercial cacao plantations throughout Central and South America, including Colombia (Merchán Vargas 1981; Jiménez et al. 2022).

FPR is widespread across all cacao-producing regions in Colombia, with a higher incidence in the Urabá region, the lower Cauca River basin, the middle Magdalena region, and Tumaco (Sáenz 2007). The incidence of the disease in commercial cacao plantations is as high as 60% (Sáenz 2007), with bean losses reaching up to 80% per tree if inappropriately practices are carried out (Fedecacao 2023). While the widespread impact of FPR is well-documented, the precise origin of the pathogen remains a subject of ongoing debate. Early reports of FPR epidemics in Colombia date back to 1817 in Norte de Santander and 1851 in Antioquia (Phillips-Mora 2003), suggesting that Colombia, particularly the Upper Magdalena Valley, may be the center of origin, rather than the widely referenced Ecuador (Jaimes et al. 2016). This hypothesis is supported by the high genetic diversity and elevated virulence levels registered in fungal populations across different Colombian producing regions (Jaimes et al. 2016), possibly explaining the aggressiveness of FPR epidemics in the country. Overall, this situation is mainly due to the lack of cultural practices and the ignorance of cacao producers to apply and adopt them (Rodríguez-Polanco et al. 2024).

The keystone of FPR management is the removal of diseased cacao pods (Ali et al. 2015) and the use of chemical applications; however, both have limitations. The first practice, i.e., the poor weekly removal of diseased pods throughout the production cycle, increases fungus sporulation and the infectious inoculum within the plantation (Ali et al. 2015; Rodríguez-Polanco et al. 2024). This persistent challenge is often attributed to the inadequate adoption and application of cultural practices by cacao producers (Rodríguez-Polanco et al. 2024). The second practice, i.e., the chemical control, including the use of copper hydroxide and systemic fungicides (e.g., strobilurins, triazoles, benzimidazoles) (Torres de la Cruz et al. 2011; Anzules et al. 2019; Torres-de-la-Cruz et al. 2019), requires frequent applications in the field. This makes chemical control inefficient and economically impossible for cacao smallholders (Torres-de-la-Cruz et al. 2019). Thus, there is a growing need for more sustainable and integrated approaches to FPR management (Reis et al. 2025). Within this search, recent research has highlighted the potential of biological control agents and natural extracts as promising alternatives to conventional chemicals (Chochocca et al. 2022; Bastidas-Ruiz et al. 2025).

The holistic integration of various agricultural practices in disease management, rather than relying on a one- or two-component approach, has proven more effective and sustainable in agriculture (Khoury and Makkouk 2016; He et al. 2021). Thus, a whole strategy requires the design of an integrated management strategy for FPR (Rodríguez-Polanco et al. 2024), as well as the application of harmless chemical pesticides that could improve disease control and, consequently, crop profitability. Integrated management approaches, which combine cultural, biological, and chemical measures, offer more effective and sustainable control of FPR (Khoury and Makkouk 2016; He et al. 2021). Core practices include regular removal of diseased fruits and annual pruning after harvest to facilitate disease detection (Rodríguez-Polanco et al. 2006; Rodríguez-Polanco et al. 2024). The complementary use of reduced-toxicity fungicides and biological products may enhance control efficiency while maintaining environmental safety and profitability.

Regarding the high persistence of FPR and its limitation in conventional management strategies, this research aimed to evaluate the application of an integrated management strategy for FPR in commercial cacao plantations. The integrated management focuses on the combined effects of cultural practices (e.g., diseased cacao pod removal) and the application of low-toxicity chemical and biological fungicide products.

MATERIALS AND METHODS

Study area

To evaluate the effect of different frequencies of diseased cacao pod removal and the additive effect of spraying low-toxicity chemical molecules in the integrated management of FPR, two experimental trials were conducted. These trials were conducted in 1-ha commercial cacao plantations of clone ICS-39 in the municipalities of Rivera (Vereda: Riverita, Farm: San José) and Gigante (Vereda: Guandinosa, Farm: La Batalla) in the Department of Huila, Colombia (Figure 1), from July 2023 to March 2024.

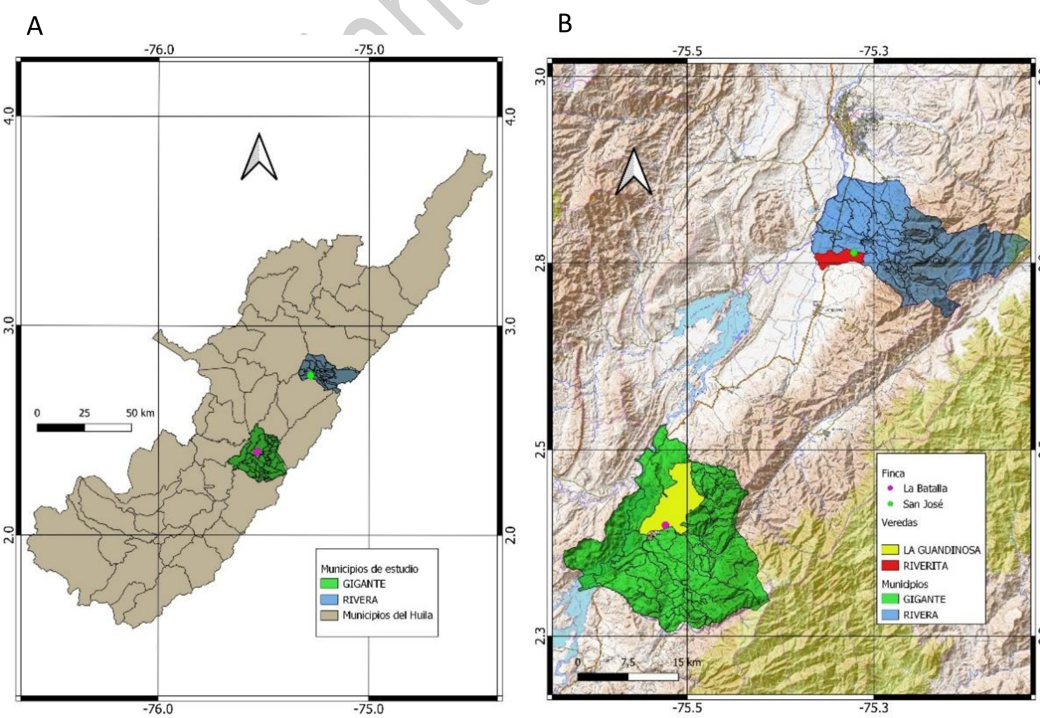

Figure 1. Geographic location of the commercial cacao plantations of clone ICS-39 in the Department of Huila, Colombia. **A**. Location of the study municipalities within the department, **B**. Location of the commercial plantations within the two study municipalities (Gigante and Rivera).

Treatments

The treatments included were the intervals for removing diseased cacao pods, which were determined according to the time required between the formation of necrosis or compact spot and fungus sporulation on the cacao pod, i.e., 7 days (Merchán Vargas 1981; Rodríguez and Medina 2005). The remaining fruit removal intervals had a weekly increase (i.e., 14 and 21 days), considering the additive effect of fungicide application (Keinath 2024).

Five treatments were designed, varying by crop management practices and the frequency of diseased pod removal. An experimental unit consisted of a single tree evaluated in the field throughout one harvest cycle (from July 2023 to March 2024). Each of the five treatments included five trees as replicates. The treatments were defined as follows: T1 (TCM-7) and T2 (TCM-14) incorporated Traditional Crop Management (TCM), with diseased pod removal every 7 and 14 days, respectively. T3 (ICM-7), T4 (ICM-14), and T5 (ICM-21) incorporated Integrated Crop Management (ICM), with diseased fruit removal every 7, 14, and 21 days, respectively. TCM included pruning, mechanical weed control, mechanical shoot removal, and fertilization based on soil analysis requirements. ICM included all TCM practices and the application of resistance enhancers, protectants, systemic fungicides, and a mixture of beneficial microorganisms. Fungicides were applied based on their mechanism of action and the age of the pod's highest susceptibility stage (Table 1) in the municipalities of Rivera and Gigante, Huila Department, Colombia, from July 2023 to March 2024. All applied products (chemical and biological) evaluated were sprayed using a STIHL SR 450 engine sprayer to ensure maximum fruit coverage. Agrotin SL was employed as an adjuvant at a dose of 1 mL L^{-1}.

Table 1. Chemical and biological products used in integrated crop management (ICM) treatments for the control of FPR (*M. roreri*) in commercial cacao plantations of clone ICS-39.

Fruit age*	Active ingredient (ai)	Classification	Action mechanism	Toxicological category	Dose (ai)
2	Potassium phosphite + Salicylic acid [FUERZA PK: (P_2O_5 450 g L^{-1}; K_2O 350 g L^{-1}; Oxidizable organic carbon 50 g L^{-1})]	Fertilizer and resistance inducer	Protectant	Uncategorized (Bioinput/fertilizer for agricultural use)	2 mL L^{-1}
2.5	Tebuconazole + Trifloxystrobin [Nativo SC 300 (200+100 g L^{-1})]	Fungicide	Systemic	III - Slightly Dangerous	1mL L^{-1}
3	Difenoconazole + Azoxystrobin [Azoxytop SC 325 (200+125 g L^{-1})]	Fungicide	Systemic	III - Slightly Dangerous	1 mL L^{-1}
3.5	Tebuconazole + trifloxystrobin [Nativo SC 300 (200+100 g L^{-1})]	Fungicide	Systemic	III - Slightly Dangerous	1 mL L^{-1}
4	Copper and calcium sulfates [Atrasin EC 300 ($CuSO_4.5H_2O$ 21 g L^{-1}; $CaSO_4.2H_2O$ 18 g L^{-1})]	Fungicide	Protectant	IV - Slightly Toxic	4 g L^{-1}
4.5	Organic materials, sulfates, and microorganisms [Bioxinis (N 17.5 g L^{-1}; P_2O_5 11.4 g L^{-1}; K_2O 19.4 g L^{-1}; CaO 3.84 g L^{-1}; MgO 0.76 g L^{-1}, S 1.66 g L^{-1}; oxidizable organic carbon	Organic fertilizer	Protectant	Uncategorized	10 mL L^{-1}

40.9 g L^{-1}; *Trichoderma harzianum, Beauveria bassiana, Bacillus thuringiensis, Metarhizium anisopliae, Paecilomyces* sp., *Gliocladium* sp., and *Verticillium* sp.)]	

* Fruit age in months at the time of application; volume of water applied 200 L ha^{-1}.

The selection of chemicals used in this study was based on the criteria of low toxicity to mammals (toxicity classes III and IV of the Environmental Protection Agency [EPA]), targeting molecules with preventive, curative, and eradicative actions. Nativo SC 300 (Tebuconazole and Difenoconazole FRAC group III) acts by inhibiting ergosterol synthesis and mitochondrial respiration (FRAC 2024a), while Azoxytop SC 325 (Trioxystrobin and Azoxystrobin; FRAC group IX) suppresses mitochondrial respiration, spore germination, zoospore mobility, and anti-sporulant activity (FRAC 2024a). These fungicide groups are known for their efficacy in controlling basidiomycetes, i.e., rusts and *Rhizoctonia* spp. (Bartlett et al. 2002; Bayer 2024; Syngenta 2024). The use of protective fungicides such as calcium copper sulfate (Toxicity class IV according to the EPA), with a curative action that destroys the cell walls of the fungus, preventing its germination and growth (FRAC 2024b), and considering its multisite action, and low risk of resistance and toxicity.

Disease and yield assessment

Disease incidence was determined during the reproductive stage of the crop cycle. The incidence was tested periodically according to the cacao pod removal time for each treatment. First, healthy and diseased cacao pods were differentiated by age: young (2 to 4 months) and adult (older than 4 months). Cacao pods in these two age ranges exhibit good development and a high probability of reaching maturity. All diseased fruits were removed from the tree. Incidence per tree was calculated using Equation 1 (Arauz 1998):

$$\text{Incidence} = \left(\text{Number of fruits with}\frac{\text{symptoms}}{\text{Total}}\text{number of fruits on the tree}\right) \text{x } 100 \quad (1)$$

Using this parameter, the disease progression in cacao pods was tested. Thus, the area under the disease progress curve (AUDPC) was assessed for each treatment. The AUDPC was calculated at three time lapses: i) when pods reached 2 to 4 months of age, ii) when they were older than 4 months, and iii) for the total incidence across the entire evaluation period, as described by Madden et al. (2007) in Equation 2:

$$\text{AUDPC} = \sum_{i=9}^{n}\left\{\left(\frac{y_i + y_{i+9}}{2}\right)(t_{i+9} - t_i)\right\} \quad (2)$$

In this equation, $\sum$ is the summation symbol, i is the index of time points, n is the total number of time points, y_i is the disease severity at time point i, and t_i is the time at point i.

Furthermore, the production of each treatment was estimated based on records of harvested cacao pods per tree. This was then extrapolated to kg of dry cacao, assuming a planting density of 1,100 trees ha^{-1}. To evaluate the impact of each treatment on reducing disease incidence and its effect on productivity, a Differential Management Index (DMI) was calculated. This index relates the production of healthy pods to disease progress (Nuryanto and Praptana 2025). This index is defined as the difference between yield (kg of dry cacao ha^{-1}) and the AUDPC. This index enabled the benefits of the treatments to be weighted in terms of relative harvest efficiency and effective disease management, providing a single indicator that combines phytosanitary and productive aspects. The DMI was calculated according to Equation 3, with prior standardization of the variables:

$$\text{DMI} = \text{Yield [kg ha}^{-1}] - \text{AUDPC}_{\text{Total}} \quad (3)$$

Where DMI is the yield of fresh cacao beans and total AUDPC (AUDPC for immature and mature pods).

A positive DMI value indicates that the treatment contributed to better disease control (lower AUDPC) and positively impacted plantation yield. Conversely, negative values may indicate that, despite reducing the disease, the treatment failed to compensate for the loss in productivity (Padi 2008).

Statistical analysis

Given the homogeneous characteristics of the experimental field and the absence of significant spatial trends that could influence measurements, a Completely Randomized Design was chosen for assigning treatments to the experimental units. The total cacao pod incidence, the incidence in pods from 2 to 4 months old, the incidence in fruits older than 4 months, yield, and the DMI did not follow a normal behavior, nor any known probability distributions validated by the R function *descdist* of the *fitdistrplus* package (Delignette-Muller and Dutang 2015). Subsequently, a non-parametric analysis of variance was performed using Kruskal-Wallis and Dunn's multiple comparisons tests employing a customized R script with the package *ggstatsplot* (Patil 2021).

RESULTS AND DISCUSSION

The statistical analysis showed significant differences between treatments for several key variables: AUDPC (Table 2), including total cacao pod incidence, pod incidence from 2 to 4 months of age, yield (Figure 2), and the DMI (Figure 3). Notably, the effectiveness of treatments varied between the two locations evaluated (Rivera and Gigante).

Table 2. Effect of TCM and ICM with different Frosty Pod Rot removal frequency (7,14, and 21 days) on AUDPC incidence in ICS-39 cacao pods across two localities and ages.

Treatments	**Locality**					
	Rivera			**Gigante**		
	AUDPC					
	Total	2-4 months	>4 months	Total	2-4 months	>4 months
T1: TCM-7	145.71^{ab}	1140^{ab}	105^{a}	111.90^{a}	246.67^{ab}	85.71^{a}
T2: TCM-14	236.188^{ab}	360.00^{ab}	116.67^{a}	187.85^{a}	50.00^{a}	115.48^{a}
T3: ICM-7	43.75^{a}	89.58^{a}	0^{a}	80.24^{a}	121.43^{a}	40.66^{a}
T4: ICM-14	50.55^{a}	50.00^{a}	0^{a}	140.97^{a}	191.67^{ab}	100^{a}
T5: ICM-21	404.68^{b}	243.75^{a}	0^{a}	229.21^{a}	488.61^{b}	36.93^{a}
$X^2_{Kruskal\text{-}Wallis}$	10.60	12.07	10.01	7.28	10.13	3.35
p-value	0.03*	0.02*	0.40^{ns}	0.12^{ns}	0.04*	0.50^{ns}

*: Significant *p*-value; ^{ns}: not significant *p*-value, using Kruskal-Wallis test. Significant differences between the levels of the analysis factor are represented by different letters.

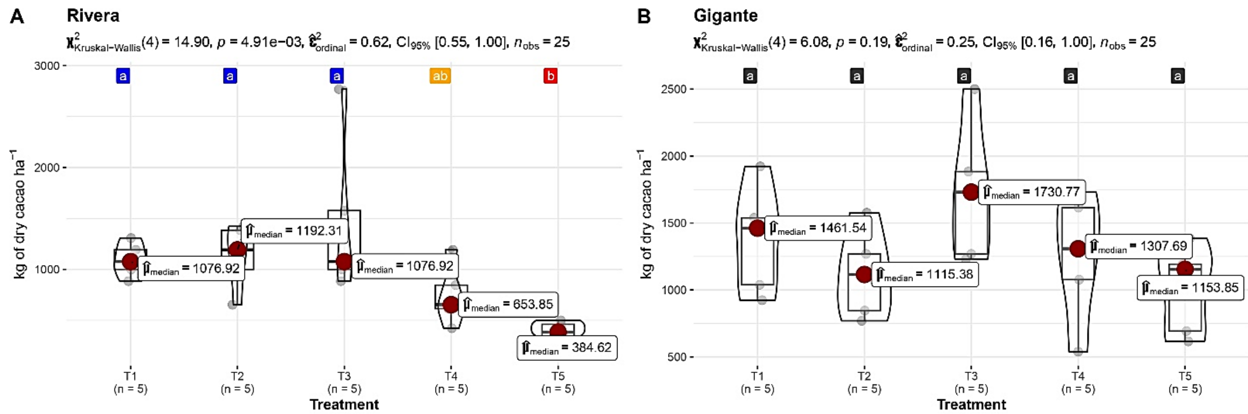

Figure 2. Effect of TCM and ICM with different Frosty Pod Rot removal frequency (7,14, and 21 days) on cacao yield (kg of cacao ha^{-1}) in ICS-39 cacao pods across two localities and cacao pod ages.

Disease Incidence

In the Rivera locality, significant differences were identified in the AUDPC of the total diseased cacao pod incidence (p=0.03) (Table 2). Dunn's post-hoc test clearly separated treatments into three groups. The lowest total incidence values were achieved by ICM-7 (43.75) and ICM-14 (50.95), forming group "a.". The statistically equal treatments TCM-7 and TCM-14 formed group "ab" with intermediate values of 145.71 and 236.18, respectively. The highest value was observed in group "b," where ICM-21 was included, with a value of 404.68. In contrast, the Gigante locality showed no significant differences (p=0.12) among treatments for the AUDPC of total incidence (Table 2), indicating that while the trends might be similar, the statistical power to detect differences was lower or the variability was higher in this location.

For the AUDPC of incidence in immature cacao pods (2 to 4 months old), significant differences were found between treatments (Rivera (p=0.02), and Gigante (p=0.04)). In Rivera, ICM-14, ICM-7, and ICM-21, the values are 50.0, 89.58, and 243.75, respectively. Treatments TCM-14 and TCM-7, statistically equal, presented the highest values with 360 and 1140, respectively. For the locality of Gigante in this same time range, group "a" (TCM-14 and ICM-7) showed the lowest values, "ab" (ICM-14 and TCM-7) registered intermediate values, and "b" (ICM-21) recorded the highest value for the AUDPC. These results for young fruits are critical because they are the most susceptible stage for *M. roreri* infection. The efficacy of early application of systemic fungicides, such as Tebuconazole + Trifloxystrobin and Difenoconazole + Azoxystrobin, may be beneficial in this crucial stage. This provides crucial protection during the cacao pods' most vulnerable periods, supplemented by subsequent applications of copper and calcium sulfates. Similar findings were reported by Bateman et al. (2005) and Torres de la Cruz et al. (2011), who also highlighted the importance of early and regular fungicide applications.

Mature cacao pods (4 months old) showed no significant differences in AUDPC between any treatment and location (Rivera (p=0.4) and Gigante (p=0.5)) (Table 2). This result indicates that mature pods are not the primary target of the pathogen (Merchán Vargas 1981; Rodríguez-Polanco et al. 2024). The evolutionary behavior of the fungi focuses on attacking fruits in the early developmental stages to produce infectious propagules, continuing with the epidemics in the field.

Results from this study indicated that the weekly removal of diseased pods and fungicide applications constitute the basis of FPR management in a highly susceptible clone such as ICS-39. Their joint integrated application significantly reduces the AUDPC of the total incidence in diseased cacao pods. The result of AUDPC in the total incidence is observed when comparing the TCM-7 and ICM-7 total fruit removal treatments, with a significant decrease of 70% in Rivera and 29.23% in Gigante (Table 2). The efficacy of weekly removal of diseased cacao pods interrupts the reproductive stage (sporulation) of the fungus in the field (Raju et al. 2022). This is essential because *M. roreri* can progress from its brown (coffee) stage to sporulation in 7 days (Cubillos 2017). The sporulation of a single diseased fruit represents a significant risk to sanitation efforts, since just 1 cm^2 of a sporulated area can yield approximately 44 million conidia (Campuzano 1976). In addition, the effective germination rate is around 5% (Rodríguez-Polanco et al. 2006; Gómez-Gutiérrez et al. 2022), equivalent to 2.2 million potential infectious units per fruit. This suggests that cultural methods, such as diseased pod removal, are insufficient for FPR control. Their success relies on the precise and timely implementation of "weekly removal" (Fedecacao 2023), which inherently limits their guaranteed efficiency.

The ICM-7 treatment, which included weekly removal of diseased cacao pods and applying chemical and biological products, showed a 70% decrease in the AUDPC of the total disease cacao pod incidence compared to TCM-7 in the Rivera department (Table 2). This significant improvement demonstrates that the strategic application of fungicides to the most susceptible fruit stages enhances the protection obtained only with the removal of diseased cacao pods within cultural practices (Abbas et al. 2022). It is essential to note that the efficiency and profitability of chemical and biological applications in cacao crops depend on their precise agronomic management. The use of cultural practices such as pruning plays a vital role in maintaining tree architecture that facilitates diseased pod removal, ensures optimal product coverage, and preserves dry microclimate conditions, which limits the multiplication of *M. roreri* (Bateman et al. 2005; Cubillos 2017; Rodríguez-Polanco et al. 2024). This synergistic interaction between cultural practices and targeted fungicide application is key to effective disease control.

Study results demonstrate the efficiency of early application of Tebuconazole + Trifloxystrobin and Difenoconazole + Azoxystrobin in fruits between 2.5 and 3.5 months old due to the protection offered by these systemic fungicides in fruit development periods when they are most susceptible to the attack of *M. roreri* (Torres de la Cruz et al. 2011; Torres-de-la-Cruz et al. 2019). This could be complemented by subsequent applications of copper and calcium sulfates. The sensitivity of *M. roreri* to copper sulfate was documented for the first time in Mexico in *in vitro* tests at a dose of 0.62 g ai L^{-1}, resulting in a 100% reduction in mycelial growth and spore germination (Torres-de-la-Cruz et al. 2019). Moreover, copper hydroxide is the most recommended protective fungicide for controlling *M. roreri* in Costa Rica (Hidalgo et al. 2003; Bateman et al. 2005).

Similar results for the control of FPR were reported by Bateman et al. (2005), who recommended the application of the systemic fungicide Flutolanil for the control of FPR in the first 60 days of cacao fruit development, followed by monthly applications of copper hydroxide. Later, Torres-de-la-Cruz et al. (2011) and Ortíz-García et al. (2015) reported spraying Azoxystrobin (0.8 g ai L^{-1}) on fruits younger than 2 months, supplemented with three monthly applications of copper hydroxide (7.5 g ai L^{-1}) to control the disease. Furthermore, rotating fungicidal molecules with different modes of action helps reduce the risk of developing resistance (FRAC 2025).

Yield and differential Management Index (DMI)

The implementation of cultural and sanitation practices, along with the application of chemical and biological molecules, resulted in an increase in yield. In the municipality of Rivera, significant differences were observed (p=4.19x10^{-3}). The treatments were grouped by Dunn's test, with treatments TCM-14, ICM-7, and TCM-7 presenting the highest yield with values of 1192.31, 1076.92, and 1076.92 kg of dry cacao ha^{-1}, respectively, which were statistically equal, followed by ICM-14 with 653.85 kg of dry cacao ha^{-1}. The lowest value was registered for ICM-21 with 384.62 kg of dry cacao ha^{-1} (Figure 2). In Gigante, although no significant differences in yield were detected (p=0.19), the values in decreasing order of yield were 1730.77, 1461.54, 1307.69, 1153.85, and 1153.38 kg of dry cacao ha^{-1} for treatments ICM-7, TCM-7, ICM-14, ICM-21, and TCM-14, respectively, with similar behavior to that found in Rivera.

Regarding the integrated management index (Figure 3), both locations showed significant differences (Rivera (p=0.02) and Gigante (p =0.04)). In Rivera, the treatments were grouped into three categories: "a" (ICM-7), "ab" (TCM-14 and ICM-14), and "b" (ICM-21 and TCM-7). In Gigante, the groups were "a" (ICM-7), "ab" (TCM-7, TCM-14, and ICM-14), and "b" (ICM-21) (Figure 3). These results suggest that treatment T3 (ICM-7), which combined integrated crop management with the removal of diseased fruit every 7 days, was the most effective in both locations, according to the integrated management index. On the other hand, treatments T2 (TCM-14) and T4 (ICM-14), which applied traditional crop management in the first, and integrated crop management in the second, both with the removal of fruit every 14 days, showed intermediate performance. In contrast, treatment T5 (ICM-21), with diseased fruits removed every 21 days, was consistently the least effective at both locations, suggesting that less frequent removal of diseased fruit reduces the effectiveness of FPR management, even when applying chemical and biological defensive products. The differences between locations underscore the impact of specific environmental or management conditions on treatment response, illustrating that the effectiveness of management practices can vary according to the local context.

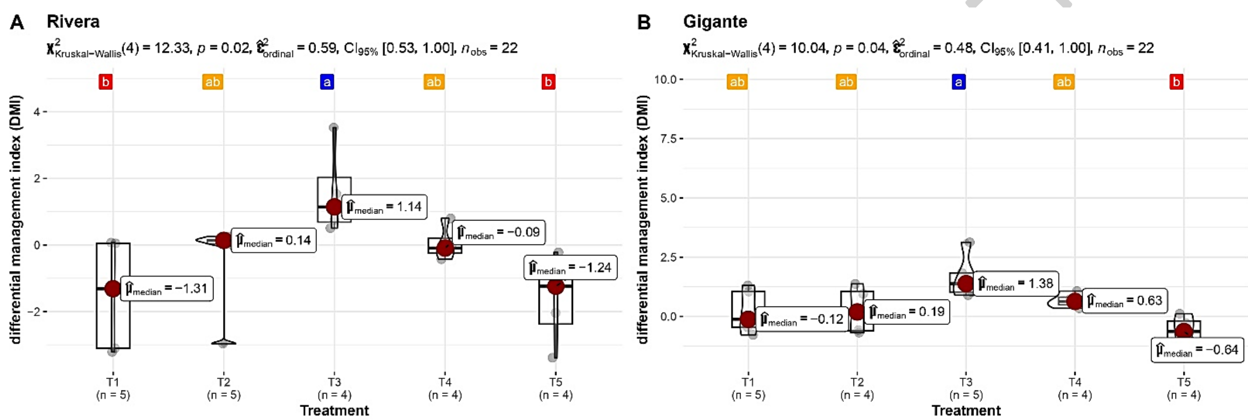

Figure 3. Effect of TCM and ICM with different Frosty Pod Rot removal frequency (7, 14, and 21 days) on the differential management index (DMI) in ICS-39 cacao pods across two localities and pod ages. Different colors and letters represent significant differences between the levels of the analysis factor.

This approach represents a novel integration of agronomic and phytopathological data, as no previous studies have formally defined or applied this type of differential index. Although the inverse relationship between AUDPC and yield has been well documented in various crops such as rice (Nuryanto and Praptana 2025), wheat (Sharma et al. 1997), and groundnut (Padi 2008), the construction of a unified, standardized metric that contrasts productivity and disease progression offers a practical and interpretable tool. Therefore, this index is proposed as an original methodological contribution of this study, enabling a more integrated assessment of treatment efficacy in both phytosanitary and productive scenarios.

The observed differences between localities for both AUDPC and yield highlight the influence of specific environmental or management conditions on treatment response, demonstrating that the effectiveness of management practices can vary depending on the local context. In cacao, genotypes can be categorized according to their resistance to *M. roreri* infection. Clone ICS-39 has been classified as susceptible (Rodríguez and Medina 2005) and moderately resistant (Jaimes et al. 2011). Therefore, spraying chemical and biological pesticides on this clone, combined with weekly or biweekly removal of diseased fruit, reduced the incidence and increased the yield and the differential management index. However, their effect is insufficient at intervals where the diseased fruits are removed every 21 days.

When plant disease management practices are combined, the effects of their application can be additive, synergistic, or antagonistic (Ritchie et al. 2018). The effect is considered additive when the level of control is approximately the sum of the control achieved when each practice is applied separately, and the analysis of variance reveals significant main effects of the two treatments without interaction between them. Synergistic effects are defined when the benefits of combining two practices are more effective than expected, based on the effects of the two management techniques applied together, and there is a significant interaction between the two treatments (Keinath 2024). The practice of eliminating diseased fruits continues to be the fundamental basis for FPR management in Colombia, since even with spraying the latest generation of chemical molecules, the worst results were obtained in eliminating diseased fruit every 21 days. Therefore, it is necessary to continue evaluating the spraying of chemical defenses for exhaustive periods to achieve more consistent and precise results that allow a more efficient combination of the intervals of elimination of diseased fruit and their application.

Results of this study indicate that the practice of removing diseased cacao pods remains the basis for FPR management. Even with the application of biological and chemical molecules, the worst results were consistently obtained when diseased fruits were removed every 21 days. This suggests that less frequent removal intervals compromise the general management strategy. Therefore, it is necessary to continue evaluating the application of both biological and chemical fungicide products during longer periods to obtain more consistent and precise results, allowing a more efficient combination of diseased fruit removal intervals and spraying calendar. This research will be crucial for developing sustainable and economically viable management strategies for Frosty Pod Rot in cacao.

CONCLUSION

The integrated management strategy reduces the incidence of FPR than other treatments in commercial ICS-39 cacao clone plantations in Huila. Combining bi-weekly application of fungicides with weekly removal of diseased pods significantly decreased the incidence of FPR in immature cacao fruits. This reduction was crucial since applications of low-toxicity fungicides provide significant protection during the most susceptible fruit stages and contribute to maintaining productivity in clone ICS-39. However, longer intervals between diseased pod removals (21 days), even when implementing an ICM approach, resulted in higher disease incidence. These results confirm the importance of integrating cultural, chemical, and biological components as complementary practices for sustainable disease management of cacao.

The research contributes to confirming the efficacy of combining diverse management practices under the conditions of the Huila region for the susceptible ICS-39 cacao clone. Future research may evaluate the consistency of these results across other cacao clones and under diverse agroecological conditions to enhance integrated management strategies and inform regional recommendations for sustainable cacao production.

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CONFLICT OF INTERESTS

The authors declare that they have no conflicts of interest concerning this article.

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