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# Control of black leaf streak disease without mancozeb in commercial plantations of Colombia

**Simon Gibert[1,3*], Romain Alcrudo[1,4], Annaïg Blouin[2,3], Richard Andrade[4,5], Ferney Cruz[4,5], Antonio Gonzales[4,5], Ines Dupouy[6], Denis Ravanas[7], Philippe Pons[7], Luc de Lapeyre[2,3]**

[1]CIRAD, UPR GECO, F-97285 Le Lamentin, Martinique, France, [2]CIRAD, UPR GECO, F-34398 Montpellier, France, [3]GECO, Univ Montpellier, CIRAD, Montpellier, France, [4]C.I. Técnicas Baltime de Colombia S.A., Santa Marta, Colombia, [5]Grupo Agrovid S.A.S., Santa Marta, Colombia, [6]LIDL France, Châtenay-Malabry, France, [7]AZ France S.A., Cavaillon, France.

***Autor de correspondencia:***
Simon Gibert
simon.gibert@cirad.fr

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## ABSTRACT

Black Leaf Streak Disease (BLSD) is the main pathogenic constraint for Cavendish banana production systems intended for export. Conventional control strategies of this damaging disease largely rely on weekly applications of mancozeb, often combined with curative fungicides that frequently lost effectiveness due to the emergence of fungal resistance driven by their intensive use. Such strategies are no longer considered sustainable due to technical, environmental, economic, and regulatory reasons. Indeed, mancozeb has been banned in the European Union (EU) since 2021, and additional restrictions on dithiocarbamates are expected under the European Green Deal. Here, we conducted a one-year evaluation of an alternative control strategy in a commercial plantation of Colombia, characterized by a humid tropical climate with a distinct dry season. This strategy is based on a biological forecasting system that supports rational treatment decisions through weekly monitoring of epidemiological and climatic parameters. It excludes mancozeb and other active substances not approved in the EU and promotes the use of mineral oil and SBI group 2 fungicides.

Results showed that this forecasting-based strategy achieved disease control comparable to the conventional program used in an adjacent plantation. The Treatment Frequency Index was reduced by 60%, the amount of active ingredients applied by 78%, and the use of non-EU-approved substances by 89%. Treatment costs were reduced by 36%, while disease pressure, fruit quality, and yield were maintained. These promising results support scaling up this approach to larger production areas.

**Keywords:** Black Leaf Streak Disease, Black Sigatoka, Banana, *Pseudocercospora fijiensis*, Biological forecasting, Colombia, Fungicide, Mancozeb, Plant protection

## RESUMEN

La Sigatoka Negra representa la principal limitación fitosanitaria para los sistemas de producción de banano Cavendish destinados a la exportación. El control convencional se basa en aplicaciones semanales de mancozeb, combinadas con fungicidas curativos cuya eficacia ha disminuido debido al desarrollo de resistencia asociado a su uso intensivo. Sin embargo, estas estrategias ya no se consideran sostenibles por razones técnicas, ambientales, económicas y regulatorias. El mancozeb fue prohibido en la Unión Europea (UE) en 2021 y se prevén restricciones adicionales sobre los ditiocarbamatos en el marco del Pacto Verde Europeo. En este estudio se evaluó durante un año una estrategia alternativa en una plantación comercial de Colombia, en clima tropical húmedo con estación seca marcada. La estrategia se basa en un sistema de alerta biológica que orienta decisiones de tratamiento mediante el monitoreo semanal de parámetros epidemiológicos y climáticos. Excluye el mancozeb y otras sustancias no aprobadas en la UE, y favorece el uso de aceite mineral y fungicidas IBS del grupo 2.

La estrategia logró un nivel de control comparable al programa convencional en una plantación adyacente. El Índice de Frecuencia de Tratamientos se redujo en un 60 %, la cantidad de ingrediente activo en un 78 % y el uso de sustancias no aprobadas en la UE en un 89 %, con una reducción del 36 % en los costos de tratamiento, sin afectar la presión de la enfermedad, la calidad del fruto ni el

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rendimiento. Estos resultados prometedores respaldan la ampliación de esta estrategia a superficies de producción más extensas.

**Palabras clave**: Sigatoka negra, Banana, *Pseudocercospora fijiensis*, Preaviso biológico, Colombia, Fungicida, Mancozeb, Protección vegetal

## INTRODUCTION

Black Leaf Streak Disease (BLSD) is the primary phytopathological constraint affecting export-oriented Cavendish banana production. The disease is caused by the ascomycete fungus *Pseudocercospora fijiensis*, which initially produces small lesions on young leaves that gradually elongate into black streaks, multiply, and eventually coalesce to form extensive necrotic zones on the leaf surface. In severe cases, the defoliation caused by the disease can significantly reduce the plant's photosynthetic capacity, leading to smaller fruit size and lower yields. However, this impact is generally limited in commercial plantations if more than 5 to 7 functional leaves are maintained at harvest (De Lapeyre de Bellaire *et al*., 2010). Most importantly, leaf necrosis can trigger premature fruit ripening and significantly reduce the post-harvest green life of bananas (Castelan *et al*., 2012, 2013). Consequently, insufficient disease control in plantations may result in bunches unsuitable for export market, thereby causing significant economic losses.

In most banana-exporting countries, conventional control strategies of this damaging disease largely rely on weekly applications of contact fungicides such as mancozeb, often combined with curative molecules that have frequently become ineffective due to the emergence of fungal resistance resulting from their intensive use over many years. Such strategies are no longer considered sustainable due to technical, environmental, economic, and regulatory concerns (De Lapeyre de Bellaire *et al*., 2010, 2024). Indeed, mancozeb was already banned in the European Union (EU) in 2021, and the forthcoming introduction of mirror clauses under the Green Deal, along with the reduction of Maximum Residue Limits (MRLs) for dithiocarbamates within the EU, may soon prohibit the use of this fungicide.

Within a collaborative framework involving actors from production, import, distribution, and research (Tecbaco Group, Orcero, AZ France, LIDL France, and Cirad), we conducted a one-year evaluation of an alternative control strategy in a pilot commercial plantation located in the Magdalena department of Colombia, a region characterized by a tropical climate with a distinct dry season. This strategy is based on a biological forecasting system that enables a rational use of fungicides in compliance with EU regulations, including the complete exclusion of mancozeb and other active substances not approved in the EU. This strategy, initially developed to control Yellow

Sigatoka and successfully implemented to control BLSD in the French West Indies (Ganry *et al*., 2008, 2012), has also been applied effectively in different production contexts, such as in the dry tropical conditions of the Dominican Republic (Guillermet et al., 2014), where fungicide resistance had already emerged, as well as in more humid conditions of commercial plantations of Ivory Coast (De Lapeyre De Bellaire et al., 2024). It relies on the weekly monitoring of epidemiological, biological, and climatic parameters to guide treatment decisions only when necessary, combined with the broader use of mineral oil and fungicides from Sterol biosynthesis Inhibitors of group 2 (SBI), which are less prone to resistance development. This study assesses the technical feasibility and phytosanitary, agronomic, and economic performance of this biological forecasting strategy under commercial conditions, with the objective of demonstrating its suitability for large-scale implementation.

## MATERIALS AND METHODS

### Pilot commercial farm selection and characteristics

In 2023, under the initiative of LIDL France, a collaborative project with Cirad was launched to evaluate, in a pilot commercial farm of the company Tecbaco, an alternative BLSD management strategy excluding mancozeb and other non-EU-approved active substances. A preliminary phytosanitary diagnostic was performed across several plantations to identify the most suitable pilot site (data not presented). The study was conducted from April 2024 to April 2025 in a commercial banana plantation located in the Zona Bananera (Magdalena, Colombia), a lowland humid tropical region characterized by stable high temperatures (27–29 °C) and a marked dry season from December to April. The plantation is divided into two operational units (i.e. two farms) with similar soils (sandy to loamy, neutral to slightly acidic pH, low salinity) and identical agronomic practices. The Farm 1 (84.9 ha) served as the conventional control while the Farm 2 (94.2 ha) was designated as the pilot farm to implement the biological forecasting strategy. Both farms are structured into cableway-delimited production blocks and employ dedicated field teams, allowing direct comparison of phytosanitary, agronomic and economic performance between the two management strategies.

### Fungicide selection and resistance assessment

In the conventional control farm (Farm 1), fungicide types and doses followed the standard spray program currently used in the plantation. In the pilot farm (Farm 2), fungicides were selected only from active ingredients authorized in the EU and were applied within the limits of the approved reference dose; mancozeb and all non-EU-approved substances were therefore excluded such as fenpropimorf (morpholine),

isopyrazam (SDHI), or epoxiconazole (triazole). Moreover, only fungicides without evidence of high resistance in local *P. fijiensis* populations were retained, as determined through the resistance evaluation protocol described below:

Sampling was carried out in 2024. Thirty banana plants were randomly selected within the Farm 2 plot, and thirty leaf pieces (25 × 25 cm) bearing stage 2–3 of *P. fijiensis* lesions according to Fouré (1988) were collected and brought to the laboratory. Single-conidium isolates were obtained from well-defined stage 2 lesions, with a maximum of three isolates retained per leaf, resulting in a final population of 22 strains. Fungicide resistance was evaluated based on mycelial growth inhibition using optical density measurements, following a method adapted from Chong *et al*. (2021). Isolates were grown on PDA for 10 days, and mycelial suspensions were prepared for liquid growth assays in 96-well microplates using PDB medium amended or not with different concentrations of fungicides. Growth was measured after 7 days at 25°C by spectrophotometry (690 nm, Tecan). Three fungicide families were tested across concentration gradients as follows: Triazoles (Demethylation Inhibitors (DMI)): difenoconazole and propiconazole (0, 0.004, 0.016, 0.04, 0.16, 0.64, 2.56, 10.24 $mg \cdot L^{-1}$); Benzimidazoles (Methyl Benzimidazole Carbamates (MBC)): thiabendazole (0, 0.1, 1, 10, 100 $mg \cdot L^{-1}$); Strobilurins (Quinone outside Inhibitors (QoI)): azoxystrobin (0.03, 0.1, 0.3, 1, 3, 10, 100 $mg \cdot L^{-1}$). For DMI fungicides, $IC_{50}$ values were calculated for each isolate and compared to the mean $IC_{50}$ of a susceptible reference population (never exposed to fungicides) in order to calculate a resistance factor (RF), defined as: *RF= Average $IC_{50}$ plantation population/Average $IC_{50}$ of reference population*. For MBC and QoI fungicides, isolates were classified as resistant based on their ability to grow at ≥1 $mg \cdot L^{-1}$ and ≥10–100 $mg \cdot L^{-1}$, respectively. The proportion of resistant isolates within the sampled population was then determined.

**Disease monitoring and decision support strategy**

In the pilot farm 2, BLSD was managed using a biological forecasting strategy developed by CIRAD (Fouré & Ganry, 2008). This approach relies on weekly monitoring of epidemiological, biological, and climatic parameters to guide fungicide applications according to epidemic risk. For this purpose, two observation plots were established in Farm 2 (Farm 2.1 and Farm 2.2), and in the conventional control Farm 1 (Farm 1.1 and Farm 1.2). Each observation plot consisted of 10 marked plants at the same physiological stage (minimum 5 functional leaves) monitored weekly until flowering, after which observation plots were renewed by selecting a next cohort of plants.

The biological information recorded consisted of the following indicators as presented by De Lapeyre De Bellaire *et al.* (2024): (i) the stage of evolution of the

disease (SED), calculated from lesion stages on leaves 2 to 4 combined with leaf emission rate (Fouré & Ganry, 2008); (ii) the youngest leaf bearing streaks (YLSt), used as an indicator of incubation duration (de Lapeyre de Bellaire et al., 2010); (iii), the youngest leaf spotted (YLS), used to estimate the total epidemic cycle duration (de Lapeyre de Bellaire *et al*., 2010); (iv) the number of functional leaves at flowering (NLF), assessed on 20 newly flowering plants; (v) the number of functional leaves at harvest (NLH), assessed on 20 plants ready for harvest; and (vi) a lesion density score (D+), corresponding to the number of leaves exhibiting more than 50 lesions during SED assessment, with a maximum possible score of 30 for 10 plants on leaves 2, 3, and 4 (Fouré & Ganry, 2008).

Each week, the indicators measured in the Farm 2 observation plots were analyzed alongside rainfall data recorded locally, and treatment decisions were made jointly by CIRAD and Tecbaco to determine whether a fungicide application was required and to select the appropriate product (type and dose). Farm 1 observations were recorded for comparison only and did not influence its conventional spray schedule, made by the company itself. All fungicide applications within each farm were carried out on the same day by aerial spraying.

**Evaluation of the performance of the strategy**

The performance of the phytosanitary strategy was evaluated using a set of indicators monitored throughout the year.

Phytosanitary status was assessed through the number of occurrences where the stage of evolution of the disease (SED) exceeded 1500, the number of high lesion density observations (D+ >10), the number of plots with an average number of functional leaves at harvest (NLH) ≤5, and the percentage of "risky bunches" harvested from plants bearing less than three functional leaves (a functional leaf is defined as a leaf with more than 1/3 of green area), recorded at packing stations.

The intensity and nature of fungicide applications were quantified using the Treatment Frequency Index (TFI = Σ [(applied dose × treated area) / (reference dose × cultivated area)]), the total quantity of active ingredient applied (kg a.i·ha$^{-1}$·year), the total number of treatments, the percentage of non-EU-approved fungicides used, and the total volume of mineral oil applied (L·ha$^{-1}$).

Agronomic performances were evaluated using production data from the producer, including yield (20-kg boxes·ha$^{-1}$), average bunch weight (kg), and fruit grade (percentage of fingers above the quality threshold defined by the company). Yield performance was expressed as the ratio of the yield obtained during the study

year to the mean yield over 2019–2023 (yield performance = $yield_{study}$/ $yield_{2019–2023\ mean}$). The same approach was used for bunch weight (bunch weight performance = $bunch\ weight_{study}$ / $bunch\ weight_{2019–2023\ mean}$).

Post-harvest quality was assessed through weekly quality scores at destination ripening rooms in France (data not shown) and by quantifying the proportion of cartons exhibiting deficient green life (GL). In Colombia, GL was evaluated weekly on bananas harvested at 10, 11, and 12 weeks after flowering in both farms. For each age class and farm, the third hand of 16 bunches was sampled, and two clusters of six fingers per hand were packed in either *Politubo* (perforated) or *Banavac* (sealed) bags. All clusters were treated with gibberellic acid (1.5 $cm^3\ L^{-1}$) prior to packing. Boxes were stored in a refrigerated container (13 °C) and inspected twice per week. Green life was determined by detecting the onset of climacteric ripening through tactile detection of loss of firmness and visual scoring; a box was classified as ripe when at least one cluster exhibited climacteric onset**.** According to company specifications, green life was considered deficient when GL < 25 days for Politubo and GL < 33 days for Banavac.

Economic evaluation was limited to compared costs associated with fungicides and aerial spraying.

## RESULTS AND DISCUSSION

### Fungicide resistance

Fungicide sensitivity analysis showed contrasted resistance patterns. A majority of isolates (59 %) were resistant to azoxystrobin, confirming that QoI fungicides are no longer suitable in this context. In contrast, all isolates (100 %) were sensitive to thiabendazole, suggesting that benzimidazoles remain effective and could be integrated into the control strategy, particularly since they are not currently used in the studied plantations, thus limiting the risk of pre-existing resistance.

For triazoles, which are subject to quantitative resistance, propiconazole showed a marked shift toward high $IC_{50}$ values, with 55 % of isolates in the 3–7 $mg{\cdot}L^{-1}$ range and one isolate >15 $mg{\cdot}L^{-1}$, and a hight RF of 107, indicating resistance levels incompatible with effective field use; it was therefore excluded from the strategy. Difenoconazole also exhibited elevated $IC_{50}$ values, with 46 % of isolates in the 0.6–1 $mg{\cdot}L^{-1}$ class, 41 % above 1 $mg{\cdot}L^{-1}$, and a RF of 84, reflecting reduced sensitivity. Given its role as one of the few systemic fungicides remaining effective, difenoconazole was retained but with strict limitations, not exceeding 2-3 applications per year to avoid further resistance selection.

Overall, these results considerably narrow the range of systemic fungicides available for BLSD control under the biological forecasting strategy. This reinforces the need for careful alternation with non-selective products, including a broad use of SBI Group 2 fungicides (morpholines, e.g., fenpropidin) and the use of mineral oil alone (12 L/ha), which provides a light curative effect generally lasting less than two weeks (Delatouche *et al*., 2022). In addition, strict limitation of triazoles (difenoconazole; maximum 2–3 applications per year), SDHI fungicides (boscalid; maximum 2–3 applications per year), and the integration of benzimidazoles (thiabendazole; maximum 2–3 applications per year) as a valuable complementary option within the limits of the formulations currently available in Colombia is required.

To compare disease dynamics under the two management strategies, several epidemiological indicators were monitored throughout the study period (Figure 1). A peak in disease pressure between weeks 40 and 45 was reflected in both farms by a marked increase in the SED, and important densities of inoculum were observed on the youngest banana leaves. Consequently, the proportion of plants reaching harvest with five or fewer functional leaves increased, reaching up to 50% in both the pilot and control plantations (data not shown). This indicates that the seasonal rise in BLSD pressure affected the farms similarly under both management strategies.

**Disease monitoring**

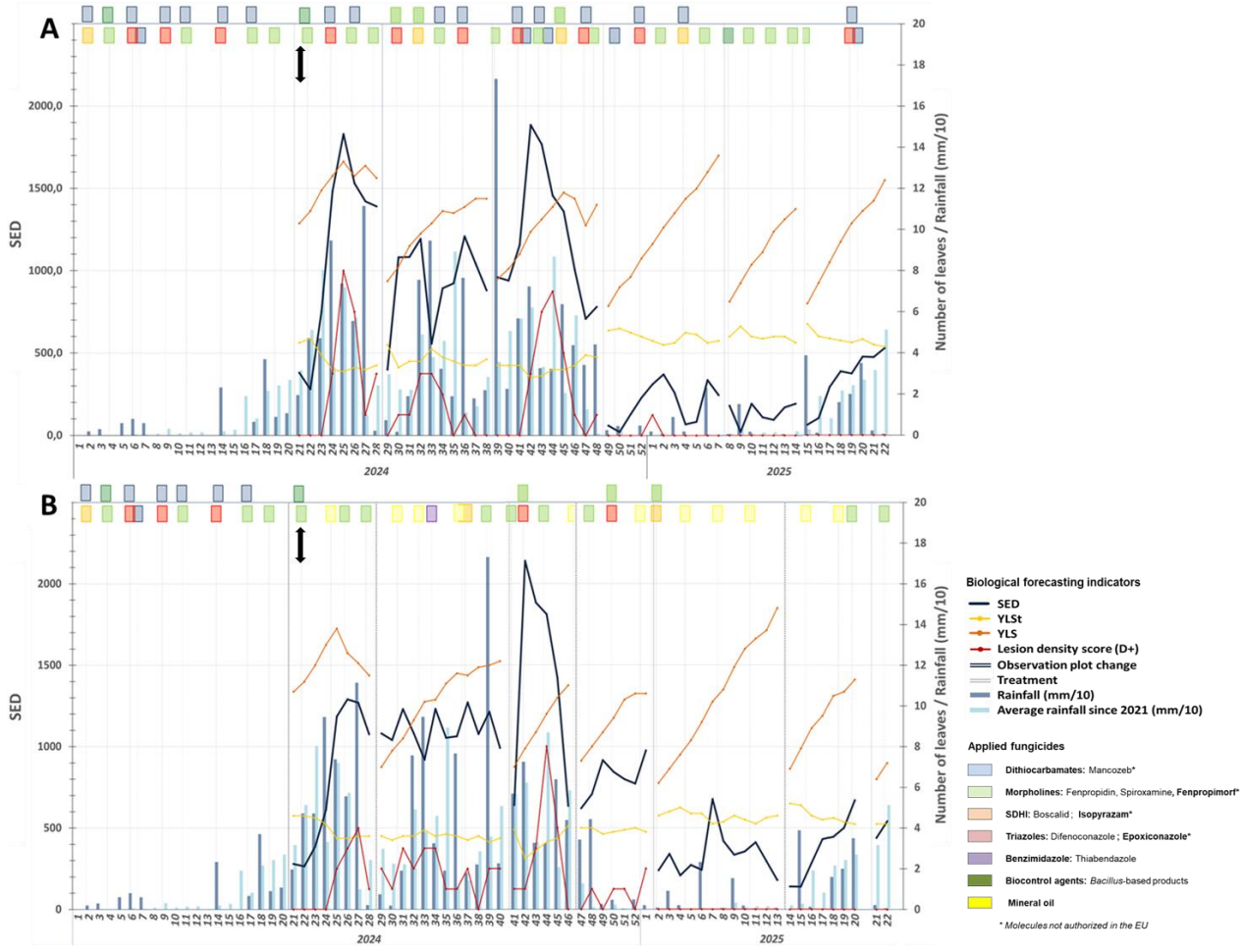



**Figure 1.** Graphical representation of indicators monitored between April 2024 and April 2025 on (A) observation plot 1 of Farm 1, representing the conventional treatment strategy, and (B) observation plot 1 of Farm 2, representing the biological forecasting–based strategy. A black double arrow marks the start of the trial, and the phytosanitary treatment sequence is shown by colored squares at the top of each graph, each color corresponding to a different product family as indicated in the legend.

**Table 1.** Comparison of performance indicators between Farm 1 (control) and Farm 2 (pilot).

| | Indicator | Farm 1 (Control) | Farm 2 (Pilot) | Relative change (Farm 2 vs Farm 1) |
|---|---|---|---|---|
| **Phytosanitary performance** | EE > 1500 (occurrence) | 8 % *(7/92)* | 10 % *(9/92)* | *negligible* |
| | High lesion density (D+ > 10) | 0 % *(0/92)* | 1.1 % *(1/92)* | *negligible* |
| | NLH ≤ 5 at harvest | 1.3 % *(2/150)* | 2.0 % *(3/150)* | *negligible* |
| | Risky bunches (≤ 3 functional leaves) | 0 % *(1/1500)* | 0.1 % *(2/1500)* | *negligible* |
| **Fungicide application intensity** | Treatment Frequency Index (TFI) | 35.2 | 14.0 | **−60 %** |
| | Active ingredient use (kg a.i./ha/year) | 21.4 | 4.7 | **−78 %** |
| | Number of aerial applications | 24 | 20 | **−17 %** |
| | Use of non-EU-approved fungicides | *18/36 (*50 %*)* | *2/23(*8.7%*)* | **−89 %** |
| | Mineral oil use (L/ha/year) | 202 | 220 | **+9 %** |
| **Agronomical performance** | Yield performance (boxes/ha) | 99 % | 93 % | **-6 %** |
| | Bunch weight performance | 97 % | 94 % | **-3 %** |
| | Deficient grade standard (%) | 0 % | 0 % | **0 %** |
| **Quality performance** | Deficient green life politubo (%) | 39 % | 40 % | **+3 %** |
| | Deficient green life banavac (%) | 27 % | 10 % | **-63 %** |
| | Deficient green life (%) | 33 % | 27 % | **-18 %** |
| **Economic performance** | Cost of products ($COP/ha) | *c.d.** | *c.d.* | **-38 %** |
| | Cost of spraying flights ($COP/ha) | *c.d.* | *c.d.* | **-31 %** |

**c.d.: Confidential data*

## Performance of the strategy

Phytosanitary monitoring showed that disease pressure remained under control in both farms throughout the year (Table 1; Figure 1). The occurrence of high disease evolution values (EE > 1500) was similar between strategies (10% in Farm 2 vs. 8% in Farm 1), and high lesion density events (D+ > 10) were rare in both cases (1 vs. 0 %). Likewise, the proportion of plants reaching harvest with fewer than five functional leaves (NLH ≤ 5) and the percentage of "risky bunches" (≤3 functional leaves at harvest) remained very low in both farms (<2%), indicating that the alternative strategy did not compromise fruit physiological maturity.

In terms of fungicide use, the contrast between strategies was substantial (Table 1). The Treatment Frequency Index (TFI) was reduced by 60 in the pilot farm 2 (14.0 vs. 35.2 in Farm 1), and the annual quantity of active ingredient applied decreased by 78% (4.7 vs. 21.4 kg a.i $ha^{-1}$ $year^{-1}$). This reduction is mainly attributable to the elimination of mancozeb and the increased use of mineral oil alone, ex5 plaining why

the total number of applications remained similar despite the strong decrease in chemical load. Furthermore, the use of active substances not approved in the EU dropped by 89%, demonstrating significant progress towards regulatory compliance. It is important to note that the two applications recorded in Farm 2 were not intentional but resulted from an operational error in the treatment preparation process.

The partial economic evaluation revealed a substantial reduction in phytosanitary treatment costs under the alternative strategy (Table 1). Using the control Farm 1 as a reference, the total treatment cost in the pilot Farm 2 was reduced by approximately 36%. This reduction was primarily driven by the lower volume of fungicide products required as well as a decrease in the number of aerial spray operations. Product costs per hectare decreased by -38%, while aerial application costs decreased by -31%. These results demonstrate that the forecasting-based strategy not only reduces chemical inputs but also provides a potential economic benefit.

Agronomic performance did not differ between the two farms throughout the evaluation period (Table 1). Yield, bunch weight, and fruit size followed similar trends under both management strategies, with no sustained decline in the pilot farm. Fruit caliber was preserved, as only one bunch in each farm failed to meet the minimum grade standard.

Post-harvest performance was assessed through green life (GL) tests and export quality evaluations (Table 1). The proportion of boxes not meeting the minimum storage duration was similar under politubo packaging (38% in Farm 1 vs. 43% in Farm 2), while banavac packaging showed fewer at-risk boxes in the pilot farm (11% vs. 29%). However, these values likely overestimate risk due to repeated container openings during the GL test. Export quality control (data not shown) confirmed comparable fruit behavior during ripening in both farms and total the absence of premature ripening in all shipments of both farms.

## CONCLUSION

Under the conditions of this evaluation, disease management using this forecasting-based strategy proved to be as effective as the conventional approach based on mancozeb applications in the adjacent control plantation. The Treatment Frequency Index (TFI) was reduced by 60% (14 vs. 35), and the amount of active ingredients applied decreased by 78% (4.7 kg of active ingredient/ha/year compared to 21.4 kg/ha/year in the conventional strategy). The number of active substances not approved in the EU was reduced by 89% (2 vs. 18), and treatment costs (fungicides products and aerial application) were reduced by 36%. In parallel, key indicators of disease pressure,

fruit quality, and yield were comparable between the two management strategies. These promising results obtained during this first year encouraged the continuation of the project, with the objective of significantly scaling up the implementation of the biological forecasting strategy to much larger areas.

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