GMR

The Original

FROM PATHOGEN ERADICATION TO FUNCTIONAL RECOVERY: AN INTEGRATED MOLECULAR DIAGNOSTIC–RHIZOSPHERE BIOLOGY FRAMEWORK FOR PRODUCTIVE CONTINUITY IN ENDEMIC *FUSARIUM ODORATISSIMUM* (TR4)-AFFECTED CAVENDISH BANANA SYSTEMS

Jessve Daypuyart[1], Ronal Tuvilla[1], Mac Harl Kenthjohn Villagracia[1]*

[1]Agright Technologies, Philippines
Corresponding Author: jdaypuyart@agrightechnologies.com, agrightech@gmail.com

ABSTRACT
Fusarium wilt of banana caused by Fusarium odoratissimum (Tropical Race 4; TR4) remains one of the most consequential biological threats to global Cavendish banana production. Management strategies have traditionally emphasized exclusion, biosecurity, eradication, and the development of resistant planting materials. However, once TR4 becomes established under endemic production conditions, the challenge extends beyond pathogen avoidance toward sustaining productive agricultural systems despite persistent disease pressure.

A four-year multi-site field investigation was conducted across approximately 30 hectares of commercial Cavendish production systems in Mindanao, Philippines, representing a production landscape of more than 50,000 plants distributed across lowland, midland, and highland agroecological zones. Within this landscape, approximately 5,000 plants were molecularly confirmed as TR4-positive and formed the primary study population. The study evaluated an integrated Molecular Diagnostic–Rhizosphere Biology Framework combining rhizosphere-targeted biological intervention, multi-enzyme rapid molecular diagnostics, and satellite-based landscape monitoring. Satellite-derived vegetation and productivity indicators were incorporated as independent landscape-scale measures of production continuity, enabling multi-scale assessment of disease dynamics, canopy vigor, and productive function across heterogeneous field environments. Treatment performance was evaluated using site-adjusted statistical models, survival analysis, and spatial epidemiological approaches.

Across diverse agroecological environments, Functional Recovery was observed in 4,987 of 5,000 molecularly confirmed TR4-positive plants (99.74%; 95% CI: approximately 99.57–99.85%). Recovery occurred through two distinct pathways: curative recovery (2,995/3,000; 99.83%) and preventive recovery (1,992/2,000; 99.60%). The overall collapse rate was 0.26% (13/5,000 plants). These outcomes were observed under molecularly confirmed pathogen presence and across multiple production environments, suggesting that productive continuity may be achievable even where pathogen elimination is no longer feasible. To our knowledge, this represents one of the largest field-scale evaluations of productive continuity under molecularly confirmed TR4-positive conditions in commercial Cavendish banana systems.

Preservation of productive function reduced the risk of premature field abandonment and supported continuity of productive hectares, thereby mitigating agronomic and economic losses commonly associated with endemic TR4 pressure. Based on these observations, this study proposes Functional Recovery as a complementary management outcome measure for Cavendish banana systems affected by endemic TR4. Functional Recovery is operationally defined as the capacity of a production system to preserve productive function, biological resilience, and economic continuity despite confirmed pathogen presence.

The findings support a broader re-examination of success metrics in TR4 management. In endemic production systems, agricultural success may need to be evaluated not solely through pathogen absence, but through the ability of production systems to sustain productive function under persistent disease pressure. Rather than replacing exclusion, containment, or resistance-based approaches, Functional Recovery is proposed as a complementary

management endpoint that expands TR4 evaluation from pathogen-centered outcomes toward preservation of productive agricultural systems under endemic disease conditions. Unlike conventional TR4 management strategies that primarily evaluate pathogen suppression or exclusion, the present framework evaluates preservation of productive function despite molecularly confirmed pathogen presence.

KEYWORDS: Fusarium odoratissimum, Tropical Race 4, Cavendish banana, Functional Recovery, production resilience, rhizosphere ecology, molecular diagnostics, satellite agriculture, regenerative agriculture.

1. INTRODUCTION

Fusarium wilt of banana, commonly known as Panama disease, remains one of the most consequential biological threats to global banana production. The Tropical Race 4 (TR4) variant, now taxonomically classified as Fusarium odoratissimum, is particularly challenging due to its persistence in soil, capacity for long-distance dissemination, and the high susceptibility of Cavendish banana cultivars, which dominate international export markets.

Over the past two decades, TR4 has expanded across Asia, the Middle East, Africa, Latin America, and Oceania, transforming from a regional phytosanitary concern into a global agricultural and food security challenge. In major banana-producing regions such as Mindanao, Philippines, the disease has contributed to substantial economic losses, declining productivity, productive-hectare degradation, and abandonment of previously cultivated farms. These impacts extend beyond farm-level economics and affect livelihoods, regional agricultural competitiveness, and the long-term sustainability of banana production systems.

Historically, TR4 management has focused on exclusion, biosecurity, containment, eradication, and the development of resistant planting materials. While these approaches remain essential, their effectiveness becomes increasingly constrained once the pathogen becomes established under endemic field conditions. In many production landscapes, the practical challenge is no longer solely preventing pathogen introduction, but sustaining productive agricultural systems despite persistent disease pressure.

This distinction raises an important question that has received comparatively limited attention in the scientific literature: how should success be defined in banana production systems where pathogen elimination is no longer immediately achievable? While most TR4 research evaluates disease suppression, pathogen exclusion, or resistance, considerably less attention has been given to productive continuity, biological resilience, and the capacity of commercial production systems to remain economically viable under confirmed pathogen presence. To date, relatively few studies have examined whether productive continuity can be sustained under molecularly confirmed TR4 presence at commercial field scale, particularly across diverse agroecological environments.

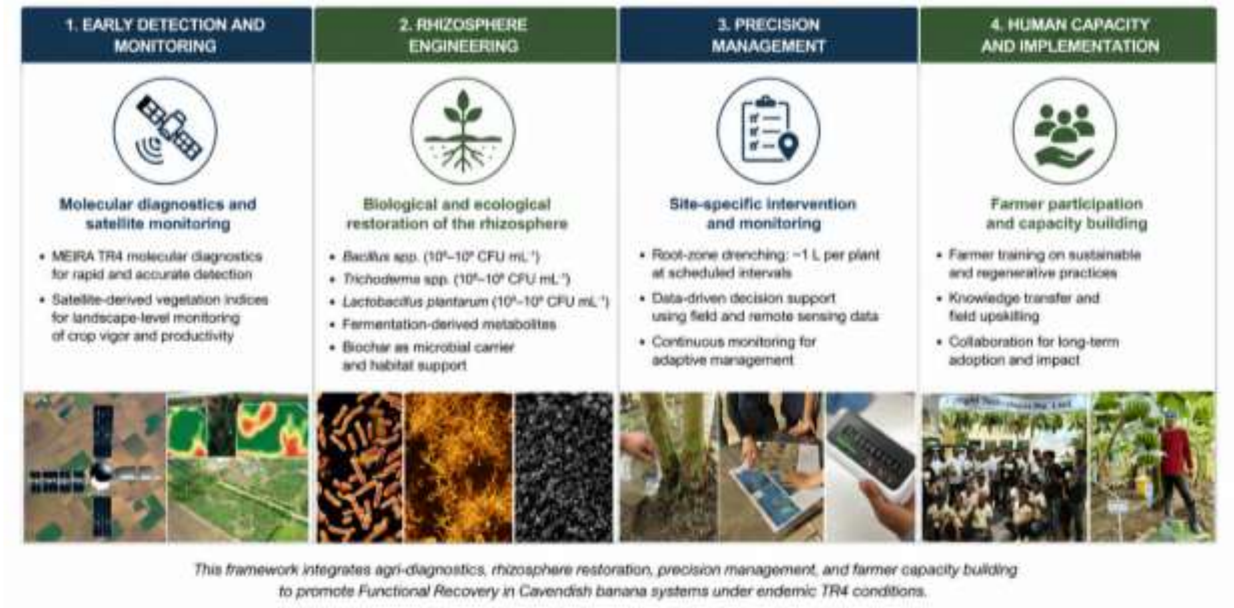
The rhizosphere represents one of the principal biological interfaces through which production resilience may be influenced. As the zone of interaction among plant roots, soil processes, and microbial communities, it mediates nutrient cycling, stress responses, plant health, and host–pathogen interactions that ultimately affect productive continuity under disease pressure. Increasing evidence suggests that manipulation of rhizosphere ecology can influence disease dynamics and enhance the capacity of agricultural systems to maintain function under biotic stress. Consequently, rhizosphere-targeted approaches may offer opportunities not only for disease suppression, but also for sustaining productive performance in pathogen-affected production environments.

This study does not propose replacement of exclusion, biosecurity, containment, eradication, or resistance-based strategies. Rather, it examines whether productive agricultural function can be preserved in situations where pathogen persistence remains a practical production reality.

Concurrently, advances in agricultural technology have expanded the capacity to monitor and manage disease at multiple scales. Molecular diagnostics enable rapid confirmation of pathogen presence, while satellite-derived vegetation and productivity indicators provide landscape-scale insights into canopy vigor, spatial disease dynamics, and production continuity. The integration of biological interventions, molecular diagnostics, and remote sensing offers an opportunity to evaluate disease management beyond pathogen detection alone and toward system-level outcomes.

Against this backdrop, the present work draws upon four years of field observations across approximately 30 hectares of commercial Cavendish production systems in Mindanao, Philippines, encompassing approximately 5,000 molecularly confirmed TR4-positive plants distributed across lowland, midland, and highland agroecological environments. By integrating rhizosphere-targeted biological intervention, multi-enzyme isothermal diagnostics, and satellite-enabled landscape monitoring, the study examines disease management not solely through the lens of pathogen suppression, but through the broader capacity of production systems to sustain productive function under persistent disease pressure.

Figure I: Components of the integrated functional recovery framework evaluated in this study



The evidence presented in this paper suggests that an exclusive focus on pathogen absence may be insufficient for evaluating success in TR4-endemic production systems. Instead, the findings support a broader perspective in which productive continuity, biological resilience, and economic viability become equally relevant outcomes. Within this context, Functional Recovery is proposed as a complementary management framework for Cavendish banana systems affected by endemic TR4, expanding the discussion from pathogen eradication toward the preservation of productive agricultural function in landscapes where the pathogen has become an enduring production reality.

2. CONCEPTUAL FRAMEWORK

The conceptual basis of this study is founded on the premise that productive agricultural systems may remain functional despite confirmed pathogen presence when biological resilience and productive continuity are preserved. Rather than viewing disease management solely through the lens of pathogen elimination, the framework recognizes the production system itself as the primary unit of recovery.

The framework begins with molecular confirmation of Fusarium odoratissimum (TR4) using multi-enzyme rapid amplification diagnostics. Unlike symptom-based assessments, molecular diagnostics establish pathogen presence directly within plant tissues and soil, enabling objective identification of infected production units and longitudinal monitoring of disease status throughout successive production cycles. This molecular foundation distinguishes the present framework from conventional symptom-based disease evaluation by ensuring that Functional Recovery is assessed under documented pathogen occurrence rather than inferred disease status.

The rhizosphere represents a critical biological interface through which production resilience may be influenced. As a highly active zone of interaction among plant roots, soil processes, and microbial communities, the rhizosphere regulates nutrient acquisition, stress responses, plant health, and host–pathogen interactions. Modification of rhizosphere ecology therefore provides a potential pathway for sustaining productive function under persistent disease pressure.

The biological system evaluated in this study consists of a consortium of beneficial microorganisms, including Bacillus subtilis, Trichoderma spp., Lactobacillus plantarum, and other Bacillus species, delivered within a biologically supportive rhizosphere environment that incorporates biochar as a microbial carrier and habitat. Biochar contributes to rhizosphere function by providing protected microsites for microbial colonization, enhancing moisture retention, improving nutrient-use efficiency, and supporting persistence of beneficial microorganisms within the root zone. Through colonization, microbial competition, and production of bioactive metabolites including lipopeptides, organic acids, and enzymatic compounds, the consortium contributes to the development of a more biologically active and functionally resilient rhizosphere.

The framework is intentionally organized across complementary biological and operational scales. Molecular diagnostics provide objective confirmation of pathogen occurrence, rhizosphere biology provides the ecological basis through which productive function may be preserved, and satellite-derived monitoring independently evaluates productive continuity at the landscape scale. Together, these complementary layers allow disease management to be evaluated from molecular confirmation through biological response to production-system performance under endemic TR4 conditions.

To evaluate system performance beyond individual plants, the framework integrates satellite-derived vegetation indicators as independent measures of canopy vigor, spatial disease dynamics, and productive continuity across the production landscape. Agritech-enabled monitoring therefore provides a systems-level assessment of resilience under heterogeneous field conditions.

Within this integrated framework, recovery is assessed not solely through pathogen suppression, but through preservation of productive function. Functional Recovery is defined as the capacity of a production system to sustain fruiting, harvest completion, productive follower establishment, and continuity of production cycles despite confirmed TR4 occurrence. Accordingly, Functional Recovery represents the biological and operational state in which productive function is preserved despite confirmed pathogen presence, while Productive Continuity represents the measurable agricultural outcome through which recovery is evaluated. Together, these concepts establish a complementary management endpoint for endemic TR4 production systems in which success is assessed not solely by pathogen absence, but by the sustained functionality of the production system.

Figure 2. Conceptual Framework for Functional Recovery and Productive Continuity under endemic Fusarium odoratissimum (TR4) conditions

3. MATERIALS AND METHODS

3.1 Study Area and Experimental Design

A four-year field investigation was conducted across multiple commercial Cavendish banana production systems in Mindanao, Philippines, between Feb 2022 and March 2026. The study encompassed approximately 30 hectares distributed across lowland, midland, and highland agroecological environments and represented a production landscape of more than 50,000 plants. Within this landscape, approximately 5,000 plants were molecularly confirmed as positive for Fusarium odoratissimum (Tropical Race 4; TR4) and formed the primary study population for Functional Recovery assessment. The study was conducted under commercial production conditions encompassing approximately 50,000 banana plants, including conventionally managed production areas that provided operational context for interpretation of field outcomes.

Study sites were selected based on documented histories of TR4 occurrence and included both previously abandoned production areas and actively managed commercial farms experiencing recurrent disease pressure. Inclusion of multiple agroecological zones was intended to capture environmental heterogeneity and evaluate performance across diverse production conditions.

A comparative field design was implemented consisting of intervention systems receiving the integrated Functional Recovery approach and reference systems managed under conventional farm practices. The study was designed to evaluate productive continuity under confirmed pathogen presence rather than pathogen exclusion alone. Accordingly, molecularly confirmed TR4-positive plants were monitored to assess disease progression, productive function, establishment of follower generations, and continuity of production cycles.

The overall study framework integrated rhizosphere-targeted biological intervention, multi-enzyme rapid amplification molecular diagnostics, and satellite-derived vegetation monitoring to evaluate resilience and production continuity at plant, field, and landscape scales under endemic TR4 conditions.

Reference systems consisted of approximately 45,000 plants located within the same production landscapes but managed under conventional farm practices. Particular attention was given to advanced-stage TR4-positive mother plants that had progressed beyond practical intervention thresholds. Historical field observations within these reference systems indicated that severely infected plants frequently collapsed before harvest completion, while productive follower generations commonly expressed Fusarium wilt symptoms during subsequent production cycles, often within one to two years following establishment.

These reference observations provided operational context for evaluating productive continuity and Functional Recovery outcomes observed within intervention systems.

3.2 Rhizosphere-Targeted Biological Intervention

The biological intervention evaluated in this study consisted of a rhizosphere-targeted delivery system designed to enhance biological resilience within the root-zone environment. The formulation was produced through a controlled bioreactor-based fermentation platform and contained a consortium of beneficial microorganisms, including Bacillus spp., Trichoderma spp., and Lactobacillus plantarum, together with fermentation-derived bioactive metabolites.

The biological formulation contained a mixed consortium of Bacillus spp., Trichoderma spp., and Lactobacillus plantarum at a combined concentration of approximately 10^8–10^9 CFU mL^{-1}, together with fermentation-derived bioactive metabolites.

Applications were conducted through root-zone drenching at approximately 1 L per plant at scheduled intervals throughout the production cycle. The intervention was designed to maintain biological activity within the rhizosphere while supporting productive function under persistent disease pressure.

Biochar was incorporated as a microbial carrier and rhizosphere-support matrix to provide protected microsites for microbial colonization, improve moisture retention, and enhance persistence of beneficial microorganisms within the root zone. The combined delivery of microorganisms, biochar, and pre-formed metabolites was intended to facilitate both immediate and sustained interaction within the rhizosphere.

Applications were conducted through root-zone drenching at predetermined intervals throughout the crop cycle. The intervention was designed to promote rhizosphere resilience through enhancement of microbial activity, ecological modulation of root-zone processes, improved nutrient-use efficiency, and support of productive function under persistent disease pressure.

3.3 Molecular Diagnostics and Disease Monitoring

Detection and monitoring of Fusarium odoratissimum (Tropical Race 4; TR4) were performed using a multi-enzyme rapid amplification (MEIRA) molecular diagnostic platform designed for field-based detection of pathogen DNA in plant tissues and soil. The assay was developed to provide rapid molecular confirmation of TR4 occurrence and facilitate longitudinal monitoring of disease dynamics under commercial production conditions.

Sampling was conducted throughout the study period and included symptomatic plants, adjacent asymptomatic plants, productive follower generations, and periodic surveillance samples collected from intervention and reference systems. Plant tissue samples were obtained from pseudostem, corm, and root tissues, while soil samples were collected from the active root zone of selected production units.

Molecular diagnostics served three primary functions within the study framework: (i) confirmation of TR4 occurrence within the production system, (ii) classification of plants and production units for Functional Recovery assessment, and (iii) longitudinal evaluation of pathogen detectability throughout successive production cycles. Unlike symptom-based assessments, the molecular diagnostic approach enabled direct confirmation of pathogen presence and provided objective evidence that productive outcomes were achieved under documented TR4 pressure.

Molecular diagnostics were used primarily as a confirmation and monitoring tool for pathogen occurrence and detectability over time rather than as a direct measure of pathogen biomass or disease severity.

Figure 3. In-field molecular detection of Fusarium odoratissimum (TR4) within commercial Cavendish banana systems.

Deployment of the multi-enzyme isothermal rapid amplification (MEIRA) platform under commercial plantation conditions, enabling molecular confirmation of TR4 occurrence directly at the point of sampling. The field-deployable diagnostic approach facilitated near real-time disease surveillance, repeated monitoring of recovered plants and productive follower generations, and integration of molecular diagnostics into operational decision-making under endemic disease conditions.

Repeated testing of recovered plants and productive follower generations was performed to evaluate changes in pathogen detectability over time. Particular attention was given to plants classified under Curative Recovery and Preventive Recovery pathways. Observations from longitudinal monitoring indicated that a substantial proportion of recovered plants and productive followers subsequently became non-detectable using the MERA platform. These findings were interpreted as evidence of reduced molecular detectability below assay detection thresholds and were not assumed to represent pathogen eradication.

Diagnostic results were integrated with field observations, production records, and satellite-derived vegetation indicators to support multi-scale assessment of Functional Recovery, productive continuity, and disease dynamics under endemic TR4 conditions.

3.4 Outcome Measures

The primary outcome of this study was Functional Recovery, defined as the capacity of a production system to preserve productive function despite molecular confirmation of Fusarium odoratissimum (TR4). Productive function was evaluated through successful fruiting, harvest completion, establishment of productive follower generations, and continuity of production cycles under confirmed pathogen presence.

To characterize recovery pathways, outcomes were classified into three mutually exclusive categories. Curative Recovery (CR) referred to molecularly confirmed TR4-positive plants that successfully completed fruiting and harvest following pathogen detection. Preventive Recovery (PR) referred to production units in which productive follower plants were successfully established and maintained despite disease occurrence in the mother plant. Collapse (COL) referred to loss of productive function resulting in failure to complete harvest or failure to establish productive follower generations.

Recovery performance was quantified using four principal metrics. Curative Recovery Rate (CRR) was defined as the proportion of curative cases that successfully completed harvest following molecular confirmation of TR4. Preventive Recovery Rate (PRR) was defined as the proportion of affected production units that successfully established productive follower generations. Functional Recovery Rate (FRR) represented the overall proportion of molecularly confirmed TR4-positive plants that maintained productive function through either curative or preventive recovery pathways. Collapse Rate (COLR) represented the proportion of TR4-positive plants that failed to maintain productive function.

Secondary outcome measures included disease progression, molecular detectability, productive continuity, canopy vigor, spatial disease dynamics, field stability, and continuity of productive hectares. Satellite-derived vegetation indicators were incorporated as independent measures of productive continuity and resilience at landscape scale.

3.5 Statistical Analysis

Functional Recovery outcomes were analyzed using a multi-level statistical framework appropriate for high-recovery, low-collapse field data. Curative Recovery Rate (CRR), Preventive Recovery Rate (PRR), Functional Recovery Rate (FRR), and Collapse Rate (COLR) were calculated as proportions with 95% confidence intervals estimated using the Wilson score method, which provides stable interval estimates for proportions approaching 0 or 1.

The primary endpoint was Functional Recovery, coded as a binary outcome indicating whether a molecularly confirmed TR4-positive plant or production unit preserved productive function through either curative or preventive recovery. Because recovery rates were expected to be high and collapse events rare, exact binomial estimates and penalized logistic regression were used as sensitivity analyses to reduce bias associated with sparse failure events.

To account for clustering and environmental variability, mixed-effects logistic regression models were fitted with treatment pathway as a fixed effect and site as a random effect. Agroecological zone, recovery pathway, crop stage at detection, and baseline disease severity were included as covariates where available. Odds ratios (OR), adjusted odds ratios (aOR), 95% confidence intervals, and p-values were reported.

Time-to-collapse was evaluated using Kaplan–Meier survival analysis and compared across groups using log-rank testing. Cox proportional hazards models with site-level frailty terms were used to estimate hazard ratios (HR) and 95% confidence intervals for progression to collapse while accounting for site-level dependence.

Spatial disease dynamics were evaluated using nearest-neighbor analysis and hotspot analysis to assess clustering of symptomatic or collapsed plants. Satellite-derived vegetation indicators were analyzed as landscape-scale measures of canopy vigor, spatial stability, and productive continuity and were integrated with field and diagnostic observations to support multi-scale interpretation of Functional Recovery.

All statistical tests were two-sided, with significance established at $p < 0.05$. Effect sizes and confidence intervals were emphasized over p-values to support biological and operational interpretation of recovery outcomes under endemic TR4 conditions.

4. RESULTS

4.1 Functional Recovery Under Confirmed Fusarium odoratissimum (TR4) Presence

Productive Cavendish banana systems were successfully maintained across multiple production environments despite molecular confirmation of Fusarium odoratissimum (TR4). The study encompassed approximately 30 hectares of commercial production systems distributed across lowland, midland, and highland agroecological zones in Mindanao, Philippines, representing a production landscape of more than 50,000 plants. Within this landscape, approximately 5,000 plants were molecularly confirmed as TR4-positive and formed the primary study population for Functional Recovery assessment.

Among 3,000 TR4-positive plants evaluated under the Curative Recovery pathway, 2,995 successfully completed fruiting and harvest following molecular confirmation of infection, corresponding to a Curative Recovery Rate (CRR) of 99.83% (2,995/3,000). Under the Preventive Recovery pathway, 1,992 of 2,000 affected production units successfully established productive follower generations, corresponding to a Preventive Recovery Rate (PRR) of 99.60% (1,992/2,000). Collectively, these outcomes indicate that productive failure was the exception rather than the dominant system response under the conditions evaluated

Overall, Functional Recovery was observed in 4,987 of 5,000 molecularly confirmed TR4-positive plants, resulting in a Functional Recovery Rate (FRR) of 99.74%. Only 13 plants failed to maintain productive function, corresponding to a Collapse Rate (COLR) of 0.26%.

Recovered plants successfully completed fruiting and harvest, while productive follower generations maintained continuity of production cycles across successive crop generations. Functional Recovery was observed across lowland, midland, and highland production environments, including sites previously considered unsuitable for continued Cavendish production due to recurring TR4 pressure. These observations indicate that productive function can be preserved despite documented pathogen occurrence and persistent disease exposure.

Figure 4. Landscape-scale evidence of productive continuity under endemic Fusarium odoratissimum (TR4) conditions.

Drone imagery of the study site illustrating changes in canopy cover and productive area between July 2023 and October 2024 under documented TR4 pressure. The upper panel shows extensive canopy gaps and areas of reduced productive function, while the lower panel demonstrates substantial restoration of canopy continuity and productive area.
Molecular diagnostics confirmed the presence of TR4 throughout the study period. Longitudinal monitoring further indicated that many recovered plants and productive follower generations subsequently became non-detectable using the multi-enzyme rapid amplification diagnostic platform. While non-detect results were not interpreted as evidence of pathogen eradication, they suggest that pathogen presence was no longer detectable by the assay in a substantial proportion of recovered production units.

Field observations indicated reduced progression to collapse, improved field stability, and sustained continuity of production cycles within intervention systems. Spatial assessments further suggested reduced clustering of severely affected plants and improved maintenance of productive areas under persistent disease pressure. Satellite-derived vegetation indicators were consistent with sustained canopy vigor and continuity of productive function across the study landscape.

Figure 5. Representative field example illustrating productive continuity under endemic Fusarium odoratissimum (TR4) conditions.

Aerial imagery and field observations from a commercial Cavendish banana production area in Panabo City, Davao del Norte, Philippines, historically affected by severe Fusarium wilt pressure. The sequence illustrates progression from a low-productivity condition to re-established productive banana generations under the management framework evaluated in this study. Representative bunch development and productive follower generations are shown for illustrative purposes. This figure is presented as a field example and is not intended as a quantitative summary of overall study outcomes.

Collectively, molecular diagnostics, field observations, spatial assessments, and satellite-derived indicators converged to support the preservation of productive function under endemic TR4 conditions. These findings demonstrate that productive continuity can be maintained despite confirmed pathogen presence and support Functional Recovery as a measurable operational outcome in Cavendish banana systems affected by endemic Fusarium odoratissimum (TR4).

Metric	**Recovered**	**Total**	**Rate (%)**
Curative Recovery	2,995	3,000	99.83
Preventive Recovery	1,992	2,000	99.60
Functional Recovery	4,987	5,000	99.74
Collapse	13	5,000	0.26

4.2 Statistical Outcomes of Functional Recovery

Wilson score confidence intervals demonstrated consistently high recovery outcomes across Functional Recovery pathways. Curative Recovery Rate was estimated at 99.83%, Preventive Recovery Rate at 99.60%, and Functional Recovery Rate at 99.74%, with narrow confidence intervals indicating stability of observed outcomes.

Functional Recovery was observed across lowland, midland, and highland production systems, suggesting reproducibility under diverse agroecological conditions. Spatial assessments further supported continuity of productive function and maintenance of productive hectares under endemic TR4 pressure.

The low frequency of collapse events (0.26%) relative to recovery outcomes indicates that productive continuity was maintained in the vast majority of molecularly confirmed TR4-positive production units.

5. DISCUSSION

The findings of this study support a broader re-examination of how success is defined in Fusarium odoratissimum (TR4)-affected Cavendish banana production systems. Historically, TR4 management has been evaluated primarily through pathogen exclusion, containment, eradication, and the development of resistant planting materials. While these approaches remain fundamentally important, they become increasingly constrained once the pathogen becomes established under endemic field conditions. Under such circumstances, the practical challenge facing growers is not solely preventing pathogen introduction, but sustaining productive agricultural systems despite persistent disease pressure.

The results presented here demonstrate that productive function can be maintained under molecularly confirmed TR4 presence. Across approximately 5,000 confirmed TR4-positive plants distributed across diverse agroecological environments, Functional Recovery was observed in 99.74% of assessed cases. Productive continuity was expressed through successful fruiting, harvest completion, establishment of productive follower generations, and maintenance of production cycles under active pathogen pressure. Importantly, these outcomes were achieved without reliance on pathogen absence as the primary measure of success.

The Functional Recovery framework proposed in this study does not seek to replace existing biosecurity, containment, eradication, or resistance-based strategies. Rather, it complements these approaches by introducing productive continuity as an additional and operationally relevant outcome in regions where TR4 has become an enduring production reality. In this context, preservation of productive function may represent a more meaningful indicator of agricultural resilience than pathogen absence alone. The Functional Recovery framework should be viewed as a hypothesis-generating framework rather than a definitive mechanistic model. While the present study demonstrates that productive continuity can be maintained under molecularly confirmed TR4 conditions, it does not establish the relative contribution of individual biological mechanisms responsible for these outcomes. Future studies integrating quantitative pathogen load measurements, microbiome dynamics, transcriptomics, metabolomics, and independent multi-location validation will be essential to refine, challenge, and further develop the framework proposed here.

Historically, disease management has been evaluated using pathogen-centered outcomes in which success is defined primarily by pathogen exclusion, disease suppression, or deployment of resistant cultivars. The findings presented here suggest that an additional systems-level endpoint may be appropriate under endemic production conditions. Functional Recovery does not redefine the biology of the pathogen; rather, it redefines how management success is evaluated. By shifting attention from pathogen absence toward preservation of productive agricultural function despite confirmed pathogen presence, the proposed framework complements existing phytosanitary strategies while expanding the range of measurable outcomes available for evaluating disease management in perennial cropping systems.

The observed recovery dynamics suggest that modification of rhizosphere ecology may contribute to preservation of productive function under persistent disease pressure. Beneficial microorganisms including Bacillus spp., Trichoderma spp., and Lactobacillus plantarum have previously been reported to promote plant health through microbial competition, production of antimicrobial metabolites, induction of systemic resistance, enhancement of nutrient acquisition, and stabilization of rhizosphere ecological processes. Biochar may further reinforce these interactions by providing protected microsites for microbial colonization and improving persistence of beneficial microorganisms within the root zone. Although the present study was not designed to determine the relative contribution of these individual mechanisms, the observed field outcomes are biologically consistent with a rhizosphere-mediated systems response rather than pathogen elimination alone.

A particularly noteworthy observation was the frequent transition of recovered plants and productive follower generations to non-detect status using the multi-enzyme rapid amplification diagnostic platform. These findings were not interpreted as evidence of pathogen eradication. However, they suggest that pathogen detectability, pathogen activity, or both may change during the recovery process. Rather than indicating pathogen eradication, these observations may represent a remission-like biological state in which productive function is restored despite the possibility of persistent pathogen presence below assay detection limits. Whether this transition reflects reduced pathogen biomass, ecological suppression, altered pathogen physiology, or changes in host–microbe interactions remains unknown and warrants future investigation using quantitative molecular diagnostics, pathogen viability assays, and microbiome characterization.

Beyond plant pathology, the implications of Functional Recovery extend to environmental sustainability, farm livelihoods, food security, and agricultural resilience. Sustaining productive hectares under endemic disease pressure reduces the risk of field abandonment, preserves agricultural productivity, and supports continuity of affordable nutrition derived from one of the world's most important staple fruit crops. From this perspective, Functional Recovery may represent not only a disease-management outcome, but also a resilience framework applicable to agricultural systems confronting persistent biological threats.

Taken together, these findings suggest that productive agricultural systems may remain functional despite confirmed pathogen presence when biological resilience and productive continuity are preserved. The present study therefore supports a shift from a strictly pathogen-centered perspective toward a production-system perspective in which preservation of productive function becomes a complementary measure of management success under endemic TR4 conditions.

Importantly, Functional Recovery should not be interpreted as evidence of pathogen eradication. Rather, it represents an operationally measurable management endpoint in which productive function is sustained despite documented pathogen presence. This distinction may be particularly relevant for perennial cropping systems where complete elimination of persistent soilborne pathogens is operationally unrealistic. Under such conditions, Functional Recovery provides a complementary scientific framework through which disease management can be evaluated while maintaining full recognition of the continuing importance of exclusion, biosecurity, containment, and resistance-based strategies.

6. Limitations:
Future studies incorporating replicated experimental designs, quantitative pathogen load measurements, microbiome characterization, and independent multi-site validation would further strengthen understanding of the mechanisms underlying Functional Recovery.

7. CONCLUSION

This study demonstrates that productive Cavendish banana systems can maintain productive function despite molecular confirmation of Fusarium odoratissimum (TR4) under endemic field conditions. Across approximately 5,000 molecularly confirmed TR4-positive plants distributed across multiple agroecological environments, Functional Recovery was consistently observed through successful fruiting, harvest completion, establishment of productive follower generations, and continuity of production cycles.

The integration of rhizosphere-targeted biological intervention, multi-enzyme rapid amplification diagnostics, and satellite-enabled monitoring provided a practical framework for evaluating productive continuity under persistent disease pressure. Collectively, field observations, molecular diagnostics, spatial assessments, and landscape-scale monitoring supported the preservation of productive function despite confirmed pathogen occurrence.

The findings support Functional Recovery as a measurable and operational outcome for Cavendish banana systems affected by endemic TR4. Rather than evaluating success solely through pathogen absence, the Functional Recovery framework emphasizes preservation of productive function, biological resilience, and economic continuity as complementary indicators of agricultural performance under disease pressure.

While further validation across additional production regions and production systems is warranted, the results suggest that productive continuity can remain achievable even where pathogen elimination is not immediately feasible. Accordingly, Functional Recovery is proposed as a complementary management framework for sustaining Cavendish banana production in landscapes where Fusarium odoratissimum (TR4) has become an enduring production reality.

Ultimately, the findings challenge the assumption that pathogen presence and productive agriculture are mutually exclusive outcomes. Instead, they suggest that resilient production systems may continue to deliver food, livelihoods, and economic value despite persistent disease pressure when productive function remains intact.

The findings suggest that productive continuity may represent a practical and measurable complement to pathogen-centered management objectives in TR4-endemic production systems.

Acknowledgments

The authors gratefully acknowledge the bananeros, farm workers, Agrarian Reform Beneficiary (ARB) communities, field technicians, supervisors, and farm managers across Mindanao, Philippines, whose dedication, observations, and stewardship of banana production systems made this multi-year study possible. Their willingness to continue farming under persistent Fusarium wilt pressure provided invaluable practical insights into the realities of disease management, resilience, and productive continuity under endemic TR4 conditions.

The authors further acknowledge the technical teams involved in field implementation, disease surveillance, molecular diagnostics, sample collection, data management, and site monitoring throughout the duration of the study. Their commitment to rigorous field observation and long-term monitoring contributed substantially to the development and evaluation of the Functional Recovery framework presented in this paper.

Finally, the authors recognize the broader banana-growing communities of Mindanao whose experiences continue to inspire the search for practical, science-based approaches that sustain livelihoods, food production, and agricultural resilience in the face of evolving biological challenges.

Conflict of Interest

The authors are affiliated with Agright Technologies, which developed the biological intervention platform and multi-enzyme rapid amplification (MERA) diagnostic technology evaluated in this study. The study was conducted under commercial field conditions using technologies developed by the authors' organization.

The authors declare that the research was designed, conducted, analyzed, and reported in accordance with accepted scientific and ethical standards. All findings, interpretations, and conclusions presented in this manuscript are based on the data generated during the study.

No external sponsor influenced the study design, data analysis, interpretation of results, or decision to publish.

REFERENCES

1. Berendsen, R. L., Pieterse, C. M. J., & Bakker, P. A. H. M. (2012). The rhizosphere microbiome and plant health. Trends in Plant Science, 17(8), 478–486. https://doi.org/10.1016/j.tplants.2012.04.001
2. Compant, S., Duffy, B., Nowak, J., Clément, C., & Barka, E. A. (2005). Use of plant growth-promoting bacteria for biocontrol of plant diseases: Principles, mechanisms of action, and future prospects. Applied and Environmental Microbiology, 71(9), 4951–4959. https://doi.org/10.1128/AEM.71.9.4951-4959.2005
3. Dita, M., Barquero, M., Heck, D., Mizubuti, E. S. G., & Staver, C. P. (2018). Fusarium wilt of banana: Current knowledge on epidemiology and research needs toward sustainable disease management. Frontiers in Plant Science, 9, 1468. https://doi.org/10.3389/fpls.2018.01468
4. Elad, Y., Cytryn, E., Harel, Y. M., Lew, B., & Graber, E. R. (2011). The biochar effect: Plant resistance to biotic stresses. Phytopathologia Mediterranea, 50(3), 335–349.
5. Food and Agriculture Organization of the United Nations. (2019). Fusarium wilt Tropical Race 4: A mounting threat to global banana production. Rome, Italy: FAO.
6. Folke, C. (2006). Resilience: The emergence of a perspective for social–ecological systems analyses. Global Environmental Change, 16(3), 253–267. https://doi.org/10.1016/j.gloenvcha.2006.04.002
7. García-Bastidas, F., Ordóñez, N., Konkol, J., Al-Qasim, M., Naser, Z., Abdelwali, M., ... Kema, G. H. J. (2020). First report of Fusarium wilt Tropical Race 4 in Cavendish bananas caused by Fusarium odoratissimum in Colombia. Plant Disease, 104(3), 994. https://doi.org/10.1094/PDIS-09-19-1922-PDN
8. Harman, G. E., Howell, C. R., Viterbo, A., Chet, I., & Lorito, M. (2004). Trichoderma species—Opportunistic, avirulent plant symbionts. Nature Reviews Microbiology, 2(1), 43–56. https://doi.org/10.1038/nrmicro797
9. Holling, C. S. (1973). Resilience and stability of ecological systems. Annual Review of Ecology and Systematics, 4, 1–23.
10. Lehmann, J., & Joseph, S. (Eds.). (2015). Biochar for environmental management: Science, technology and implementation (2nd ed.). Routledge.
11. Lugtenberg, B., & Kamilova, F. (2009). Plant-growth-promoting rhizobacteria. Annual Review of Microbiology, 63, 541–556. https://doi.org/10.1146/annurev.micro.62.081307.162918
12. Maryani, N., Lombard, L., Poerba, Y. S., Subandiyah, S., Crous, P. W., & Kema, G. H. J. (2019). Phylogeny and genetic diversity of the banana Fusarium wilt pathogen Fusarium odoratissimum. Studies in Mycology, 92, 155–194. https://doi.org/10.1016/j.simyco.2018.06.003
13. Mulla, D. J. (2013). Twenty-five years of remote sensing in precision agriculture: Key advances and remaining knowledge gaps. Biosystems Engineering, 114(4), 358–371. https://doi.org/10.1016/j.biosystemseng.2012.08.009
14. Notomi, T., Okayama, H., Masubuchi, H., Yonekawa, T., Watanabe, K., Amino, N., & Hase, T. (2000). Loop-mediated isothermal amplification of DNA. Nucleic Acids Research, 28(12), E63. https://doi.org/10.1093/nar/28.12.e63
15. Ongena, M., & Jacques, P. (2008). Bacillus lipopeptides: Versatile weapons for plant disease biocontrol. Trends in Microbiology, 16(3), 115–125. https://doi.org/10.1016/j.tim.2007.12.009
16. Ordóñez, N., Seidl, M. F., Waalwijk, C., Drenth, A., Kilian, A., Thomma, B. P. H. J., ... Kema, G. H. J. (2015). Worse comes to worst: Bananas and Panama disease—When plant and pathogen clones meet. PLoS Pathogens, 11(11), e1005197. https://doi.org/10.1371/journal.ppat.1005197
17. Pieterse, C. M. J., Zamioudis, C., Berendsen, R. L., Weller, D. M., Van Wees, S. C. M., & Bakker, P. A. H. M. (2014). Induced systemic resistance by beneficial microbes. Annual Review of Phytopathology, 52, 347–375. https://doi.org/10.1146/annurev-phyto-082712-102340
18. Ploetz, R. C. (2015). Management of Fusarium wilt of banana: A review with special reference to Tropical Race 4. Crop Protection, 73, 7–15. https://doi.org/10.1016/j.cropro.2015.01.007
19. Walker, B., Holling, C. S., Carpenter, S. R., & Kinzig, A. (2004). Resilience, adaptability and transformability in social–ecological systems. Ecology and Society, 9(2), 5.
20. Warnock, D. D., Lehmann, J., Kuyper, T. W., & Rillig, M. C. (2007). Mycorrhizal responses to biochar in soil—Concepts and mechanisms. Plant and Soil, 300, 9–20. https://doi.org/10.1007/s11104-007-9391-5
21. Woo, S. L., Ruocco, M., Vinale, F., Nigro, M., Marra, R., Lombardi, N., ... Lorito, M. (2014). Trichoderma-based products and their widespread use in agriculture. Open Mycology Journal, 8(Suppl 1), 71–126.