



A Review of the Prospects in the Control of *Phytophthora Megakarya* in Cocoa Production

*¹Olaomi Adeyemi Afeez, ²Odehale Gbolabo, ⁵Braimoh Justinah Edith, ⁴Alege Gbenga Olorunshola and ³Suleiman Mohammed Nasirudeen

¹Department of Biology, Federal University Lokoja, Kogi State, Nigeria.

²Department of Microbiology, Federal University Lokoja, Kogi State, Nigeria.

³Department of Botany, Federal University Lokoja, Kogi State, Nigeria.

⁴Department of Biotechnology, Federal University Lokoja, Kogi State, Nigeria.

⁵Department of Biology, Confluence University of Science and Technology, Osara, Kogi State, Nigeria.

*Corresponding authors' email: adeyemi.olaomi@fulokoja.edu.ng

ABSTRACT

Cocoa despite being one of the most economically valuable cash crops globally, faces a great limitation by black pod disease caused by *Phytophthora megakarya*. *P. megakarya* is a devastating pathogen that causes significant yield losses in key cocoa-growing regions in West and Central Africa, and poses a threat to cocoa productivity, farmer livelihood, and the global cocoa supply. This review explores the current and future opportunities for the control of *P. megakarya*, with focus on sustainable and integrated disease management strategies that are enabled by recent advances in host plant resistance, molecular breeding, and genomic technologies, as well as biotechnological approaches such as gene-editing and genetic transformation to enhance cocoa defense mechanisms. The review as well emphasizes the role of biological control agents and plant-derived antifungal compounds, as well as agroecological practices, climate-smart farming systems, and digital agriculture technologies for improving disease monitoring, prediction, and management, although challenges with climate change, the variable field performance of biological products, and limited adoption of emerging technologies remain. The review concludes that a combination of resistant varieties, biological and botanical control agents, cultural practices, precision agriculture, and judicious fungicide use offers the most sustainable pathway for the long-term control of *P. megakarya* and the resilience of cocoa production systems.

Keywords: *Phytophthora Megakarya*, Black Pod Disease, Cocoa Production, Biological Control, Integrated Disease Management

INTRODUCTION

The persistent threat of *Phytophthora megakarya* to cocoa (*Theobroma cacao* L.) production has prompted extensive research to develop sustainable and effective control strategies, and although traditional approaches such as cultural practices and chemical fungicides have played a role in disease management, these methods have not been effective enough to eradicate the pathogen because of its high reproductive capacity, environmental adaptability, and persistence in cocoa ecosystems. Therefore, recent research has focused on innovative and integrated control strategies that combine advances in plant breeding, biotechnology, biological control, ecological management, and digital agriculture technologies, which hold promising prospects for enhancing the long-term control of black pod disease in cocoa plantations (Merga, 2022).

Phytophthora megakarya control will be greatly enhanced by the development of cocoa varieties with enhanced genetic resistance to black pod disease. Host plant resistance is considered to be the most sustainable management approach for plant diseases because it offers ongoing protection without the need for reapplication of chemicals. Molecular breeding methods have sped up the identification and deployment of resistant cocoa genotypes, and genome-wide association studies and QTL mapping have revealed several genomic regions associated with resistance to *Phytophthora* species (Winters, 2022). These studies have shown that resistance to *P. megakarya* is usually polygenic and multifactorial, with multiple defense pathways such as lignin biosynthesis, oxidative stress responses, and production of antimicrobial compounds (Foka *et al.*, 2025). Marker-assisted selection has been implemented into cocoa breeding programs to screen large populations of seedlings for resistance traits at an early

developmental stage, reducing the time to develop improved varieties (Foka *et al.*, 2025).

Genomic studies have also shed light on the molecular interactions between cocoa and *Phytophthora* pathogens, as transcriptomic analyses have identified several defense-related genes that are expressed in cocoa plants after infection by *P. megakarya*, including genes that encode pathogenesis-related proteins, chitinases, glucanases, and enzymes involved in phytoalexin biosynthesis (Baruah *et al.*, 2022). These findings provide insight into mechanisms of host resistance and may lead to new breeding strategies to increase disease resistance in cocoa. In addition, recent advances in genomic sequencing technologies have allowed characterization of the genome of *P. megakarya*, which will allow researchers to identify genes related to pathogenicity and virulence (Talero, 2024).

Prospective Approaches to the Control of *Phytophthora Megakarya*

Biotechnological Approach

There is potential in biotechnological approaches to the control of *Phytophthora megakarya*. Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR)/CRISPR-associated protein (Cas) systems, which are a group of gene-editing technologies, provide new avenues to introduce resistance to disease in cocoa through targeted gene modification of genes involved in plant defense responses, including the enhancement of expression of resistance genes and the disruption of susceptibility genes that allow for pathogen infection (Gutiérrez *et al.*, 2021). While gene editing in cocoa is in its infancy, the technology may help to speed the development of disease-resistant cocoa with desirable agronomic traits like yield and bean quality. Other

approaches for introducing antifungal genes into cocoa plants include genetic transformation, such as transgenic cocoa plants expressing antifungal proteins or defense-related enzymes that show increased resistance to *Phytophthora* infections in experimental conditions (Guiltinan et al., 2026). Although regulatory and public acceptance issues are still significant, biotechnology could have an important role in future control of black pod disease.

Biological Control Approach

Biological control is also an effective strategy for *Phytophthora megakarya* disease management, and many studies have described the antagonistic action of various fungal and bacterial species against *P. megakarya*, including species of *Trichoderma* that have been shown to colonize plant roots and rhizosphere environments, suppress *Phytophthora* pathogens through the production of antifungal metabolites, degradation of pathogen cell walls through enzymatic activity, and induction of systemic resistance in host plants (Lahlali et al., 2022).

Besides fungal biocontrol agents, a number of bacterial species have been effective in suppressing *Phytophthora* infections. Plant growth-promoting rhizobacteria such as *Bacillus subtilis*, *Bacillus amyloliquefaciens*, and *Pseudomonas fluorescens* produce antibiotics, lytic enzymes, and volatile organic compounds that inhibit pathogen growth and reduce disease severity (Larbi-Koranteng et al., 2020), and also improve plant growth and nutrient uptake, making the cocoa plant more robust to disease stress. While biological control agents have performed well in laboratory and greenhouse studies, their field performance is affected by environmental conditions like temperature, soil moisture, and microbial competition.

Plant-Derived Antifungal Agents

Another promising approach to the management of *P. megakarya* is the use of plant-derived antifungal compounds, as botanical fungicides derived from plant extracts are increasingly being explored as an alternative to synthetic chemical fungicides (Olaomi et al., 2026). Many tropical plants contain bioactive compounds with antifungal activity against *Phytophthora* pathogens. *Azadirachta indica*, *Ocimum gratissimum*, *Allium sativum*, *Zingiber officinale*, and *Chromolaena odorata* have all been found to inhibit *P. megakarya* growth and sporulation (Carlos et al., 2025; de Oliveira Santos et al., 2025; Olaomi, 2023).

Olaomi (2023) evaluated the antifungal efficacy of crude aqueous extracts of *Chromolaena odorata* against *Phytophthora megakarya*, the causal agent of black pod disease in cocoa, as an alternative to synthetic fungicides in cocoa disease management due to the increasing awareness of the environmental and health hazards associated with the prolonged use of synthetic agrochemicals. The study results showed that different concentrations of the plant extract inhibited the growth of the pathogen at different levels after incubation for 72, 120, and 168 hours, with the 50% concentration showing the most inhibitory activity against *P. megakarya* followed by 100% and 75% concentrations, while 25% concentration showed the least antifungal effect. The results suggest that *Chromolaena odorata* has potent antifungal activity against *P. megakarya*, which could be used as a source of natural biofungicides in cocoa production.

Botanical fungicides have the advantages of being generally biodegradable (Olaomi et al., 2026), less toxic to non-target organisms, often locally available to smallholder farmers, and potentially less likely to contaminate the environment as a result of repeated chemical applications, however, issues such

as variability in chemical composition, limited shelf life, and inconsistent field performance must be overcome before their widespread use in cocoa production systems (Danial et al., 2025). Therefore, the use of plant-derived fungicides will require standardization of extraction methods and formulation technologies to improve the effectiveness and reliability of plant-based fungicides.

Agroecological Approaches

Agroecological approaches are also an important option for *P. megakarya* management, for example, agroforestry systems that combine cocoa cultivation with shade trees and other crops may impact microclimatic conditions in the cocoa plantation, reducing humidity, increasing air circulation, and improving soil health, which can reduce disease incidence (Tijani 2025), and shade trees may harbor populations of microorganisms that suppress plant pathogens. But excessive shade can result in higher humidity, promoting pathogen development, therefore, proper shade management is critical to agroforestry systems. Climate-smart cocoa farming practices have shown that agroforestry systems can increase the resilience of cocoa production systems to disease pressure and climate variability (Delgado-Ospina et al. 2021).

Recent developments in digital agriculture and precision farming technologies have provided new avenues for enhancing disease monitoring and management in cocoa plantations, such as remote sensing technologies using drones, satellite imagery, and multispectral cameras to detect the early symptoms of black pod disease and identify disease hotspots within cocoa farms (Alsadik et al., 2024), as well as geographic information systems and predictive disease models that combine weather data with epidemiological information to predict disease outbreaks and optimize fungicide application schedules (Talero, 2024), which may reduce the unnecessary use of fungicides and enhance the efficacy of disease control programs.

Potential Constraints to the Prospects

Climate change is a factor that may affect future control of *Phytophthora megakarya*; climate change, including changes in rainfall patterns, temperature regimes, and humidity levels, is anticipated to change the epidemiology of black pod disease in many cocoa-growing areas (Cilas and Bastide, 2020), and future disease management strategies will need to include adaptation to climate, including the development of climate-resilient cocoa varieties, better shade management, and modification of planting calendars to minimize exposure to favorable disease conditions. Although several disease control strategies have been developed, none offer full protection against *P. megakarya*, and integrated disease management remains the most promising strategy for sustainable black pod disease control (Akrofi et al., 2015). Integrated management strategies involve combining cultural practices, resistant varieties, biological control agents, botanical fungicides, and judicious use of synthetic fungicides to reduce disease pressure while minimizing environmental impacts (Akrofi et al., 2015).

CONCLUSION

In conclusion, while *Phytophthora megakarya* continues to threaten cocoa sustainability, integrating host resistance (via conventional and CRISPR-enhanced breeding), biological and botanical agents, optimized agroecological practices, and precision digital tools within a robust IDM framework offers the most viable path forward. Realizing these potential demands accelerated research translation, policy support for technology adoption, and participatory extension to empower

smallholder farmers. Future studies should prioritize multi-location field validation, economic analyses, and climate-resilient variety development to ensure long-term viability of cocoa production in vulnerable regions." This sharpens the synthesis, adds specificity, and provides a stronger, more actionable close

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