VOL. 12 NO. 1,
MAY, 2026
E-ISSN 3027-0995
P-ISSN 3026-8265

African Scholar Publications & Research International
www.africanscholarpub.com

Journal of Biotechnology and Agricultural Research (JBAR)

Comparative Economic Analysis of Botanical and Synthetic Fungicides for the Management of Cocoa Black Pod Disease (*Phytophthora* spp) in Nigeria

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DOI: https://doi.org/10.70382/ajbar.v12i1.037

Abstract

Cocoa production in West Africa continues to suffer significant yield losses due to black pod disease caused by *Phytophthora* spp. Conventional synthetic fungicides, though widely used, are increasingly constrained by rising costs, environmental risks, and variable field effectiveness. This study evaluates the economic viability of botanical fungicides specifically aqueous and ethanolic extracts of *Eucalyptus grandis* and *Datura stramonium* relative to synthetic fungicides using a comprehensive Cost-Benefit Analysis (CBA) and Benefit-Cost Ratio (BCR) approach under weekly and bi-weekly treatment regimes. A Completely Randomized Design with three replications was employed, with seven treatments: (i) 4% aqueous *E. grandis*, (ii) 4% aqueous *D. stramonium*, (iii) 3% aqueous mixture of *E. grandis* + *D. stramonium*, (iv) 1% ethanol extract of *E. grandis*, (v) 1% ethanol extract of *D. stramonium*, (vi) synthetic fungicide (commercial standard), and (vii) control. Spraying costs were included for weekly and bi-weekly schedules. Data were analyzed using ANOVA and means separated with New Duncan Multiple Range Test ($p \leq 0.05$). Results show that aqueous botanical treatments provided the highest economic returns, with the mixture of *E. grandis* + *D. stramonium* achieving the highest weekly BCR of 180.0 followed by aqueous *D. stramonium* (158.0). Under bi-weekly schedule, the mixture maintained strong performance (BCR 45.0), while aqueous *D. stramonium* recorded (BCR 28.0). Aqueous *E. grandis*, with no extraction cost, was economically dominant, yielding net benefits of ₦89,000 weekly and ₦50,000 bi-weekly. Synthetic

fungicides showed the lowest BCR (7.17), confirming economic inefficiency. Conclusively, aqueous botanicals demonstrated superior profitability, cost efficiency, and sustainability, providing strong justification for their integration into cocoa disease management strategies in Nigeria and similar regions.

Keywords: Blackpod Disease*, Eucalyptus grandis, Datura stramonium, Botanical fungicides,* Cost–Benefit Analysis.

Introduction

Cocoa (*Theobroma cacao* L.) is a critical cash crop that supports the livelihoods of millions of smallholder farmers in West Africa, particularly in Nigeria (Esan *et al*., 2025). However, its productivity is consistently constrained by black pod disease caused primarily by *Phytophthora* spp, which accounts for 20–30% annual losses and can reach up to 90% during severe outbreaks (Oladokun *et al*., 2025). Although synthetic fungicides remain the dominant control strategy, their use is increasingly criticized due to high costs, environmental contamination, pathogen resistance, and health concerns for farmers (Ofor *et al*., 2021). These limitations have prompted growing interest in botanical fungicides that are locally available, environmentally benign, and cost-effective. Studies have demonstrated strong antifungal activity of *Eucalyptus grandis* and *Datura stramonium* extracts against *Phytophthora* spp (Erfandari *et al*., 2022; Fovo *et al*., 2018). Morphologically, *Pythopthora s*pp comprise hyphae that are coenocytic, branched and irregularly shaped. Furthermore, it has a sporagia that is semi-papillate and ovoid which contains the zoospores and chlamydospores (Opoku *et al*., 2002). The isolate utilized in this experiment was molecularly identified and confirmed to be *Phytophthora megakarya.*

Economic evaluation of black pod disease control in cocoa has a longer history than economic evaluation of botanical fungicides specifically, and the two literatures have only recently begun to converge. In Ghana, Opoku *et al.* (2007) tested reduced fungicide-application schedules combined with crop sanitation against the standard six-to-eight sprays per season recommended for *Phytophthora megakarya* control, and found that all tested regimes remained profitable, with Benefit–Cost Ratios ranging from 1.8 to 2.1, but also reported that farmer adoption of even the standard fungicide regime remained extremely low because of its cost and labour burden. This is a useful economic benchmark: it indicates that BCRs in the 2-3 range are already considered a meaningful improvement for cocoa growers, which throws into sharper relief how substantial the BCRs reported for aqueous botanical extracts in the present study (up to 180.0) actually are. In Nigeria specifically, Oladokun *et al*. (2025) quantified the direct economic burden of black pod disease and cherelle wilt on cocoa farmers, estimating losses running into hundreds of thousands of naira per hectare from infected pods alone, showing that the

cost of disease itself, not just the cost of control, is a critical part of the economic calculus smallholders face when deciding which treatment, if any, to adopt.

The broader literature on cocoa pest and disease management in West and Central Africa consistently frames fungicide-based control as necessary but economically and logistically constrained for smallholders. Sonwa *et al.* (2008), studying the humid forest zones of southern Cameroon, documented that farmer routinely struggle to acquire and apply pesticides correctly and consistently, owing to cost, limited access to appropriate equipment, and inadequate technical knowledge, constraints that apply just as directly to any new class of input, botanical or synthetic. Similarly, Asogwa and Dongo (2009) reviewed the problems associated with pesticide usage in Nigerian cocoa production and highlighted high procurement costs, inconsistent supply, and health and safety concerns among the persistent barriers limiting effective disease control at the farm level.

While previous research has established the biological efficacy of plant extracts, few studies have assessed their economic viability for cocoa farmers. This is critical given that smallholder farmers make input decisions based on profitability rather than biological efficacy alone. This study therefore performs a comprehensive cost-benefit analysis (CBA) of botanical versus synthetic fungicide treatments under weekly and bi-weekly application regimes, providing evidence to inform a sustainable and economically sound disease management strategies.

Objectives of the Study

1. To assess the yield benefits of cocoa trees treated with botanical extracts (aqueous and ethanolic) relative to synthetic fungicides under weekly and bi-weekly treatment regimes.
2. To compare the economic costs associated with aqueous, ethanolic, and synthetic fungicide treatments used in the management of cocoa black pod disease.
3. To conduct a cost-benefit analysis (CBA) to determine the net economic returns of each treatment option.
4. To compute and compare the Benefit–Cost Ratio (BCR) of botanical and synthetic fungicide treatments under weekly and bi-weekly application schedules.

Materials and Methods

Evaluation of Botanical Extracts for the Management of *Phytophthora* Black Pod Disease

The trial was set up on cocoa experimental plots of Cocoa Research Institute of Nigeria (CRIN) Ibadan, which is one of the major and marginal cocoa-growing ecologies of Nigeria. The selected cocoa plantations for the trial pilot have a history of high incidence of black pod disease during both major and light cocoa seasons. The trial plots contained F_3 Amazon cocoa variety planted in rows at the spacing of 3.1 x 3.1 m. Plots consisted of four trees in a row separated by a border row to buffer spray drift. The experiment was fitted into a Completely Randomized Design with three replications. Seven treatments were imposed on the plots. Six treatment options were assessed: (i) 4 % aqueous *E. grandis* extract, (ii) 4 % aqueous *D.*

stranomium extract, (iii) 3 % mixture of aqueous *E. grandis* and *D. stramonium* (iv) 1 % ethanol extract of *E. grandis,* (v) 1 % ethanol extract of *D. stranomium*, (vi) Synthetic Fungicide (Commercial standard) and (vii) Control (non-sprayed plot). A separate cost item was included for spraying operations, which differ between weekly and bi-weekly schedules.

Benefit Measurement

Benefits were measured as the monetary value of healthy cocoa pods:

Benefit (₦) = Number of healthy pods × ₦1,000 (Market price of healthy pod)

Cost Measurement

Costs included: materials (extracts or fungicides), spraying labour and equipment.

Cost-Benefit Analysis

Net benefit was computed as:

Net Benefit (₦) = Total Benefit (₦) − Total Cost (₦)

CBA was conducted separately for weekly and bi-weekly treatments.

Benefit–Cost Ratio (BCR)

The Benefit–Cost Ratio was computed to evaluate the economic efficiency of each treatment.

BCR was calculated as: $BCR = \frac{Total\ Benefit\ (₦)}{Total\ Cost(₦)}$

A BCR > 1 indicates that the treatment provides economic gains, while a BCR < 1 indicates a loss. Treatments with higher BCR values were interpreted as more cost-efficient and preferable for adoption by farmers. Benefits were computed as the market value of healthy pods (₦1,000 per pod). BCR was computed separately for weekly and bi-weekly treatments.

Results and Discussion

Effects of Treatment Application on Number of Healthy Pods

Table 1: Effect of Treatment Combinations on Weekly and Bi-Weekly Production of Healthy Cocoa Pods on the Field

Treatments (%)	2 WAS	4WAS	6WAS	8 WAS	10 WAS
E.G (4%)WKLY	4.66a	6.83ab	6.58ab	7.67a	7.42a
D.S (4%) WKLY	7.50a	7.00ab	6.67ab	6.50a	6.58a
MIXED (3%) WKLY	9.83a	8.58a	7.75a	6.58a	7.50a
E.G ETH (1%) WKLY	4.00a	6.08ab	5.92ab	3.41a	4.08a
D.S ETH (1%) WKLY	4.00a	6.25ab	5.50ab	5.17a	5.83a
E.G (4%) BI-WKLY	4.67a	6.83ab	6.58ab	7.76a	7.42a
D.S (4%) BI-WKLY	7.50a	7.00ab	6.67ab	6.50a	6.58a
MIXED (3%) BI-WKLY	9.83a	8.58a	7.75a	6.58a	7.50a
E.G ETH (1%) BI-WKLY	4.00a	6.08ab	5.92ab	3.42a	4.08a
D.S ETH (1%) BI-WKLY	4.00a	6.25ab	5.50ab	5.17a	5.58a
Cu- Oxide	2.08a	2.00b	2.08b	3.17a	3.58a
CONTROL	5.50a	4.92ab	5.25ab	3.42a	3.08a

*E.G = *Eucalyptus grandis** D.S = *Datura stramonium** E.G ETH = Ethanol *Eucalyptus grandis** D.S ETH= Ethanol *Datura Stranomim*WKLY=weekly, BI-WKLY=Bi-weekly *WASp = Weeks after spraying *Means of same alphabet are not significant using DMRT at ($p \leq 0.05$) * Means of different alphabet are significant using DMRT at ($p \leq 0.05$)

The result from Table 1 shows the effect of treatment on the production of healthy pod. Synthetic fungicides (Cu Oxide) had the least healthy pod production (2.00) at 4 weeks after spraying (WASp). Mixed concentration of *E. grandis* and *D. stranonium* had the highest pod production (9.83) at 2 weeks after spraying. It was further observed on Table 3 that there was no significant difference amongst all the treatment at 2 WASp, Copper oxide had the lowest healthy pod production (2.08), the mixed concentration had the highest pod production (9.83) and there was a progressive increase across the treatment. At 10 WASp, the treatment was found not to be significantly different from each other, the control had the lowest healthy pod production (3.08) while the bi-weekly mixed concentration at 3% had the highest healthy pod production per tree (7.50).

Cost Benefit Analysis

Table 2: Cost-Benefit Analysis of Weekly Cocoa Tree Treatments

Treatment	Cost (₦)	Benefit (₦)	Net Benefit (₦)
Aqueous Eucalyptus grandis	0	89,000	89,000
Aqueous Datura stramonium	500	79,000	78,500
Mixture of E. grandis + D. stramonium	500	90,000	89,500
EthanolicE. Grandis	5,500	49,000	43,500
EthanolicD. Stramonium	5,500	67,000	61,500
Synthetic Fungicides	6,000	43,000	37,000
Spraying of Treatments	10,000		-10,000
Total Cost/Benefit	**28,000**	**417,000**	**389,000**

Table 3: Cost-Benefit Analysis of Bi-Weekly Cocoa Tree Treatments

Treatment	Cost (₦)	Benefit (₦)	Net Benefit (₦)
Aqueous Eucalyptus grandis		50,000	50,000
Aqueous Datura stramonium	1,000	28,000	27,000
Mixture of E. grandis + D. stramonium	1,000	45,000	44,000
Ethanolic E. grandis	4,500	50,000	45,500
Ethanolic D. stramonium	4,500	49,000	44,500
Synthetic Fungicides	6,000	43,000	37,000
Spraying of Treatment	5,000		-5,000
Total Cost/Benefit	**22,000**	**265,000**	**243,000**

Note: Spraying was applied to treatments periodically irrespective of treatment (Hence the calculated spraying cost on weekly and bi-weekly basis)

All cost items in this analysis were valued using prevailing market prices at the time the trial was conducted (the 2024 cropping season), in order to reflect the actual cost environment faced by farmers rather than standardized or historical price assumptions. Labour costs for spraying operations were computed using the prevailing daily wage rate for casual farm labour in the study locality at the time of the trial, applied to the actual person-hours required to complete each spraying round under the weekly and bi-weekly regimes; this explains why spraying cost scales directly with application frequency (₦10,000 weekly vs. ₦5,000 bi-weekly) while material costs vary by treatment. Extraction costs for ethanolic treatments were derived from the prevailing local market price of ethanol at the time of purchase, plus the labour time required for extraction (weighing of plant material, blending, and filtering), which together account for the substantially higher cost of ethanolic extracts (₦5,500 weekly; ₦4,500 bi-weekly) relative to aqueous extracts. Aqueous extraction was assigned negligible/zero direct cost because water was sourced on-farm at no monetary cost and the associated labour (weighing and blending of plant material) was incorporated into the general spraying-labour estimate rather than costed separately; we acknowledge this as a simplifying assumption that may understate the true opportunity cost of aqueous extract preparation. The price of healthy cocoa pods (₦1,000/pod) used to value benefits reflects the prevailing farmgate/local market price for cocoa pods at the study site during the trial period, as reported by CRIN Economics Section market survey (2024). Because all cost and price parameters are location and time-specific, absolute BCR values reported here should be interpreted as reflecting the cost environment prevailing at the time of the study rather than as fixed, universally transferable figures; future applications of this framework in other locations or periods would need to be re-parameterized using local prevailing prices.

The cost-benefit analysis presented in Tables 2 and 3 reveals clear economic distinctions among the cocoa tree treatment options. Across both treatment regimes, aqueous extracts of *Eucalyptus grandis* and *Datura stramonium* provided the highest net economic returns, outperforming both ethanolic extracts and synthetic fungicides.

Under the weekly application regime, the Mixture of *E. grandis* and *D. stramonium* produced the highest net benefit (₦89,500), closely followed by Aqueous *E. grandis* (₦89,000). The high profitability of aqueous extracts can be attributed to their minimal preparation costs and strong antifungal properties, which result in significant yield improvement relative to input expenditure. The total benefit accrued across all weekly treatments amounted to ₦417,000 against a total cost of ₦28,000, yielding a substantial overall net benefit of ₦389,000.

For the bi-weekly application, a similar trend was observed aqueous *E. grandis* recorded the highest net benefit (₦50,000), followed by ethanolic *E. grandis* (₦45,500) and ethanolic *D. stramonium* (₦44,500). Despite the relatively lower number of healthy pods under the bi-weekly regime, the treatments remained profitable, with a total benefit of ₦265,000 and a total cost of ₦22,000, resulting in a net benefit of ₦243,000.

The results demonstrated that aqueous botanical treatments are both agronomically effective and economically superior to synthetic fungicides. This finding supports the growing body of

evidence that botanical extracts possess significant antifungal potential against cocoa pathogens, particularly *Phytophthora megakarya* the causal agent of black pod disease and the most virulent in Africa (Erfandari *et al*., 2022; Fovo *et al*., 2018). Moreover, aqueous formulations are known to maintain sufficient concentrations of active compounds to suppress disease, while eliminating the high extraction costs associated with ethanol-based preparations (Azwanida, 2015).

These findings are consistent with the work of Sofowora *et al*. (2013), who highlighted that water-based medicinal plant extracts offer a low-cost and environmentally friendly approach to disease management. Similarly, Stouvenakers *et al*. (2019) observed that water-based botanical treatments provide effective pest and disease suppression in tropical cropping systems with considerably reduced input costs, making them more viable for smallholder farmers.

The relatively poor performance of synthetic fungicides (net benefit ₦37,000 weekly; ₦37,000 bi-weekly) shows the economic inefficiency of conventional chemical control, largely due to their high procurement and application costs. In addition, reliance on synthetic fungicides raises environmental and health concerns, further justifying the adoption of plant-based alternatives (Ofor et al., 2021).

From a practical standpoint, the combination of *Eucalyptus* and *Datura* aqueous extracts offers a synergistic advantage, maximizing pod yield while minimizing expenditure. The spraying operation cost (₦10,000 weekly and ₦5,000 bi-weekly) represents the main operational expense; nonetheless, total benefits far outweighed costs under both regimes, confirming positive net returns and profitability potential.

Overall, the analysis indicates that aqueous *E. grandis* and its mixture with *D. stramonium* are the most economically viable options for managing cocoa tree diseases. Their low-cost preparation, accessibility, and high efficacy make them suitable for adoption by smallholder cocoa farmers seeking affordable and sustainable plant protection strategies in Nigeria and similar tropical regions.

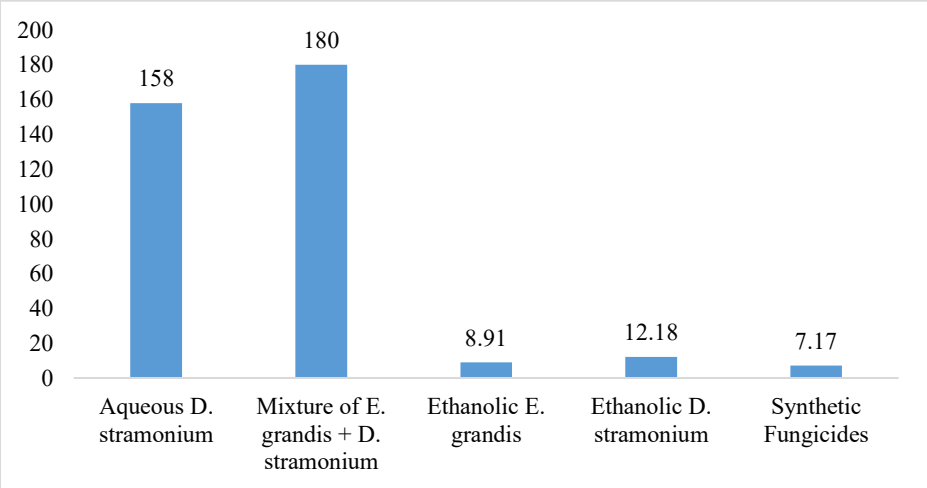


Figure 1: Cost Benefit Ratio of Weekly Cocoa Tree Treatment

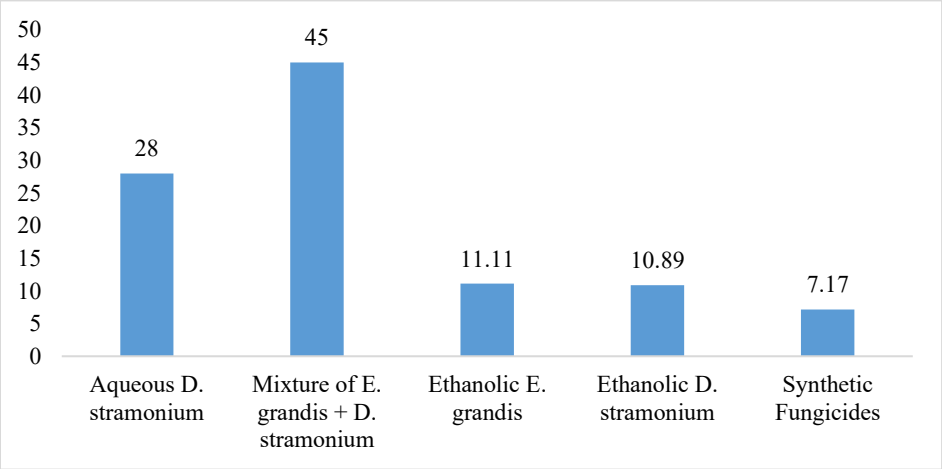


Figure 2: Cost Benefit Ratio of Bi-Weekly Cocoa Tree Treatment

The results of this study demonstrate that botanical fungicides, particularly aqueous extracts of *Eucalyptus grandis* and *Datura stramonium*, provide substantial economic advantages over ethanolic extracts and synthetic fungicides in the management of cocoa black pod disease. The Benefit–Cost Ratio (BCR) (see Figure 1 and 2) analysis further reinforces the economic viability of these plant-based treatments. Both weekly and bi-weekly application regimes showed that aqueous botanical treatments offered the highest levels of economic efficiency, driven by their very low input costs and strong capacity to enhance pod yield.

Within the weekly regime, the mixture of *E. grandis* and *D. stramonium* achieved the highest BCR value of 180.0, indicating that each naira spent on treatment generated ₦180 in return. Aqueous *D. stramonium* also exhibited a remarkably high BCR of 158.0, while aqueous *E. grandis* produced the highest net benefit but recorded an undefined (mathematically infinite) BCR because its extraction cost was zero. Economically, this positions aqueous *E. grandis* as a dominant treatment option. These exceptionally high ratios illustrate the effectiveness of botanical treatments in producing large financial gains for smallholder cocoa farmers relative to their minimal production costs.

The bi-weekly treatments revealed a similar pattern, with aqueous extracts again outperforming alternative treatments. The mixture of *E. grandis* and *D. stramonium* recorded a BCR of 45.0, while aqueous *D. stramonium* yielded a BCR of 28.0, confirming that the economic benefits of botanical fungicides are retained even when application frequency is reduced. The favorable results of the aqueous extracts correspond with previous findings demonstrating that medicinal and aromatic plants contain bioactive compounds capable of suppressing *Phytophthora* spp, the pathogen responsible for black pod disease (Erfandari *et al.*, 2022; Fovo *et al.*, 2018). Their efficacy in disease control, when combined with negligible extraction costs, explains the exceptionally high BCR values observed. Sofowora *et al.* (2013) noted that water-based plant preparations provide a low-cost yet effective method for disease management, and the present findings offer strong economic evidence supporting that assertion. Stouvenakers *et al*. (2019) similarly reported that water-extracted botanical

treatments can be highly effective in tropical crop protection while offering substantial cost savings relative to synthetic alternatives.

In contrast, ethanolic extracts demonstrated moderate yield benefits but comparatively weaker economic outcomes. Although ethanolic *E. grandis* and *D. stramonium* performed reasonably well biologically, their higher production costs, driven by the price of ethanol and the additional labour involved in ethanolic extraction, substantially lowered their BCR values. For example, ethanolic *E. grandis* recorded BCRs of 8.91 (weekly) and 11.11 (bi-weekly), far below those of the aqueous treatments. These results are consistent with Azwanida (2015), who emphasized that although ethanol extraction can improve the concentration of active phytochemicals, the associated costs limit its economic feasibility for smallholder farmers.

Synthetic fungicides consistently ranked lowest in both BCR and net benefit analyses. Their BCR value of 7.17 across both regimes reflects the high cost of procurement and application relative to the benefits generated. This finding aligns with evidence from Ofor *et al.* (2021), which demonstrated declining profitability among cocoa farmers dependent on synthetic fungicides, largely due to increasing chemical prices and the need for repeated applications. Furthermore, beyond economic inefficiency, synthetic fungicides pose environmental and health risks, reinforcing the argument for shifting toward plant-based alternatives in line with Bermudez *et al*. (2022) recommendations for sustainable cocoa production.

The superior economic performance of aqueous *E. grandis* extracts is best explained by a combination of biological and economic mechanisms rather than either alone. Biologically, *Eucalyptus* antifungal activity is largely attributed to its essential oil fraction, dominated by monoterpenes and sesquiterpenes such as 1,8-cineole and α-pinene, with terpenes shown to play a key role in the inhibitory effects of *E. grandis* × *E. urophylla* oil against *Phytophthora capsici* and related pathogenic fungi. More directly relevant to the present study, Coulibaly *et al.* (2021), working with cocoa clones and *P. palmivora*/*P. megakarya* in Côte d'Ivoire, found that *Eucalyptus citriodora* essential oil significantly reduced in vitro mycelial growth of both *Phytophthora* strains and reduced leaf susceptibility on cocoa leaf discs, providing a cocoa-specific precedent for the antifungal mechanism proposed here. Aqueous extraction may preserve a water-soluble bioactive fraction relevant to *Phytophthora* suppression while avoiding the compound degradation or altered ratios that can accompany solvent-based extraction, which may partly explain why the aqueous form outperformed the ethanolic form of the same species. The mixture treatment's strong performance is consistent with an additive or synergistic effect between the terpenoid-rich *E. grandis* fraction and the tropane-alkaloid/flavonoid fraction characteristic of *D. stramonium*, two chemically distinct classes of antifungal compounds acting jointly rather than redundantly. Economically, however, the magnitude of the observed BCRs is driven less by extraordinary biological superiority than by a cost-side effect: because aqueous extraction requires no purchased inputs, a given increment of disease control converts into a disproportionately larger benefit-to-cost ratio than the same efficacy would under ethanolic extraction or synthetic fungicide use, where input price inflates the denominator. This reframes the central finding more precisely aqueous *E. grandis* does

not necessarily control black pod disease dramatically better than other treatments in absolute biological terms, but it converts a given level of control into substantially more economic value per naira invested, a distinction consistent with reduced-input cocoa disease management studies elsewhere in West Africa (Opoku *et al*., 2007) and with the broader botanical pest-control literature showing low material cost, rather than superior efficacy alone, as the main driver of favorable cost-benefit outcomes (Mkenda *et al*., 2015; Mkindi *et al*., 2021).

Limitations and Suggestions for Future Studies

Several limitations should be acknowledged. The trial was conducted over a single season and site, so pod counts, disease pressure, and the input prices underlying the cost-benefit estimates may not generalize across years or locations with different rainfall patterns or market conditions. The use of only three replications limits statistical power to detect real differences between treatments with confidence. Benefits were valued using pod count at a fixed price without accounting for possible differences in bean quality, size, or fermentation characteristics across treatments, and the extracts were not chemically characterized in this study (e.g., via GC-MS), meaning the specific bioactive compounds responsible for the observed antifungal effects are inferred from prior literature rather than confirmed directly. The zero-cost assumption applied to aqueous extraction likely understates its true labour opportunity cost, which may inflate the reported benefit-cost ratio for that treatment relative to a fuller accounting. Future research should prioritize multi-season, multi-site trials to test the consistency of the observed cost-benefit advantage under varying agroecological and market conditions; phytochemical profiling of the specific *E. grandis* and *D. stramonium* extracts used to confirm their active compounds; on-farm participatory trials with smallholder cooperatives to assess real-world adoption, correct preparation practices, and shelf-life under farm storage conditions; and willingness-to-adopt or willingness-to-pay studies to complement the efficacy and cost evidence presented here with direct behavioral evidence on farmer uptake.

Conclusion

This study demonstrates that aqueous botanical extracts, particularly *Eucalyptus grandis* and its mixture with *Datura stramonium*, are far more economically viable than both ethanolic extracts and synthetic fungicides for managing cocoa black pod disease. Aqueous *E. grandis* emerged as the most cost-effective treatment, generating the highest net benefits under both weekly and bi-weekly regimes, while the mixture treatment produced the strongest Benefit–Cost Ratios (BCRs). In contrast, synthetic fungicides consistently recorded the lowest economic returns. Overall, the results confirm that low-cost aqueous botanical treatments offer a profitable, sustainable, and accessible alternative for smallholder cocoa farmers.

Recommendations

Aqueous *E. grandis* should be promoted as the primary treatment option due to its superior economic performance and ease of preparation. The mixture of *E. grandis* and *D. stramonium* also warrants adoption where resources permit, given its strong BCR results. Extension services should prioritize training farmers on the preparation and application of aqueous botanicals to reduce reliance on costly synthetic fungicides. Further research should focus on optimizing formulations and validating their effectiveness across different cocoa-growing regions.

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