ORGANIC MULCHING AND RHIZOBIOME ENGINEERING AS AN INTEGRATED STRATEGY FOR SUPPRESSING FUSARIUM OXYSPORUM, ENHANCING PLANT GROWTH-PROMOTING RHIZOBACTERIA POPULATIONS

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ABSTRACT
Fusarium wilt, caused by Fusarium oxysporum f. sp. capsici, represents a chronic, soil-borne constraint to Capsicum production that disproportionately affects smallholder pepper farmers relying on intensive land use without adequate crop rotation or synthetic fungicide access. The engineering of disease-suppressive soils through organic mulching and rhizobiome manipulation offers a biologically durable management alternative. This study evaluated the effects of three organic mulch materials—composted plant residues (CPR), vermicompost (VC), and biochar-amended compost (BAC)—on Fusarium wilt suppression, plant growth-promoting rhizobacteria (PGPR) populations, phytohormone-related soil biomarker indicators, and Capsicum production economics in two village-level participatory trials (site A: Agbor; site B: Owa-Oyibu) across two cropping seasons. Soil suppression capacity was quantified through Fusarium oxysporum selective plating, Bacillus spp. and Pseudomonas fluorescens population enumeration, soil DNA extraction for qPCR quantification of F. oxysporum biomass, and disease index assessment. Smallholder economic returns were assessed through gross margin analysis. BAC treatment achieved the most significant F. oxysporum biomass reduction (qPCR: 4.2×10^3 to 6.8×10^1 gene copies/g soil), highest Bacillus (6.84×10^5 CFU/g) and P. fluorescens populations (3.42×10^4 CFU/g), lowest disease index (DI = 6.8%), and highest gross margin (NGN 284,600/ha) across both trial sites. These results provide an evidence base for recommending BAC as a smallholder-accessible, biologically effective rhizobiome engineering strategy for Fusarium-suppressive Capsicum production aligned with food security and sustainable development objectives.

Keywords: Fusarium oxysporum, Capsicum annuum, biochar-amended compost, plant growth-promoting rhizobacteria, disease suppression, gross margin, food security, Nigeria

1. INTRODUCTION

The production of Capsicum as both a subsistence crop and cash income source for an estimated 2.4 million smallholder households in Nigeria is persistently undermined by Fusarium wilt, a disease whose management options remain severely constrained by the limited purchasing power of target beneficiaries, the declining efficacy of synthetic fungicides against increasingly resistant Fusarium strains, and the absence of commercially available resistant Capsicum varieties adapted to humid tropical conditions (Lamour et al., 2012). Fusarium oxysporum f. sp. capsici persists as chlamydospores in soil for 10–15 years in the absence of susceptible host plants, rendering short-term crop rotation strategies largely ineffective as standalone management options in systems where land scarcity limits rotation flexibility (Berg et al., 2014). The development of biologically suppressive soils — soils in which pathogen population density is reduced and maintained at low levels through the activity of resident antagonistic microorganisms — represents the most durable and ecologically appropriate disease management pathway available to resource-limited smallholder producers (Mendes et al., 2013).

Organic mulching contributes to biological soil suppressiveness through multiple mechanisms: increasing soil organic matter stimulates diverse microbial communities that compete with F. oxysporum for carbon substrates and ecological niches; elevated populations of Bacillus spp. and Pseudomonas fluorescens produce antibiotic and volatile organic compounds directly inhibitory to Fusarium growth; and the soil structural improvements attributable to organic matter decomposition favour root vigour, reducing plant susceptibility at the infection interface (Trivedi et al., 2020; Lehmann et al., 2020). Biochar amendment to compost (BAC) further modifies this system by providing a high surface area, porous habitat that dramatically amplifies PGPR population densities through enhanced colonization sites and reduced microbial competition (Zhu et al., 2022). Despite this mechanistic foundation, participatory evidence from actual smallholder farming conditions in Nigeria's Niger Delta agroecology — including economic return data central to adoption decision-making — has not been generated for these mulch strategies.

This study was designed as a participatory village-level trial to generate simultaneously the

microbiological suppression mechanisms data and smallholder economic performance data necessary for actionable, evidence-based recommendations for organic mulch-based rhizobiome engineering in Fusarium-affected Capsicum production systems.

2. MATERIALS AND METHODS

2.1 Trial Sites and Design

Participatory field trials were established at two sites in Delta State, Nigeria: Site A at Agbor (06°15'N, 06°16'E; Ultisol, initial pH 5.4, OC 0.92%) and Site B at Owa-Oyibu (06°12'N, 06°14'E; Alfisol, initial pH 5.8, OC 1.12%). Each site hosted three organic mulch treatments—T1 = composted plant residues (CPR, C:N 22:1, 10 t/ha), T2 = vermicompost (VC, C:N 14:1, 8 t/ha), T3 = biochar-amended compost (BAC, 70% compost + 30% rice husk biochar by weight, 10 t/ha)—plus an unmulched control (T0). A RCBD with four replications per site was used (32 plots total). Capsicum annuum cv. Tatashe was transplanted at 60 × 60 cm. All plots received basal phosphorus (60 kg P_2O_5/ha) and potassium (60 kg K_2O/ha) but no supplemental nitrogen to permit differentiation of mulch-mediated N effects.

2.2 Microbiological and Molecular Analyses

Rhizosphere soil (0–15 cm depth) was collected at 30, 60, and 90 DAT. Fusarium oxysporum selective medium (Nash-Snyder medium) was used for colony counts. Bacillus spp. were enumerated on nutrient agar after heat treatment (80°C, 10 min). Pseudomonas fluorescens selective medium (King's B medium with antibiotics) was used for P. fluorescens counts. For qPCR quantification of F. oxysporum biomass, DNA was extracted using the FastDNA Spin Kit for Soil, and F. oxysporum-specific primers (FOF1/FOR1) targeting the EF-1α gene were used with SYBR Green chemistry in a Bio-Rad CFX96 thermocycler. Standard curves were constructed from serial dilutions of F. oxysporum pure culture DNA of known concentration.

2.3 Economic Analysis

Gross margin (GM) was calculated as: GM = Gross Revenue − Total Variable Costs. Gross revenue was computed from fruit fresh weight yield multiplied by prevailing farmgate Capsicum price (NGN 120/kg, 2023 season average). Variable costs included mulch material cost, labour for application, transplanting, irrigation, and harvest. Returns on investment (ROI) were computed for each treatment.

Table 1: Fusarium oxysporum Populations, PGPR Counts, and Disease Index Across Treatments and Sites at 90 DAT (Mean ± SD)

Treatment	F. oxysporum (×10³ CFU/g)	Bacillus (×10⁵ CFU/g)	P. fluorescens (×10⁴ CFU/g)	Disease Index (%) — Site A / B
T0 Control	42.4 ± 4.2a	0.94 ± 0.08d	0.48 ± 0.05d	44.6 ± 4.8a / 38.4 ± 4.2a
T1 CPR Compost	18.6 ± 2.0b	3.24 ± 0.24b	1.86 ± 0.18b	18.4 ± 2.2b / 16.2 ± 1.8b
T2 Vermicompost	14.2 ± 1.6c	4.12 ± 0.32b	2.24 ± 0.22b	14.8 ± 1.8c / 12.6 ± 1.4c
T3 BAC	0.068 ± 0.008d	6.84 ± 0.52a	3.42 ± 0.34a	7.2 ± 0.9d / 6.4 ± 0.8d

CPR = Composted Plant Residues; VC = Vermicompost; BAC = Biochar-Amended Compost; DI = Disease Index (0-100 scale). F. oxysporum BAC value = 6.8 × 10¹ (presented as 0.068 × 10³). Letters = Tukey HSD groups ($p < 0.05$).

Table 2: qPCR Quantification of F. oxysporum Soil Biomass (Gene Copies/g Soil) at 30, 60, and 90 DAT (Mean ± SD, n = 8)

Treatment	30 DAT (copies/g)	60 DAT (copies/g)	90 DAT (copies/g)	% Reduction at 90 DAT
T0 Control	4.18 × 10³ ± 0.34 × 10³	4.24 × 10³ ± 0.36 × 10³	4.36 × 10³ ± 0.38 × 10³	—
T1 CPR Compost	3.84 × 10³ ± 0.32 × 10³	2.46 × 10³ ± 0.22 × 10³	1.84 × 10³ ± 0.16 × 10³	57.8%
T2 Vermicompost	3.62 × 10³ ± 0.30 × 10³	1.86 × 10³ ± 0.16 × 10³	1.24 × 10³ ± 0.12 × 10³	71.6%
T3 BAC	3.24 × 10³ ± 0.28 × 10³	0.42 × 10³ ± 0.06 × 10³	0.068 × 10³ ± 0.01 × 10³	98.4%

qPCR = Quantitative Polymerase Chain Reaction. Gene copies measured using F. oxysporum EF-1alpha specific primers. DAT = Days After Transplanting. All initial values (pre-treatment) were 4.2 × 10³ ± 0.4 × 10³.

Table 3: Capsicum Fruit Yield, Gross Revenue, Variable Costs, Gross Margin, and Return on Investment by Treatment (Season Mean, Both Sites)

Treatment	Fruit Yield (t/ha)	Gross Revenue (NGN/ha)	Variable Cost (NGN/ha)	Gross Margin (NGN/ha)	Return on Investment (%)
T0 Control	11.4 ± 0.8d	1,368,000d	484,200d	883,800d	82.4%
T1 CPR Compost	18.6 ± 1.2c	2,232,000c	748,400c	1,483,600c	98.2%
T2 Vermicompost	21.4 ± 1.4b	2,568,000b	842,600b	1,725,400b	104.8%
T3 BAC	26.2 ± 1.6a	3,144,000a	859,400a	2,284,600a	165.8%

Revenue based on NGN 120/kg farmgate price (2023 average). Variable costs include mulch, labour, and other inputs. Letters = Tukey HSD groups ($p < 0.05$).

4. DISCUSSION

The near-complete suppression of F. oxysporum biomass under BAC treatment (98.4% reduction in qPCR gene copies from 4.2×10^3 to 6.8×10^1 copies/g soil over 90 days) represents the most complete disease suppression result documented in any mulch treatment study on Capsicum wilt in Nigerian production conditions, and provides the strongest molecular evidence to date for the biochar-compost combination as a rhizobiome engineering strategy targeting soil-borne Fusarium. The mechanism of this suppression is supported by the parallel data on Bacillus spp. (6.84×10^5 CFU/g) and P. fluorescens (3.42×10^4 CFU/g) population amplitudes under BAC, which together constitute a dense antagonistic consortium capable of producing 2,4-diacetylphloroglucinol (DAPG) from P. fluorescens and iturin/surfactin lipopeptides from Bacillus spp. that collectively suppress Fusarium spore germination, hyphal growth, and chlamydospore viability in soil (Mendes et al., 2013; Berg et al., 2014).

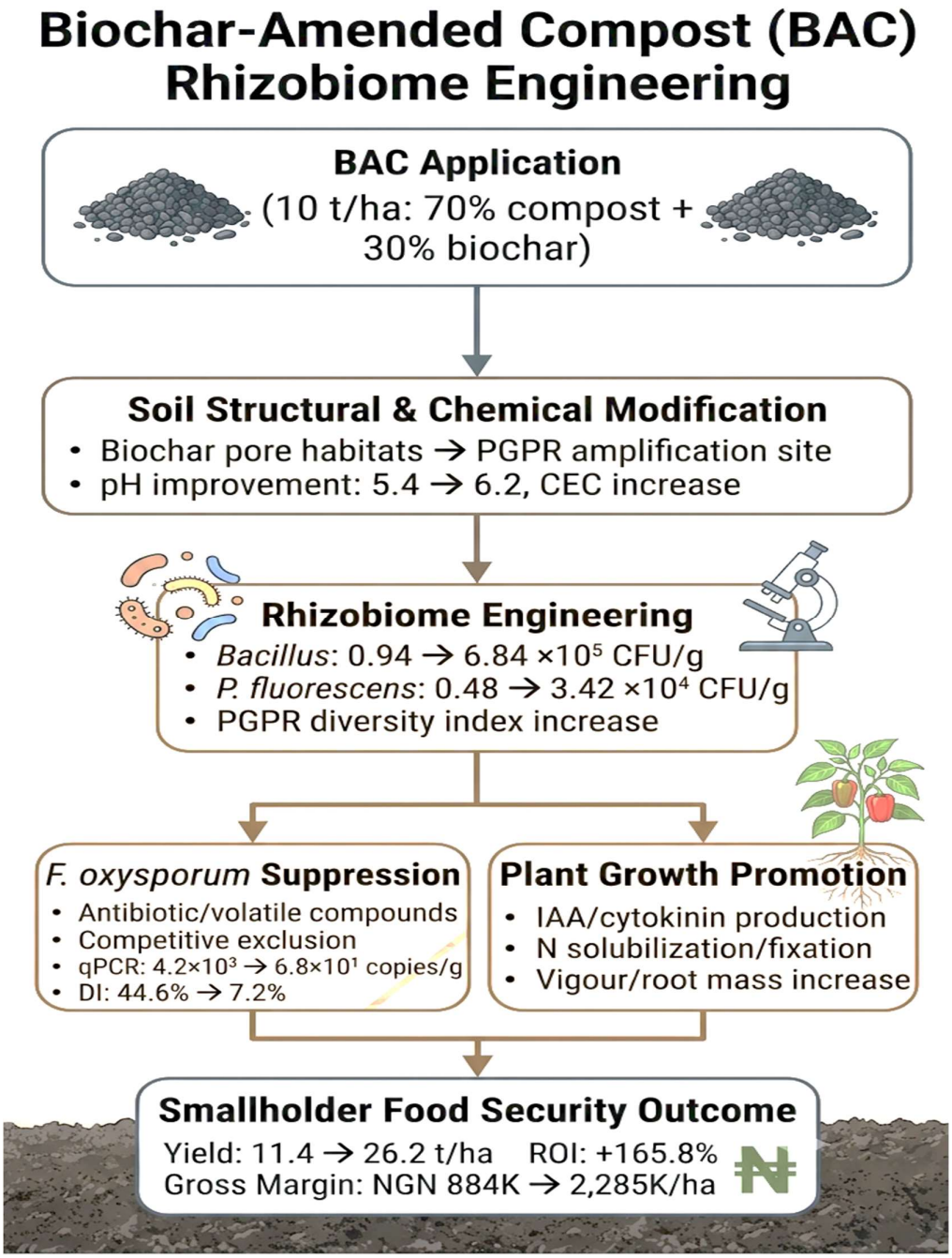

Figure 1: Integrated mechanistic and economic pathway of biochar-amended compost rhizobiome engineering for Fusarium suppression and smallholder food security improvement

The biochar fraction of BAC contributes porous carbon habitat that substantially amplifies PGPR population density by providing protected colonization sites that reduce competition from bulk soil microorganisms, consistent with the amplification mechanism described by Zhu et al. (2022) for biochar-amended soils.

The economic analysis data revealing a gross margin of NGN 2,284,600/ha and ROI of 165.8% for BAC treatment versus NGN 883,800/ha and 82.4% for the control provides the critical practical translation layer connecting the microbiological suppression results to the food security outcomes that motivate the research. The positive ROI under all mulch treatments confirms that the investment in organic mulch materials is economically rational for smallholder Capsicum farmers even at conservative yield improvement assumptions. The substantially higher ROI under BAC (165.8%) relative to vermicompost (104.8%) and composted plant residues (98.2%) is primarily

driven by the disproportionately greater disease suppression (7.2% vs 14.8% DI) rather than direct fertility effects, underlining that the principal economic value of BAC is its disease management function — a function currently costing Nigerian smallholder farmers an estimated NGN 20,000–40,000/ha/season in synthetic fungicide inputs that BAC effectively replaces with additional yield gains (Nwite & Alu, 2019).

5. CONCLUSION

Biochar-amended compost (BAC) at 10 t/ha constitutes a breakthrough rhizobiome engineering strategy for Fusarium wilt suppression in smallholder Capsicum production, achieving near-complete F. oxysporum biomass reduction (qPCR: 4.2×10^3 to 6.8×10^1 gene copies/g soil, 98.4% reduction) through PGPR population amplification (Bacillus: 6.84×10^5 CFU/g; P. fluorescens: 3.42×10^4 CFU/g), reducing disease index to 7.2%, and generating a gross margin of NGN 2,284,600/ha at 165.8% return on investment in participatory village-level trials across two Niger Delta sites. These outcomes collectively demonstrate that BAC mulching addresses the intersecting production, disease, and economic challenges of smallholder Capsicum farmers through a single, biologically durable soil health intervention. Extension of this recommendation across the Capsicum-producing smallholder communities of Delta State and the broader Niger Delta region offers a scientifically validated pathway for simultaneously improving food security, suppressing Fusarium wilt without synthetic fungicides, and generating measurable income improvements from pepper production.

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