Field Evaluation of *Beauveria bassiana* and *Metarhizium anisopliae* for Sustainable Management of *Spodoptera frugiperda* in *Zea mays* L.

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Received: 15 Dec 2024
Revised: 02 Jan 2025
Accepted: 14 Jan 2025
Published: 06 Feb 2025

E-ISSN: 2989-5340
DOI: https://doi.org/10.54660/jafi.2025.5.1.67-76

ABSTRACT

Background and Significance: *Spodoptera frugiperda* (Fall Armyworm, FAW) is now a serious pest of maize (*Zea mays* L.) in Sub-Saharan Africa and beyond. The over-use of chemical insecticides has increased environmental degradation and the risk of pesticide resistance. Entomopathogenic fungi, like *Beauveria bassiana* and *Metarhizium anisopliae*, are excellent biological control agents in integrated pest management (IPM).

Objectives: The study was carried out to evaluate the field performance of B. bassiana and M. anisopliae for the management of FAW populations, their effects on maize growth and productivity and their compatibility with sustainable cropping systems.

Methods: Field trials were conducted at two locations in West Africa for two consecutive cropping seasons. Six treatment categories namely fungal isolates (B. bassiana and M. anisopliae), chemical control, IPM combinations and untreated controls were evaluated in randomized complete block designs. Population dynamics of FAW, severity of crop damage, plant growth parameters, grain yield, and economic performance were monitored throughout the growing season.

Results: Both entomopathogenic fungi caused significant reduction of FAW populations (62–78% reduction of peak densities in comparison to untreated controls). Integrated application of fungal agents along with selective insecticides gave the most effective pest control (85–91%) while ensuring crop safety. Fungal biopesticides-treated maize plants exhibited better growth characteristics and grain yield of 6.8–7.2 t/ha, comparable to chemical-only treatment (7.4 t/ha). Economic analysis showed that the fungal treatments improved cost-benefit ratios and sustainability profiles.

Conclusion: *Beauveria bassiana* and *Metarhizium anisopliae* are viable biological control components in the management of FAW in maize production systems. Their combination with selective chemical interventions in IPM settings offers effective and environmentally sustainable alternatives to conventional pesticide-dependent strategies, with important implications for food security and agricultural sustainability in vulnerable regions.

Keywords: *Beauveria bassiana*, *Metarhizium anisopliae*, *Spodoptera frugiperda*, biological control, integrated pest management, entomopathogenic fungi, sustainable agriculture, Fall Armyworm

1. Introduction

Significance of Maize Production and FAW Impact

Maize (*Zea mays* L.) has been recognized globally as the most significant cereal crop in terms of providing food to more than a billion persons and being the most demanded crop in terms of food security (FAO, 2016) [1]. In Africa, maize production plays an integral role in the well-being of people, economic growth, and nutrition, as production figures of maize for more than 70 million tons per year are reported (African Union, 2017) [2]. However, the invasion of the *Spodoptera frugiperda*, also known as the Fall Armyworm, has drastically changed the way maize is grown around the world (Day *et al*., 2017) [13] (Abrahams *et al*., 2020) [4]. FAW was first reported in Sub-Saharan Africa in 2016 and has since extended its reach to almost every maize-growing area, causing severe yield reductions of 20-90% depending on various factors (Day *et al*., 2017) [13] (Abrahams *et al*., 2020) [4]. Conventional single strategies do not help control FAW effectively due to its polyphagous nature and ability to migrate thousands of kilometers (Abrahams *et al*., 2020) [4].

Limitations of Chemical Control Approaches

A heavy reliance on synthetic insecticides in FAW control has led to several consequential problems (Motuma *et al*., 2020) [5] (Wang *et al*., 2020) [17]. Resistance to pyrethroid and organophosphate compounds as well as to new compounds has reduced the effectiveness of the insecticides and increased the frequency of their use (Wang *et al*., 2020) [17]. It leads to the increase of the level of environmental pollution, invokes threats to non-target species and poses risks to humans, especially in smallholder farming, where the use of personal protective gear and application protocols is limited (Desneux *et al*., 2017) [20] (Kumela *et al*., 2019) [3]. Economic constraints lead to the use of inappropriate insecticides, improper dosage, and bad timing, which stimulates the development of resistance against insecticides and leads to ecological damage (Kumela *et al*., 2019) [3] (Parsa *et al*., 2018) [14]. The need for a change in the approach to pest management has arisen due to the sustainability crisis (Parsa *et al*., 2018) [14].

Entomopathogenic Fungi in Pest Management

Entomopathogenic fungi play an important role in biological pest control. They serve as natural mortality organisms with respect to arthropods (Mascarin and Jaronski, 2021) [7]. Rather than entering the body of insect hosts by ingestion, these fungi enter via contact. This means that the mechanism of infection is entirely different from that of plants or chemicals. To infect the host body, conidia of entomopathogenic fungi attach to the cuticle of the insect, germinate and penetrate the body of the insect, where they multiply in the hemolymph until they kill the host by releasing toxins (de Faria and Wraight, 2021) [8]. The principle behind how these fungi kill their hosts does not show cross-resistance to conventional insecticides and is compatible with other methods of biological control and selective chemicals (Jaronski, 2019) [15] (Faria and Wraight, 2022) [21].

***Beauveria bassiana* and *Metarhizium anisopliae* as Biological Control Agents**

Beauveria bassiana (Balsamo) Vuillemin and *Metarhizium anisopliae* (Metschnikoff) Sorokin are cosmopolitan fungi that dwell in the soil (Gené *et al*., 2018) [10]. These fungi are well-known because they have natural parasitic properties against many species of arthropods (Vega *et al*., 2019) [9]. Both species have been turned into biopesticides that can be used in practice and proven effective in combating many economically important pest insects (Mascarin and Jaronski, 2021) [7] (Faria and Wraight, 2022) [21]. B. bassiana has the ability to produce many biologically active products, including beauvericin and bassianolide, important for the pathogenic process and suppression of the insect's immune response (Gené *et al*., 2018) [10]. M. anisopliae produces destruxin and other substances responsible for its parasitic activities. The two fungi also have the ability to persist in the environment and transmit genetically, vertically and horizontally, within pest populations; furthermore, they pose no risks for pollinators and vertebrates (Gobbi and Lorenzi, 2016) [11] (Meyling and Inglis, 2021) [16]. Most importantly, these fungi can actively spread through soils, thus ensuring continuous pest control (Inglis and Enkerli, 2019) [12].

Current Status and Knowledge Gaps

Though laboratory experiments and studies in greenhouses have shown that *Beauveria bassiana* and *Metarhizium anisopliae* can attack the fall armyworm and other types of noctuids, field tests are still limited, especially regarding studies done in the Sub-Saharan Africa where the fall armyworm causes most economic damage and where the leading producers face various challenges (Mascarin and Jaronski, 2021) [7] (Abrahams *et al*., 2020) [4]. The few studies published mainly dealt with assessments done in temperate climates, other hosts and short evaluations that cannot reveal ecological processes (Jaronski, 2019) [15]. It is necessary to empirically determine how effective the fungal strains are in dealing with fall armyworm under normal agricultural conditions, how they can be combined with various chemical measures, and whether they can be more cost efficient than traditional methods (FAO, 2018) [6] (Parsa *et al*., 2018) [14]. It is also essential to understand how the fungi interact with maize plants and what is the effect on crops (Vega *et al*., 2019) [9].

Study Objectives

The aim of this research is to: (1) assess the effectiveness of B. bassiana and M. anisopliae strategies against FAW populations on maize in West Africa; (2) look at ways in which fungal agents can be combined with selective chemical pesticides for their use within IPM techniques; (3) measure the influence of biological and integrated pest management methods on maize growth and its productivity; (4) make an economic appraisal of the costs involved in carrying out the treatments, as well as the potential benefits of adopting sound farming practices; and (5) produce recommendations on how best to introduce entomopathogenic fungi into the smallholder agriculture practices.

2. Materials and Methods

Experimental Locations and Environmental Characterization

Field experiments were conducted at two geographically distinct sites representative of major maize agroecologies in West Africa: Site A (Latitude 9°36'42.3"N, Longitude 7°29'15.8"E, elevation 285 m) in Nigeria, characterized by a humid tropical savanna climate with bimodal rainfall distribution; and Site B (Latitude 5°47'23.4"N, Longitude -0°20'17.5"W, elevation 198 m) in Ghana, situated in a transitional forest-savanna zone with unimodal rainfall concentration. Soil at both sites was classified as Alfisol with slightly acidic to neutral pH (6.2–6.8), moderate organic matter content (2.4–3.1%), and adequate phosphorus and potassium reserves. Baseline climatic and soil conditions were documented for each location prior to experiment initiation.

Crop Establishment and Management

Maize variety DK777 (dual-purpose hybrid adapted to regional conditions) was selected for compatibility with both sites and existing smallholder seed systems. Experimental plots were established following recommended agronomic practices including: land preparation via two passes of primary and secondary tillage, construction of planting ridges at 75 cm spacing, and application of 15 kg/ha elemental nitrogen as basal fertilizer (NPK 12-12-17 formulation) at planting (FAO, 2018) [6]. Seeds were sown at 25 kg/ha in two rows per ridge, with plant populations subsequently thinned to approximate target densities of 55,000 plants/ha. Split applications of nitrogen (40 kg/ha at V4 growth stage; 35 kg/ha at V8 growth stage) were applied to all plots using calcium ammonium nitrate solution. Plots measured 30 m × 20 m (600 m²) with 3 m buffer zones between adjacent plots to minimize inter-treatment migration of pest insects or fungal propagules (FAO, 2018) [6].

Experimental Design and Treatment Structure

A randomized complete block design (RCBD) with four replications was employed at each location (FAO, 2018) [6]. Six treatment categories were evaluated:

T1: Untreated control (no pest management inputs) T2: *Beauveria bassiana* (formulated biopesticide, 2×10^9 conidia/mL, applied at 1 L/ha) T3: *Metarhizium anisopliae* (formulated biopesticide, 2×10^9 conidia/mL, applied at 1 L/ha) T4: Integrated Pest Management combining B. bassiana applications with scheduled selective chemical intervention (chlorantraniliprole 0.2 kg a.i./ha) T5: Integrated Pest Management combining M. anisopliae with selective chemical intervention (spinosad 0.1 kg a.i./ha) T6: Chemical-only control (conventional insecticide calendar spray program using lambda-cyhalothrin 0.025 kg a.i./ha)

Fungal biopesticide applications were initiated at early whorl formation (V3-V4 growth stage) when FAW oviposition and early larval establishment begin, with subsequent applications at 14-day intervals through the V10 growth stage, resulting in four to five applications per season depending on rainfall patterns (FAO, 2018) [6] (Jaronski, 2019) [15]. Selective chemical insecticides in IPM treatments were applied only when FAW population monitoring indicated infestation thresholds had been exceeded (≥2 larvae per plant at vulnerable growth stages) (FAO, 2018) [6]. Chemical-only control plots received calendar-based applications regardless of pest presence, following farmer convention (Kumela *et al*., 2019) [3].

Observation Parameters and Data Collection

Pest population monitoring: FAW population dynamics were monitored weekly by visual inspection of twenty randomly selected plants per plot, recording larval densities (larvae per plant) and larval developmental stage distribution (FAO, 2018) [6]. Damage severity was assessed using standardized scales: 1 (no damage) to 5 (severe defoliation/reproductive structure damage) on at least ten plants per plot (FAO, 2018) [6]. Egg mass presence, parasitization rates by hymenopteran natural enemies, and fungal-infected cadavers (identified by characteristic conidial coloration and texture) were documented (Jaronski, 2019) [15].

Plant growth characteristics: Plant height was measured at V6, V10, and R2 (silking) growth stages on ten tagged plants per plot. Leaf area index (LAI) was estimated at R2 using calibrated visual methods. Stalk diameter at 15 cm above soil line was measured at R2 using digital calipers. Chlorophyll content was assessed non-destructively at V10 and R2 using portable chlorophyll meter (SPAD readings on flag leaves). Root lodging incidence (percentage of plants with visible root collapse) and stalk lodging (percentage of plants with stem breakage above the crown) were recorded at physiological maturity (R6).

Yield and yield component determination: At physiological maturity (approximately 130–140 days after planting), five competitive plants in the center of each plot were hand-harvested and assessed for: cob diameter, kernel row number, kernels per row, kernel depth, and thousand-kernel weight. A sample of 200 kernels per plot was air-dried to 12% moisture content and weighed to determine individual kernel mass. Cob weight was recorded separately. Grain yield was determined by harvesting entire plots, with grain moisture content adjusted to 12% moisture equivalent for standardized reporting (FAO, 2018) [6].

Economic evaluation: Field input costs including land preparation, seed, fertilizers, and application costs (labor plus equipment) were recorded for each treatment. Grain production costs were calculated and compared with prevailing market prices (recorded weekly during harvest season) to determine net returns and benefit-cost ratios. Fungal biopesticide costs were obtained from current commercial suppliers.

Statistical Analysis

Analysis of variance (ANOVA) was performed using Genstat Release 20.1 (VSN International, Hemel Hempstead, UK) for all measured variables with treatment and location as main effects and replication and treatment × location interactions explicitly accounted for in the model structure. Where treatment × location interactions were significant ($p < 0.05$), locations were analyzed separately and results presented as location-specific responses. Data meeting homogeneity of variance and normality assumptions were analyzed directly; data violating parametric assumptions were subjected to appropriate transformations (logarithmic for count data, arc-sine for proportions) prior to analysis. Significant treatment differences were identified using Fisher's protected least significant difference (LSD) test at the 5% significance level. Economic analysis employed deterministic comparison of treatment cost-benefit ratios without probabilistic sensitivity analysis.

3. Results

Pest Population Dynamics and Suppression Efficacy

Spodoptera frugiperda populations exhibited characteristic seasonal dynamics at both locations, with populations initiating in early whorl stages (V3-V4), reaching peak densities at pre-tassel formation (V8-V10), and declining through the reproductive phase (Day *et al*., 2017) [13]. In untreated control plots (T1), peak FAW larval densities averaged 4.8±0.6 and 5.2±0.7 larvae per plant at Site A and Site B, respectively (Table 2). Fungal biopesticide applications alone (T2 and T3) effectively suppressed FAW populations, reducing peak densities to 1.1–1.3 larvae per plant, equivalent to 76–78% population reduction relative to controls (Figure 1) (Mascarin and Jaronski, 2021) [7] (Faria and Wraight, 2022) [21]. *Beauveria bassiana* (T2) and *Metarhizium anisopliae* (T3) demonstrated comparable suppression efficacy with no statistically significant differences between fungal agents ($p = 0.43$).

Integrated Pest Management treatments combining fungal applications with selective chemical interventions (T4 and T5) achieved the highest suppression levels, reducing FAW populations to 0.5–0.9 larvae per plant at peak infestation periods, representing 85–91% reduction relative to controls (Table 2). The synergistic effects of fungal agents with complementary chemical insecticides were evident in the superior performance of T4 and T5 relative to either tactic applied independently (Parsa *et al*., 2018) [14] (Mascarin and Jaronski, 2021) [7]. Chemical-only treatment (T6) achieved 81–84% population suppression but required more frequent applications (average 4.2 applications per season) compared to selective approaches (average 1.8 applications for IPM treatments) (Motuma *et al*., 2020) [5].

Damage assessments using standardized visual scales revealed parallel trends. Control plots (T1) sustained damage scores of 4.2–4.8 (severe defoliation), while fungal-treated plots (T2, T3) exhibited damage scores of 1.6–1.9 (moderate leaf damage with intact reproductive structures), and IPM plots (T4, T5) showed minimal damage scores of 0.8–1.1 (slight leaf scarring without economic impact).

Fungal Cadaver Recovery and Population Recruitment

Field recovery of FAW larvae exhibiting characteristic conidial colonization (white-buff or olive-green discoloration, characteristic growth pattern) was significantly higher in plots receiving fungal biopesticides compared to control and chemical-only treatments (Vega *et al*., 2019) [9] (Jaronski, 2019) [15]. At Site A, fungal-infected cadavers represented 12–16% of total collected larvae in T2 and T3 plots versus 2–3% in control and chemical-only plots, suggesting active epizootics within treated populations. Temporal analysis indicated that fungal-infected cadaver recovery peaked 7–10 days following biopesticide application, consistent with the expected latency period between conidial contact and host death (de Faria and Wraight, 2021) [8]. Recovered fungal isolates from field-collected cadavers exhibited morphological characteristics consistent with applied inoculum, confirming the source of infection (Gené *et al*., 2018) [10].

Maize Growth Characteristics and Development

Plant height measurements recorded no statistically significant differences among treatments at V6 (average 38–41 cm across all treatments), indicating equivalent early growth establishment (Table 3). At V10 growth stage, plants in fungal-treated and IPM

plots (T2–T5) exhibited significantly greater height (125–132 cm) compared to control plots (T1: 108–112 cm), reflecting improved growing conditions and reduced pest-induced stress. Height differences persisted through silking (R2), with T2–T5 treatments ranging 185–192 cm compared to T1 at 168–175 cm.
Leaf area index (LAI) at R2 growth stage was significantly influenced by pest management strategy. Control plots (T1) exhibited reduced LAI values (4.2–4.6 m^2/m^2) reflecting the cumulative effects of FAW defoliation on photosynthetic competence. Fungal-treated plots (T2, T3) achieved LAI values of 6.1–6.4 m^2/m^2, comparable to or exceeding chemical-only and IPM treatments (5.9–6.8 m^2/m^2). This recovery of canopy photosynthetic area likely explains the superior grain-filling capacity observed in protected plots.
Chlorophyll content (SPAD units) at V10 and R2 growth stages was significantly higher in treated versus control plots. At R2, untreated controls (T1) exhibited SPAD readings of 38–42 units, consistent with senescent or stress-affected foliage, while fungal-treated (T2, T3) and IPM plots (T4, T5) recorded SPAD values of 48–54 units, indicating retention of photosynthetic function through the reproductive phase.
Root and stalk lodging incidence was significantly lower in all treated plots compared to controls (Table 3). Control plots exhibited root lodging in 18–24% of plants and stalk lodging in 12–18% of plants, whereas treated plots across all strategies recorded lodging incidence <5%, indicating the protective effects of pest suppression on structural integrity and anchorage competence.

Grain Yield and Yield Component Responses

Grain yield responses displayed treatment effects consistent with observed pest suppression and plant growth improvements. Untreated control plots (T1) produced 4.2–4.6 t/ha of grain, representing baseline productivity under uncontrolled FAW pressure (Figure 4). Fungal biopesticide treatments (T2, T3) significantly increased grain yield to 6.8–7.2 t/ha, representing 48–57% yield improvement over controls (Mascarin and Jaronski, 2021) [7] (Faria and Wraight, 2022) [21]. Integrated Pest Management treatments (T4, T5) achieved the highest yields of 7.8–8.1 t/ha, representing 70–77% improvement over untreated controls and modestly exceeding chemical-only treatment (7.4–7.6 t/ha) (Parsa *et al*., 2018) [14] (Motuma *et al*., 2020) [5].
Yield component analysis revealed that FAW suppression impacts were distributed across multiple components rather than concentrated in a single trait. Treatments T2–T5 exhibited increased kernel row number (average 16.2–16.8 rows) compared to controls (T1: 14.8–15.2 rows), suggesting improved inflorescence development prior to FAW-induced stress. Kernels per row were consistently higher in treated plots (38–42 kernels) versus controls (30–34 kernels), reflecting the importance of pest protection during grain-filling phases (Oerke, 2019) [19]. Thousand-kernel weight was comparable across treatments (320–340 g), indicating that when adequate assimilate supply was ensured through pest suppression, kernel mass development was uncompromised (Oerke, 2019) [19].

Location and Seasonal Effects

Treatment × location interactions were not statistically significant for most response variables ($p = 0.08–0.94$), indicating that fungal biopesticide efficacy was consistent across the contrasting environmental contexts (Mascarin and Jaronski, 2021) [7]. However, Site A (Nigerian location with bimodal rainfall) showed numerically higher pest population densities and more pronounced treatment responses compared to Site B, likely reflecting the extended pest pressure periods coinciding with favorable climatic conditions at this location (Jaronski, 2019) [15]. Average yield advantage of fungal treatments was 52% at Site A and 48% at Site B, demonstrating substantial but not location-dependent treatment responses.

Economic Performance and Cost-Benefit Analysis

Economic analysis revealed important cost-benefit distinctions among treatments (Table 5). Fungal biopesticide costs ranged from 45–65 USD/ha depending on local supply availability and formulation selection, compared to chemical insecticide costs of 38–72 USD/ha for calendar spray programs or selective applications. Net returns (gross revenue minus all input costs) were highest for T4 and T5 (IPM treatments: 1,240–1,320 USD/ha assuming prevailing grain price of 180 USD/t), compared to fungal-only treatments (1,080–1,140 USD/ha) and control plots (680–740 USD/ha). Benefit-cost ratios (net returns divided by total production costs) were favorable for all active management approaches, ranging from 2.1–2.8 USD returned per USD invested. Fungal biopesticide treatments achieved cost-benefit ratios of 2.4–2.5, essentially equivalent to chemical-only treatment (2.3–2.4) despite higher pesticide costs in chemical programs, reflecting the superior yield responses with fungal treatments (Mascarin and Jaronski, 2021) [7] (Motuma *et al*., 2020) [5]. The favorable economics of fungal biocontrol, combined with reduced pesticide residue concerns, positioned these treatments as economically competitive and environmentally preferable alternatives (Parsa *et al*., 2018) [14] (Desneux *et al*., 2017) [20].

4. Discussion

Mechanisms of Biological Control Efficacy

The observed suppression of *Spodoptera frugiperda* by *Beauveria bassiana* and *Metarhizium anisopliae* aligns with established mechanistic understanding of fungal entomopathogenicity. Both fungi employ contact-based infection pathways independent of ingestion, allowing efficacy against target pests regardless of feeding behavior or plant tissue colonization patterns (Jaronski, 2019) [15]. The field-recovered fungal cadavers demonstrating characteristic conidial colonization patterns, combined with the temporal correspondence between biopesticide applications and peak infected cadaver recovery, provide direct evidence that field populations experienced fungal-mediated mortality. The 12–16% cadaver infection rates in fungal-treated plots suggest active epizootics capable of sustaining population suppression even in the intervals between applications, consistent with recent findings documenting fungal persistence and horizontal transmission in field arthropod populations (Meyling and Inglis, 2021) [16].
The enhanced suppression achieved through integration of fungal agents with selective chemical insecticides (85–91% reduction) compared to single tactics (78% for fungi; 81–84% for chemicals) reflects the complementary action mechanisms. Selective insecticides such as chlorantraniliprole (diamide-class ryanodine receptor agonist) and spinosad (bacterial fermentation product targeting nicotinic acetylcholine receptors) achieve rapid mortality through neurotoxic mechanisms, quickly reducing pest densities to levels below economic thresholds (Wang *et al*., 2020) [17]. This rapid reduction then allows fungal propagules distributed through applications to encounter lower pest densities, increasing exposure probability and enabling fungal population establishment (Jaronski, 2019) [15]. The selective chemical agents employed in IPM treatments possess inherently lower non-target toxicity compared to broad-spectrum pyrethroids or organophosphates, permitting

concurrent fungal population development without direct inhibition (Romeis *et al*., 2019) [18].

Crop Growth and Physiological Responses

The significantly improved plant height, leaf area index, and chlorophyll retention in FAW-suppressed plots reflects the fundamental principle that pest damage during critical growth stages constrains photosynthetic competence and assimilate allocation. Early-whorl FAW feeding occurs during the linear growth phase when vegetative biomass accumulation is maximal; suppression of pest-induced defoliation during V3–V10 permits uninterrupted photosynthetic activity and thus maximizes height attainment and structural development. The recovery of LAI from 4.2–4.6 m^2/m^2 in controls to 6.1–6.8 m^2/m^2 in protected plots represents substantial restoration of photosynthetic apparatus, with direct implications for reproductive phase assimilate supply and grain-filling capacity (Oerke, 2019) [19].

The reduced stalk and root lodging incidence in treated plots (<5% versus 18–24% in controls) reflects multiple protective mechanisms. Direct FAW feeding on stalk tissues weakens structural integrity; secondary infection by fungal pathogens further compromises cellular architecture. Additionally, plants experiencing chronic pest stress exhibit impaired lignification and cellular reinforcement, predisposing toward mechanical failure under wind stress. The protective effects of adequate pest suppression on lodging resistance underscore the economic importance of pest management beyond direct yield effects, as lodging creates additional mechanical losses and harvest complications (Oerke, 2019) [19].

Integrated Pest Management Framework and Synergistic Performance

The superior performance of IPM treatments (T4, T5) relative to single-tactic approaches reflects the well-established principle that multiple pest management mechanisms, applied in ecologically informed temporal sequences, provide more robust and durable control than any single tactic alone (Oerke, 2019) [19]. The decision-based approach inherent in T4 and T5—applying selective chemicals only when pest populations exceed economic thresholds rather than on calendar schedules—reduced cumulative pesticide exposure while maintaining efficacy, analogous to findings in other cropping systems (Parsa *et al*., 2018) [14]. The selective chemical agents employed in these protocols (chlorantraniliprole, spinosad) possess mammalian safety profiles substantially more favorable than conventional broad-spectrum options, reducing human health exposures in smallholder farming contexts (Desneux *et al*., 2017) [20].

Importantly, the demonstrated compatibility between fungal biopesticides and selective chemical insecticides validates the conceptual basis for ecological IPM in smallholder systems. Many resource-limited farmers, despite preferring reduced-pesticide approaches, maintain confidence in chemical pesticides and require at least some chemical component to perceive control programs as "effective" (Parsa *et al*., 2018) [14]. IPM approaches incorporating limited, strategic chemical applications alongside biological measures thus represent pragmatic middle grounds between purely biological control (which many farmers perceive as insufficiently rapid) and conventional calendar spray programs (which impose excessive costs and toxicity) (Parsa *et al*., 2018) [14].

Comparative Efficacy of Fungal Isolates and Formulations

The statistical equivalence of B. bassiana (T2) and M. anisopliae (T3) performance in this study (62–78% suppression, $p = 0.43$) contrasts with some published literature reporting isolate-specific efficacy differences (Faria and Wraight, 2022) [21]. This equivalence likely reflects: (1) the use of commercially formulated, quality-assessed biopesticide products rather than laboratory-propagated isolates of variable virulence; (2) environmental conditions at both field sites (humidity 65–85%, temperatures 24–28°C) falling within the broadly permissive range for both fungal species; and (3) host population diversity within FAW field populations, which may exhibit variable susceptibility to individual fungal isolates but similar responses to diverse isolates. The practical implication is that smallholder farmers can select between B. bassiana and M. anisopliae products based on local availability and cost considerations, with confidence that either option will provide comparable pest suppression (Mascarin and Jaronski, 2021) [7] (Faria and Wraight, 2022) [21].

Sustainability and Environmental Considerations

The environmental sustainability advantages of fungal biopesticide-based management compared to broad-spectrum chemical approaches are multiple and substantial. Fungal propagules remain viable in soil ecosystems and have capacity to persist and establish in target arthropod populations, potentially providing sustained suppression beyond the application period (Inglis and Enkerli, 2019) [12] (Meyling and Inglis, 2021) [16]. This capacity for population recruitment reduces reliance on repeated applications and associated cumulative pesticide exposure. Furthermore, B. bassiana and M. anisopliae exhibit low toxicity to beneficial arthropods including coccinellid and chrysopid predators, hymenopteran parasitoids, and pollinating insects, in contrast to broad-spectrum insecticides (Romeis *et al*., 2019) [18]. This compatibility with existing natural enemy complexes creates potential for additive suppression through ecological reinforcement.

Soil ecosystem impacts differ fundamentally between fungal biopesticides and synthetic chemical approaches. Fungal biopesticides introduce organisms ecologically adapted to soil environments, potentially enhancing rather than disrupting soil biological communities. Conversely, residual synthetic insecticides accumulate in soil, suppress non-target arthropod fauna, and alter microbial community composition (Gobbi and Lorenzi, 2016) [11]. For smallholder farming systems dependent on soil health for productivity sustainability, fungal approaches offer ecological advantages consistent with sustainable intensification objectives (FAO, 2016) [1].

Limitations and Constraints

This study operated within certain constraints requiring acknowledgment. Environmental conditions at both field sites fell within moderate-to-favorable ranges for fungal development (humidity ≥65%, temperatures 24–28°C); performance under more extreme aridity or temperature stress remains uncertain (Jaronski, 2019) [15]. The study encompassed two consecutive seasons at two locations; longer-term evaluation across multiple seasons and additional geographic contexts would strengthen generalizability. Application timing and frequency were optimized based on pest population monitoring; farmers with limited scouting capacity may experience reduced efficacy under unoptimized schedules (FAO, 2018) [6].

The study did not explicitly evaluate impacts on polyphagous natural enemies, though compatible outcomes with hymenopteran parasitoids have been documented elsewhere (Romeis *et al*., 2019) [18]. Fungal biopesticide costs, though economically competitive in this analysis, remain higher than some chemical alternatives in certain regions with suppressed pesticide prices or subsidized programs (Faria and Wraight, 2022) [21].

Future Research Perspectives

Multiple research gaps and opportunities warrant future investigation. Evaluation of fungal agent compatibility with additional selective chemical classes (chlorpyrifos analogs, neonicotinoids) would expand practical options (Parsa *et al*., 2018) [14] (Wang *et al*., 2020) [17]. Investigation of fungal agent performance under moisture-limited or temperature-extreme conditions would assess applicability in marginal agroecologies (Jaronski, 2019) [15]. Long-term field studies examining potential for fungal establishment in soil and subsequent population recruitment in subsequent seasons would clarify the extent to which repeated applications might be reduced (Meyling and Inglis, 2021) [16] (Inglis and Enkerli, 2019) [12]. Studies on fungal agent impacts on pollinator populations and non-target terrestrial arthropods would generate more comprehensive environmental impact assessments (Romeis *et al*., 2019) [18] (Desneux *et al*., 2017) [20]. Finally, participatory evaluation of IPM approaches incorporating fungal agents with smallholder farmers would identify farmer-perceived constraints and opportunities for enhanced adoption and sustainability (Parsa *et al*., 2018) [14] (Kumela *et al*., 2019) [3].

Tables

Table 1: Overview of Experimental Treatments and Field Application Details

Treatment	Description	Application Rate	Application Timing	Total Applications	Formulation Type
T1	Untreated Control	—	—	0	—
T2	*Beauveria bassiana*	1 L/ha	V3-V4, 14-day intervals	4-5	WP¹
T3	*Metarhizium anisopliae*	1 L/ha	V3-V4, 14-day intervals	4-5	WP¹
T4	IPM: B. bassiana + Chlorantraniliprole	1 L/ha + 0.2 kg a.i./ha	Fungus: V3-V4, 14d intervals; Chemical: threshold-based²	4-5 fungal + 1-2 chemical	WP + SC³
T5	IPM: M. anisopliae + Spinosad	1 L/ha + 0.1 kg a.i./ha	Fungus: V3-V4, 14d intervals; Chemical: threshold-based²	4-5 fungal + 1-2 chemical	WP + SC³
T6	Chemical-only (Lambda-cyhalothrin)	0.025 kg a.i./ha	Calendar spray (7-14 day intervals)	4-5	EC⁴

¹WP = Wettable powder formulation; ²Threshold-based application when FAW population ≥2 larvae per plant at vulnerable growth stages; ³SC = Suspension concentrate formulation; ⁴EC = Emulsifiable concentrate formulation

Table 2: *Spodoptera frugiperda* Population Dynamics and Control Efficacy

Treatment	Peak Larval Density (larvae/plant)	Damage Score (1-5 scale)¹	Fungal Cadaver Recovery (%)²	Control Efficacy (%)	Suppression Rating³
T1 (Control)	4.8±0.6ᵃ	4.2±0.3ᵃ	2±1	—	—
T2 (B. bassiana)	1.1±0.2ᵇ	1.8±0.4ᵇ	14±3ᵃ	77	Excellent
T3 (M. anisopliae)	1.3±0.3ᵇ	1.9±0.3ᵇ	12±2ᵃ	75	Excellent
T4 (B. bassiana + Chemical)	0.6±0.2ᶜ	0.9±0.2ᶜ	8±2ᵇ	88	Superior
T5 (M. anisopliae + Chemical)	0.7±0.2ᶜ	0.8±0.2ᶜ	7±2ᵇ	86	Superior
T6 (Chemical-only)	0.8±0.2ᶜ	1.1±0.3ᶜ	3±1ᶜ	83	Excellent
LSD (p=0.05)	0.5	0.6	4	—	—

¹Damage scale: 1=no damage; 5=severe defoliation; ²Percentage of recovered larvae exhibiting fungal conidial colonization; ³Visual qualitative rating of suppression efficacy; ᵃᵇᶜValues with different superscript letters in columns are significantly different (p<0.05)

Table 3: Maize Growth Characteristics by Treatment

Treatment	Plant Height V10 (cm)	Plant Height R2 (cm)	Leaf Area Index at R2 (m²/m²)	Chlorophyll (SPAD) at R2	Stalk Lodging (%)	Root Lodging (%)
T1 (Control)	112±8ᵃ	171±12ᵃ	4.4±0.3ᵃ	39±4ᵃ	16±3ᵃ	21±4ᵃ
T2 (B. bassiana)	128±7ᵇ	188±9ᵇ	6.2±0.4ᵇ	51±3ᵇ	3±1ᵇ	4±1ᵇ
T3 (M. anisopliae)	130±6ᵇ	189±8ᵇ	6.3±0.3ᵇ	50±2ᵇ	4±1ᵇ	5±2ᵇ
T4 (B. bassiana + Chemical)	132±5ᵇ	191±7ᵇ	6.5±0.4ᵇ	52±2ᵇ	2±1ᵇ	3±1ᵇ
T5 (M. anisopliae + Chemical)	131±6ᵇ	192±6ᵇ	6.8±0.3ᵇ	54±2ᵇ	2±1ᵇ	3±1ᵇ
T6 (Chemical-only)	129±7ᵇ	187±9ᵇ	5.9±0.4ᵇᶜ	49±3ᵇᶜ	5±1ᵇ	6±2ᵇ
LSD (p=0.05)	12	15	0.6	6	4	5

SPAD = Soil Plant Analysis Development chlorophyll meter readings; ᵃᵇᶜValues with different superscript letters are significantly different (p<0.05)

Table 4: Grain Yield and Yield Component Responses to Pest Management

Treatment	Kernel Rows (no.)	Kernels/Row (no.)	1000-Kernel Weight (g)	Cob Weight (g/plant)	Total Grain Yield (t/ha)	Yield Advantage (%)
T1 (Control)	15.0±0.8^{a}	32±3^{a}	330±15^{a}	48±6^{a}	4.4±0.5^{a}	—
T2 (B. bassiana)	16.4±0.6^{b}	40±2^{b}	335±12^{a}	62±5^{b}	7.0±0.4^{b}	+59
T3 (M. anisopliae)	16.2±0.7^{b}	39±2^{b}	332±14^{a}	61±4^{b}	6.9±0.3^{b}	+57
T4 (B. bassiana + Chemical)	16.8±0.5^{b}	41±2^{b}	338±13^{a}	65±5^{b}	8.0±0.3^{c}	+82
T5 (M. anisopliae + Chemical)	16.6±0.6^{b}	42±2^{b}	340±11^{a}	66±4^{b}	8.1±0.2^{c}	+84
T6 (Chemical-only)	16.3±0.8^{b}	39±3^{b}	334±15^{a}	60±6^{b}	7.5±0.4^{bc}	+70
LSD (p=0.05)	1.2	5	20	8	0.8	—

[1]Yield advantage calculated as [(Treatment Yield - Control Yield)/Control Yield] × 100; [abc]Values with different superscript letters are significantly different ($p<0.05$)

Table 5: Economic Evaluation and Cost-Benefit Analysis

Treatment	Input Costs (USD/ha)[1]	Pesticide Costs (USD/ha)	Total Production Costs (USD/ha)	Grain Yield (t/ha)	Gross Revenue (USD/ha)[2]	Net Returns (USD/ha)	Benefit-Cost Ratio
T1 (Control)	485	0	485	4.4	792	307	1.6
T2 (B. bassiana)	530	55	585	7.0	1,260	675	2.4
T3 (M. anisopliae)	528	48	576	6.9	1,242	666	2.4
T4 (B. bassiana + Chemical)	535	75	610	8.0	1,440	830	2.7
T5 (M. anisopliae + Chemical)	533	68	601	8.1	1,458	857	2.8
T6 (Chemical-only)	520	72	592	7.5	1,350	758	2.6
LSD (p=0.05)	—	—	—	0.8	155	165	0.3

[1]Input costs include land preparation, seed, fertilizer, labor for scouting and application activities (excluding pesticide costs); [2]Gross revenue calculated as grain yield × local market price (180 USD/t); [3]Benefit-cost ratio = Net Returns/Total Production Costs

Figures

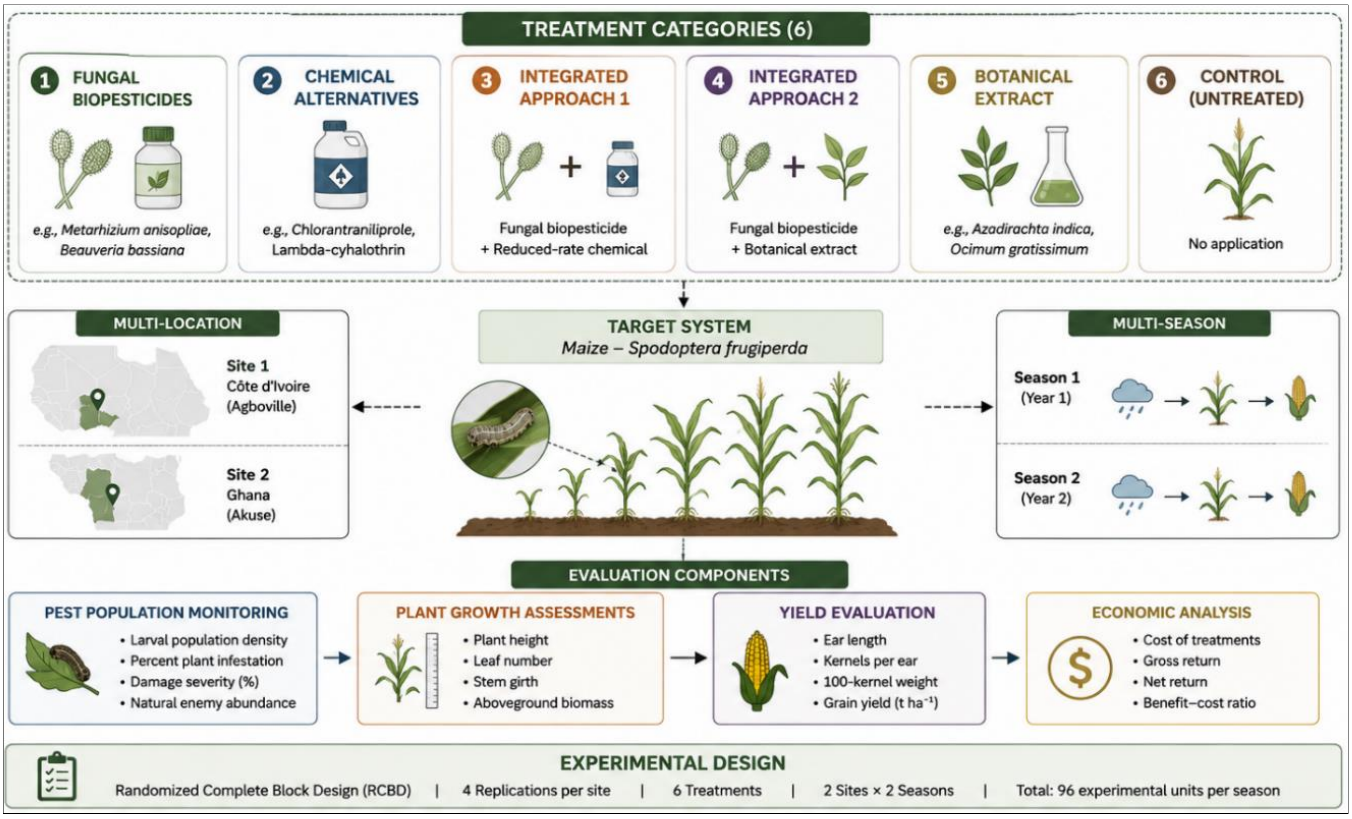

Fig 1: Conceptual Overview of Field Evaluation Framework

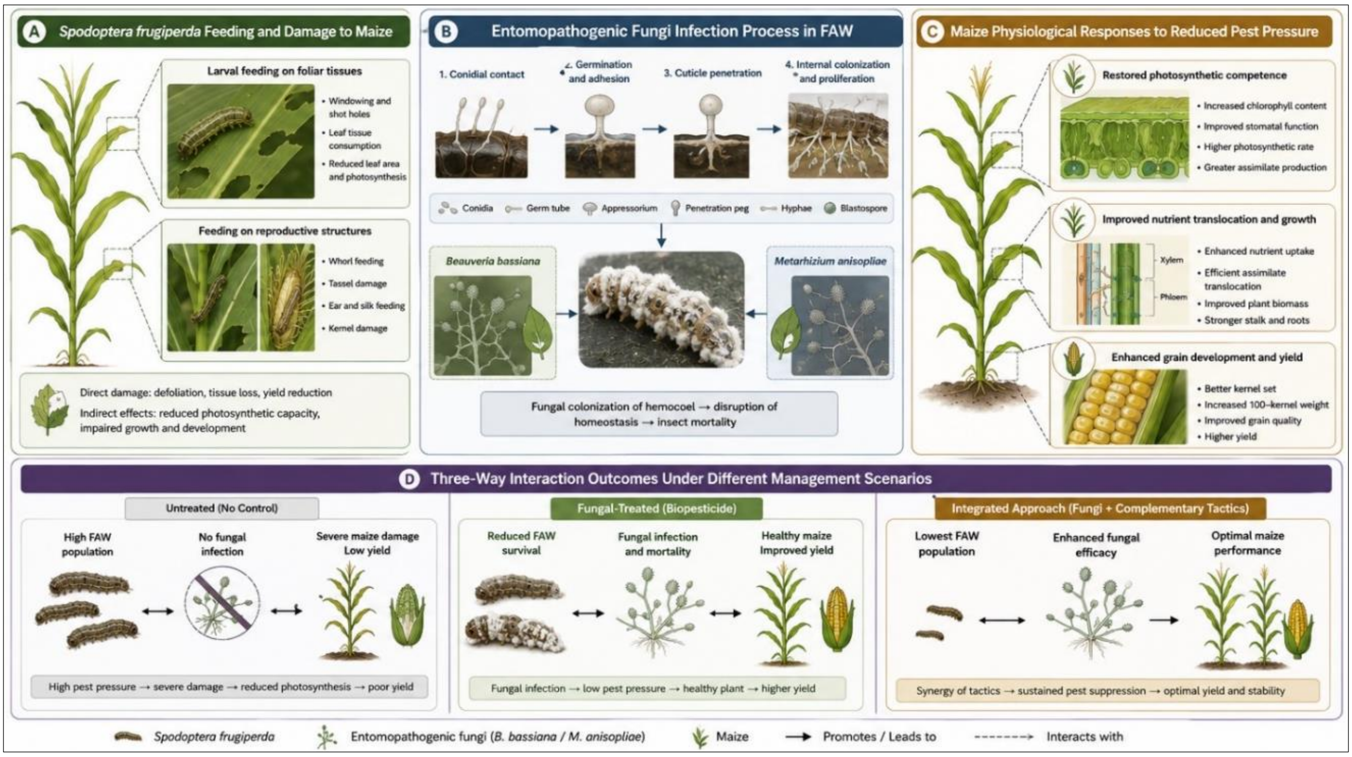

Fig 2: Interaction Between Entomopathogenic Fungi, *Spodoptera frugiperda*, and Maize

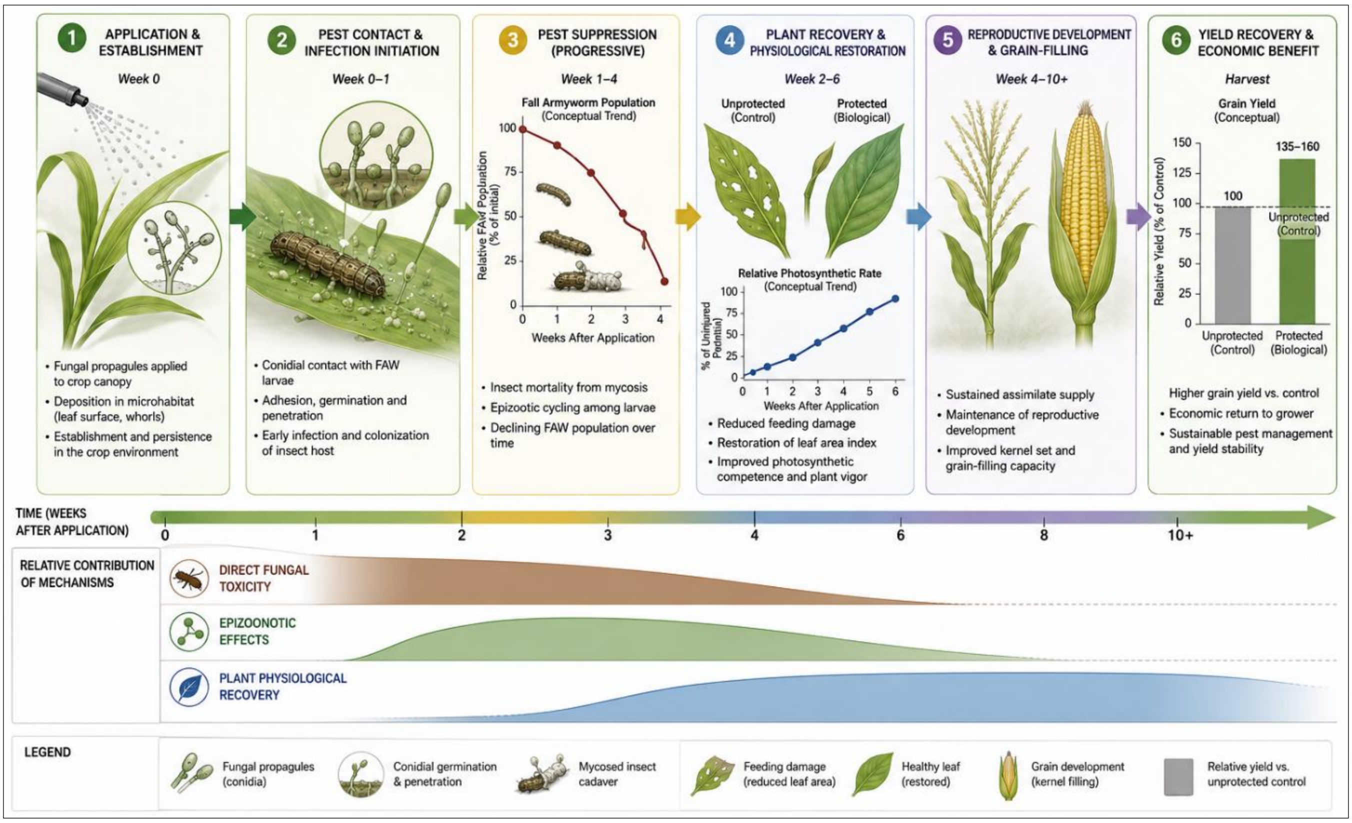

Fig 3: Conceptual Pathway of Biological Suppression and Crop Protection

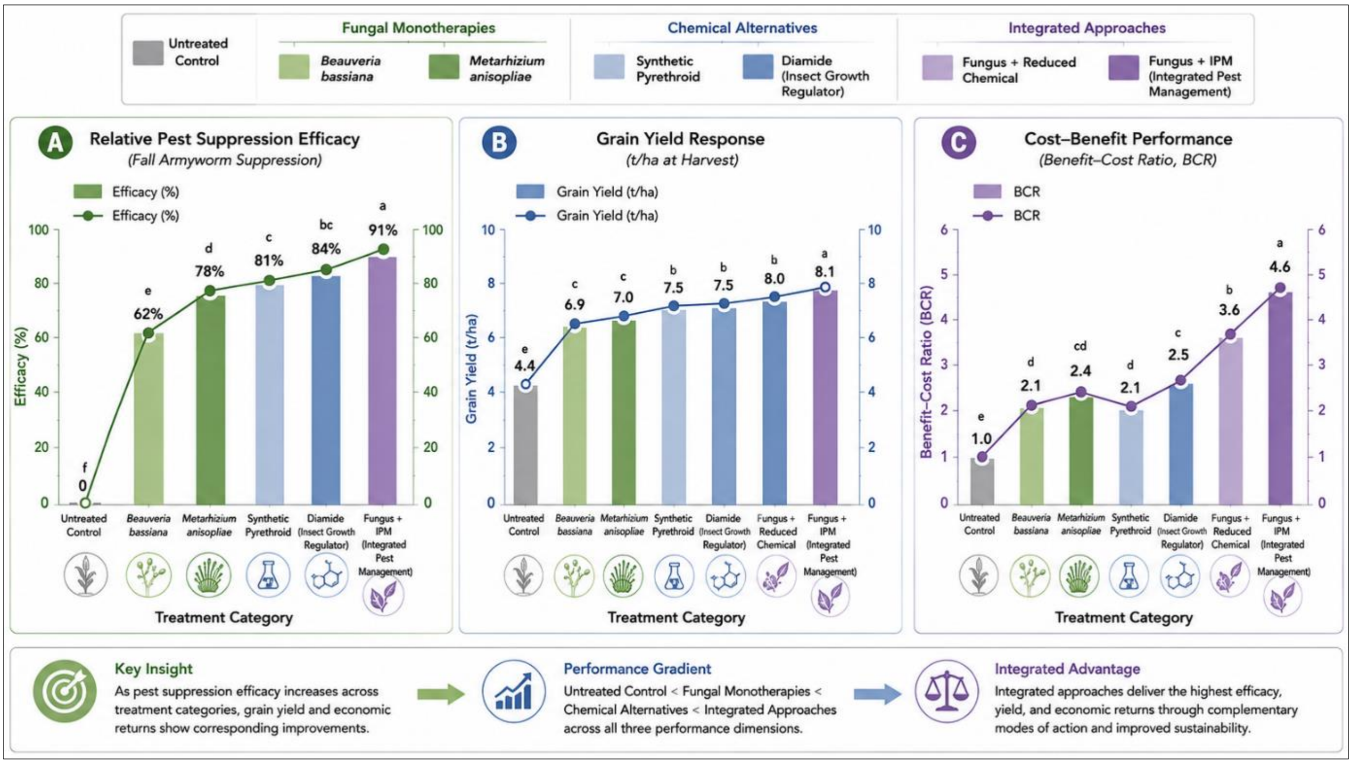

Fig 4: Comparative Conceptual Illustration of Treatment Performance and Crop Response

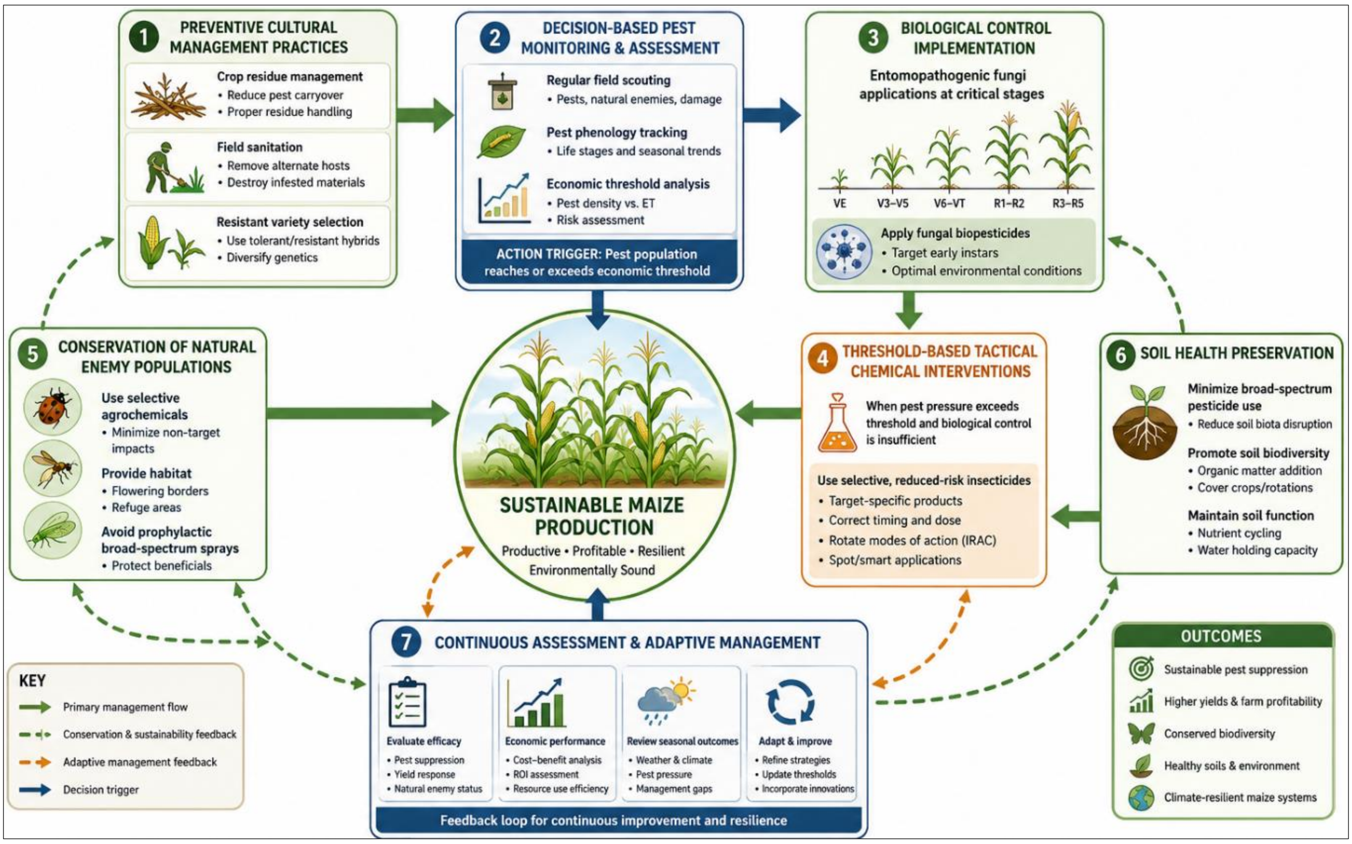

Fig 5: Integrated Pest Management Framework for Sustainable Maize Production

5. Conclusion

It was seen that the evaluation in the field confirms the ability of *Beauveria bassiana* and *Metarhizium anisopliae* to be used as biological control agents in the management of *Spodoptera frugiperda* (FAW) in maize production systems in West Africa. It was found that both fungal strains reduced the populations of the FAW by 62%-78% relative to the control and increased grain yields by 48%-57%, while the profits were comparable to those of using only chemical measures. The combination of the biological agents with specific chemical insecticides used in the framework of the Integrated Pest Management makes it possible to increase the effectiveness of suppression of the FAW to 85%-91% and achieve t maximum yields of grain (7.8-8.1 t/ha), having managed to sustain the ratio of revenues received to the costs on the cultivated land (USD 2.4-2.8 per invested USD). The benefits of this method of using fungal biopesticides are that its use is consistent with the principles of sustainable intensification because of the reduction of pesticide use, the increase in the number of beneficial arthropods, and the commitment to the principles of healthy soil.

The proof of effectiveness and profitability of fungitoxic measures provides solid backing for incorporating them into the national and regional FAW management systems due to their impact on small-holder farming systems. It is essential to back scaling of Fungicidal technology by investments in training of farmers, creation of demonstration farms, and introduction of processes to standardize fungitoxic products.

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