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Weed Community Structure Enhances the Persistence of Entomopathogenic Fungi in Peri-Urban Rice Bund Soils

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Abstract: The persistence of entomopathogenic fungi (EPF) in agricultural soils is influenced by aboveground vegetation, yet the role of weed community structure remains underexplored. This study evaluated how weed cover, diversity, and abundance affect EPF persistence in bund soils of a peri-urban rice agroecosystem in Mulyoagung, Indonesia. Twenty-five bunds (five replicates per bund type) were sampled using quadrat-based vegetation surveys (125 quadrats total), and composite soil samples were collected for EPF isolation. EPF persistence was assessed using two indicators: (1) colony-forming unit (CFU) counts on selective medium, representing the abundance of fungal propagules regardless of taxonomic identity, and (2) Tenebrio molitor larval bioassays to measure infection potential. Vegetation variables were analyzed using Spearman correlation and Generalized Linear Models (GLMs). Weed cover was significantly associated with higher CFU counts (P = 0.008), and weed diversity was positively correlated with infection rates (P = 0.038); weed abundance showed no significant effect. These findings indicate that complex and diverse weed communities improve microhabitat conditions favorable to EPF survival and pathogenicity. Promoting weed canopy structure and species diversity on bunds may enhance EPF persistence and contribute to sustainable biological control in peri-urban rice farming systems.

Keywords: Entomopathogenic fungi; Rice bunds; Weed diversity.

Introduction

The urgent need for sustainable pest control strategies has intensified amid increasing concerns over pesticide resistance, soil degradation, and biodiversity loss in modern agroecosystems. Conventional chemical based approaches, while initially effective, have been shown to disrupt non target organisms, accelerate resistance development, and degrade key ecological functions in soil (Khalid et al., 2024; Sharma et al., 2021). In response, entomopathogenic fungi (EPF), particularly *Beauveria bassiana* and *Metarhizium anisopliae*, have gained traction as eco-compatible biological control agents due to their host specificity and ability to naturally infect insect pests via cuticular contact and internal colonization (Iwanicki et al., 2024; Tuão Gava et al., 2021).

Despite their biocontrol potential, the success of EPF in field applications is fundamentally constrained by their limited persistence in soil environments. EPF propagules, especially conidia, are vulnerable to environmental stressors such as UV radiation, desiccation, antagonistic microbes, and unstable soil physical conditions, which collectively impair their viability and infectivity in the absence of insect hosts (Ding et al., 2023; Du et al., 2022; Head et al., 2022). Therefore, persistence must be understood not merely as a biological trait, but as a critical ecological determinant of long-term efficacy in pest suppression programs. Although numerous studies have examined the effects of abiotic factors such as pH, moisture, and organic matter content on fungal persistence, the influence of vegetation, particularly weed communities, has been relatively overlooked (García-Cela et al., 2016; Wang et al., 2023).

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Weed vegetation constitutes a major ecological component of low input and transitional agricultural systems, where it modulates microclimatic conditions, contributes to soil organic inputs, and mediates rhizospheric interactions. These attributes influence microbial community dynamics and habitat stability (Li et al., 2022; Miranda-Fuentes et al., 2020; Swathy et al., 2024). Emerging evidence further suggests that EPF are capable of forming facultative endophytic associations with plant tissues, including roots of weedy species, thereby gaining access to carbon-rich microsites that may promote conidial viability and extend infective lifespan (Head et al., 2022; Islam et al., 2023; Sharma et al., 2021). Consequently, the structure of weed communities including canopy coverage, species richness, and abundance could have a profound influence on EPF persistence, yet these potential links remain empirically underexplored.

In peri-urban rice agroecosystems, such ecological dynamics are especially pertinent. These landscapes are shaped by anthropogenic disturbance, land-use fragmentation, and marginal microhabitats such as bunds raised earthen ridges that separate paddy plots. These bunds, typically unmanaged and vegetated by spontaneous weeds, receive minimal tillage and external inputs, rendering them ecologically stable refuges for soil biota including EPF (Gideon et al., 2017; Sari & Yuliani, 2022; Wang et al., 2025). Moreover, dominant weed species on bunds, such as *Digitaria ischaemum* and *Eleusine indica*, possess functional traits (e.g., dense canopies, shallow roots) that may regulate microhabitat moisture and soil temperature, both crucial for EPF survival.

Despite such theoretical linkages, very few studies have integrated quantitative weed parameters such as cover percentage, species diversity, and abundance with direct indicators of EPF persistence like CFU (colony forming units) or host infection rates (Hallouti et al., 2020; Iwanicki et al., 2024; Tkaczuk et al., 2013). As a result, the role of bund weed communities in regulating fungal persistence remains an overlooked frontier in agroecological pest management.

This study aims to investigate how weed community structure defined by cover, diversity, and abundance influences the persistence of EPF in bund soils across a peri-urban rice landscape in Mulyoagung, Indonesia. By integrating field-based vegetation assessments with standardized fungal isolation and larval bioassays, this research seeks to address a critical ecological gap in our understanding of vegetation microbe interactions. The findings are expected to inform habitat based biological control strategies by emphasizing the ecological importance of bund vegetation management in supporting native EPF populations within transitional agroecosystems.

Method

Location and Research Design

This research was conducted from February to May 2025 in the peri-urban agricultural area of Mulyoagung Village, Dau District, Malang Regency, East Java Province, Indonesia (7.922207° S, 112.582775° E), at an elevation of approximately 600 meters above sea level. The average daily temperature and humidity conditions in Mulyoagung Village are around 24.7°C and 82% during January 2025 (BMKG, 2025).

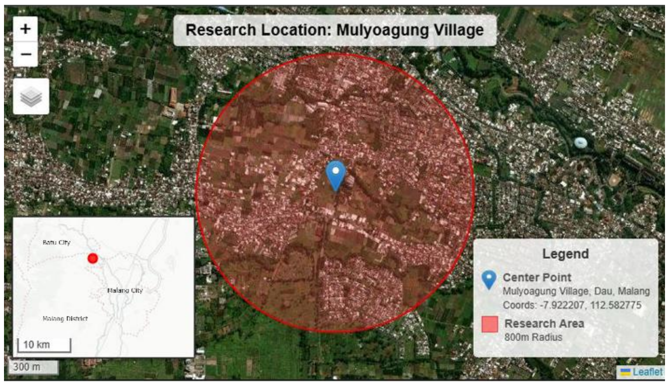

Figure 1. Map of the research location, peri-urban agricultural area of Mulyoagung Village (Gemini, 2024).

The research employed a descriptive observational approach, utilizing purposive sampling based on specific considerations aligned with the study's objectives (Ames et al., 2019). A total of 25 rice field bunds were randomly selected from various locations within the study area, which is situated in a peri-urban agricultural zone characterized by a mosaic of land uses, including agricultural fields, residential settlements, and commercial areas.

Each bund was subdivided into five segments, each with a minimum dimension of 1 × 0.5 meters, serving as replicates for vegetation observation and soil sampling at representative points. Measurements were conducted using 0.5 × 0.5 meter quadrats, systematically placed at five points along each bund, resulting in a total of 125 quadrats. All bund points were located within an 800-meter radius (Figure 1).

Characterization and Identification of Weed Vegetation

Vegetation on the rice field bunds was initially identified using the PlantNet mobile application (PlantNet, 2025) and subsequently verified using the Handbook on Weed Identification (Naidu, 2012), along with other relevant taxonomic references. Weed cover (WC) was assessed following the guidelines provided by Auld (2009), in Guidelines for Monitoring Weed Control and Recovery of Native Vegetation (Table 1 and Figure 2). Weed diversity (WD) was determined by counting the number of weed species, while weed abundance (WA) was quantified based on the total number of individual weed plants recorded.

Table 1. A set of possible classes for vegetation

Vegetation Class	Value Range %
1	0
2	0 – 5
3	6 – 25
4	26 – 50
5	51 – 100

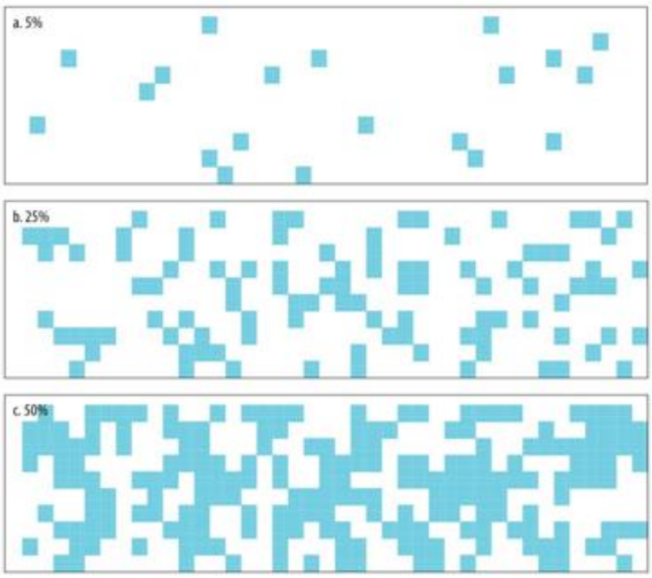

Figure 2. Illustration of Estimated Weed Vegetation Cover Percentage

Subsequently, the Summed Dominance Ratio (SDR) was calculated to determine the dominance of weed species on each bund, based on the formula proposed by Tjitrosoedirdjo et al (1984):

$$Absolute\ Density\ (AD) = \frac{(Number\ of\ individuals\ of\ species\ i)}{(Total\ number\ of\ sample\ plots)} \quad (1)$$

$$Relative\ Density\ (RD) = \frac{(Absolute\ density\ of\ species\ i)}{(Total\ absolute\ density\ of\ all\ species)} \times 100\% \quad (2)$$

$$Absolute\ Frequency\ (AF) = \frac{(Number\ of\ plots\ in\ which\ species\ i\ occurs)}{(Total\ number\ of\ sample\ plots)} \quad (3)$$

$$Relative\ Frequency\ (RF) = \frac{(Absolute\ frequency\ of\ species\ i)}{(Total\ absolute\ frequency\ of\ all\ species)} \times 100 \quad (4)$$

$$Importance\ Value\ (IV) = Relative\ Density\ (i) + Relative\ Frequency\ (i) \quad (5)$$

$$Summed\ Dominance\ Ratio\ (SDR) = \frac{Importance\ Value}{2} \quad (6)$$

Soil Sampling and Isolation of Entomopathogenic Fungi

Soil samples were collected from a depth of 0–15 cm using a soil scoop at three points within each replicate bund. These three subsamples were composited to form a single representative sample per bund replicate. Samples were placed in sterile plastic bags and kept in a cooled container at approximately 4 °C during transport to the laboratory (Iwanicki et al., 2024). All procedures were conducted under aseptic conditions to prevent contamination.

To assess the abundance of EPF, the pour plate method was used in combination with a serial dilution technique. 1 gram of composite soil (a mixture of three sampling points per replicate) was suspended in 9 mL of sterile distilled water containing 0.05% Triton X-100 as a surfactant (Tkaczuk et al., 2013). The suspension was shaken for 1 minute until homogenized. A 0.1 mL aliquot from the 10^{-3} dilution was poured into 90 mm Petri dishes containing selective Sabouraud Dextrose Agar Yeast (SDAY) medium and incubated at 25 °C for 4–7 days.

The SDAY medium was prepared following (Strasser et al (1996), with modifications: 18 g agar, 20 g dextrose, 10 g peptone, and 2.5 g yeast extract were dissolved in 1 L of sterile distilled water. To suppress bacterial growth, 0.5 g/L chloramphenicol was added, along with 0.6 g/L cetyl trimethyl ammonium bromide (CTAB) to inhibit the growth of non-target fungi (Posadas et al., 2012). Fungal colonies were counted and expressed as colony forming units (CFU) per gram of dry soil for EPF, representing the abundance of fungal propagules capable of growing on selective medium, irrespective of their taxonomic identity (Iwanicki et al., 2024).

$$CFU/gr = \frac{Number\ of\ colonies\ counted}{Dilution\ factor \times Inoculum\ volume\ (mL)} \quad (7)$$

Larval Infection Assay (Baiting Bioassay)

To evaluate the infectivity of EPF in soil, a baiting method was employed using freshly molted early-instar larvae of *Tenebrio molitor*. Twenty healthy larvae were placed into a thinwall container filled with 200 g of soil from each bund sample. Soil moisture was maintained by spraying with sterile distilled water. The containers were incubated at room temperature (25 ± 1 °C) for 14 days. Starting on day 3, the soil was gently stirred daily to increase contact between the larvae and fungal propagules.

Larval mortality was monitored daily. Dead individuals were surface-sterilized by immersion in 1% sodium hypochlorite (NaOCl) for 30 seconds, followed by three rinses in sterile distilled water. The sterilized cadavers were then incubated in thinwall containers lined with moist tissue paper to induce fungal sporulation. Larvae exhibiting characteristic sporulation of EPF were recorded as positively infected. The infection rate (%) was calculated based on the number of infected larvae out of the total 20 individuals, using the formula (Hallouti et al., 2020):

$$I = \frac{N}{20} \times 100\% \quad (8)$$

Note: I = Infection percentage, and N = Number of larvae infected by EPF

Data Analysis

All data were tested for normality using the Shapiro–Wilk test. Since the data were not normally distributed ($p < 0.05$), a non-parametric statistical approach was applied. The relationship between vegetation parameters and indicators of EPF persistence was analyzed using Spearman's rank correlation. To evaluate the simultaneous effect of weed vegetation on the persistence of EPF, a Generalized Linear Model (GLMs) was applied using the quasipoisson family. All statistical analyses were conducted using R Studio (Team RStudio, 2024).

Result and Discussion

Weed Composition, Structural Variability, and Dominance Patterns

Weed community structure across bund soils showed notable variability in cover, diversity, and abundance, with boxplot analysis (Figure 3) indicating that most bunds had moderate weed cover (Class 3: 26–50%) and stable species richness, while weed abundance varied greatly with several extreme values. A total of 38 species and 6,759 individuals were recorded, with a skewed distribution dominated by *Digitaria ischaemum*, *Eleusine indica*, and *Bonnaya antipoda*, which accounted for over one-third of all individuals and exhibited the highest SDR values. These dominant species likely reflect strong ecological adaptation to bund conditions—low disturbance, partial shade, and intermittent moisture—through traits such as rapid growth, fibrous rooting, and ground-level canopy formation that may influence EPF-associated microhabitats.

The architectural traits of these dominant weeds such as low-growing dense canopies and shallow fibrous root systems create bund microenvironments that regulate temperature, reduce evaporation, and retain moisture. These traits are ecologically significant because they facilitate microbial survival, including EPF propagules, by enhancing litter accumulation and improving infiltration capacity (Pérez-Méndez et al., 2025; Yang et al., 2019). Dense vegetation may act as a physical shield for EPF, protecting conidia from UV radiation and desiccation, while consistent organic matter input supports microbial activity.

Nevertheless, the ecological influence of dominant species presents a functional trade off. While their presence can stabilize microclimatic conditions and promote fungal persistence, it may also suppress subordinate flora through asymmetric competition or allelopathic interactions. Some dominant weeds are known to release phytotoxic compounds or acidify the rhizosphere, which may disrupt microbial diversity or inhibit EPF viability (García-Cela et al., 2016). Hence, the role of weed structure in supporting EPF is nuanced—offering both microhabitat benefits and potential inhibitory effects depending on species composition and interaction intensity.

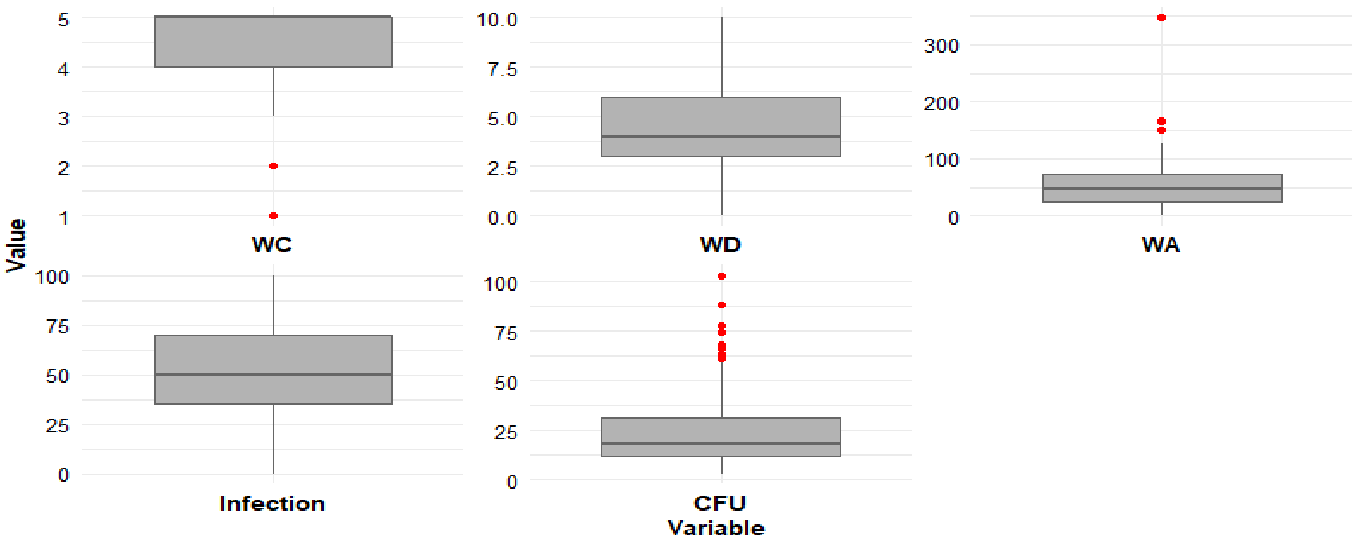

Figure 3. Boxplot showing variation in weed cover (WC), weed diversity (WD), weed abundance (WA), CFU abundance, and larval infection rate across bund samples.

Variation in EPF Persistence Across Bund Microhabitats

The analysis of fungal persistence revealed substantial heterogeneity across the bund samples. Colony-forming unit (CFU) counts ranged from 0.8 to 5.2×10^3 CFU g^{-1} soil, while larval infection rates spanned from 15% to 60%. This variation coincided with differences in vegetation metrics such as weed cover and diversity, suggesting strong vegetation–fungi interactions.

Bundles with denser vegetation tended to exhibit higher CFU values. These findings support the hypothesis that surface plant coverage provides a buffering effect on environmental fluctuations, including desiccation, thermal stress, and UV exposure—all known threats to EPF survival (Sutanto et al., 2022; Tuão Gava et al., 2021; L. Wang et al., 2023). This buffering effect is particularly relevant in exposed bunds where microhabitat conditions can vary dramatically over short spatial scales.

In terms of larval infection, bunds with higher weed species richness tended to support higher infection rates. This may reflect increased host-pathogen contact probabilities and improved fungal sporulation due to resource heterogeneity. Such effects resonate with ecological theories suggesting that plant diversity enhances microbial niche availability, resource cycling, and conidial dispersal (Li et al., 2022; Miranda-Fuentes et al., 2020).

Table 2. Summed Dominance Ratio (SDR) of Weed Species Identified on Bund Soils in a Peri-Urban Rice Agroecosystem.

Weed Species	Number of Individuals	Number of Sample Plots	SDR (%)
Acmella peniculata	52	11	1.37
Acmella uliginosa	104	6	1.30
Ageratum conyzoides	333	48	6.74
Alternathera philoxeroides	245	22	3.77
Bonnaya antipoda	843	30	8.91
Cantella asiatica	39	7	0.91
Cleome rutidosperma	62	11	1.44
Clitoria ternatea	4	2	0.21
Comellina diffusa	52	13	1.54
Cyanthilium cinereum	79	16	2.01
Cynodon dactylon	712	29	7.85
Cyperus brevifolia	493	34	6.68
Cyperus rotundus	190	15	2.74
Digitaria ischaenun	1725	47	16.95
Eleusine indica	445	81	10.51
Emilia sonchifolia	86	14	1.88
Euphorbia hirta	57	17	1.94
Fallopia convolvulus	20	8	0.86
Fimbristylis milacea	17	2	0.30
Imperata cylindrica	65	6	1.02
Ipomoea cairica	7	3	0.32
Mecardonia procumbens	204	13	2.67
Mimosa pudica	5	1	0.13
Oplismenus undulatifolius	28	3	0.48
Oxalis barrelieri	101	2	0.93
Paspalum distichum	48	7	0.98
Pauzolzia zeylanica	14	2	0.28
Pennisetum purpureum	37	7	0.90
Peperomia pellucida	16	1	0.21
Phylantus urinaria	100	21	2.61
Phyllantus amarus	10	3	0.34
Polypogon viridis	67	18	2.10
Portulaca oleracea	177	18	2.91
Rorippa dubia	79	19	2.28
Rubia tinctorum	10	5	0.52
Scoparia dulcis	6	1	0.13
Spermacoce remota	42	7	0.94
Stemodia verticallata	150	8	1.82
Torenia crustacea	35	3	0.53
Total	6759	-	100

Statistical Relationships Between Vegetation and EPF Performance

Spearman correlation tests showed that weed cover was significantly associated with CFU abundance (ρ = 0.58, p = 0.003), while weed diversity correlated with infection rate (ρ = 0.51, p = 0.004). Weed abundance showed weaker, non-significant relationships with both metrics. These findings highlight the differentiated roles of vegetation structure (cover) and composition (diversity) in modulating fungal persistence.

Generalized Linear Model (GLM) analysis confirmed these relationships. Weed cover significantly increased CFU counts (Estimate = 0.202, p = 0.008), suggesting that denser vegetation improves fungal propagule survival. Weed diversity had a significant positive effect on infection rate (Estimate = 0.043, p = 0.038), implying that more diverse communities enhance ecological functionality and biocontrol efficiency.

In contrast, weed abundance contributed marginally to the models, with no significant effect on infection and a slightly negative trend on CFU (p = 0.097). This indicates that the sheer number of weed individuals is less important than their spatial configuration and species-specific functional traits. This supports the principle that microbial habitat quality depends on vegetation heterogeneity rather than biomass alone (Head et al., 2022; Sharma et al., 2021).

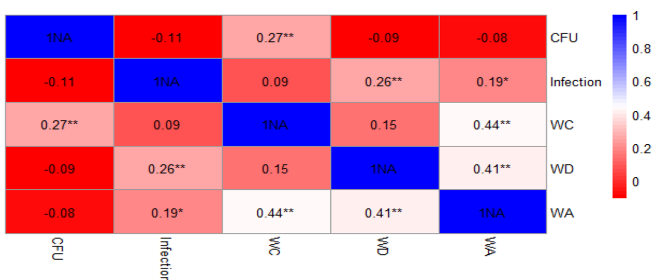

Figure 4. Spearman Correlation Heatmap between Weed Community Metrics and EPF Persistence Indicators on Bund Soils, Note: p values < 0.01, ** and < 0.05, *.

Table 3. Spearman Correlation P-Values between Weed Parameters and EPF Persistence (CFU and Infection Rate).

Variable	EPF Abundance	Infection
Weed cover	0.003	0.324
Weed diversity	0.327	0.004
weed abundance	0.394	0.036

Microclimatic and Edaphic Modulation by Weed Canopy

The positive correlation between dense canopy cover and CFU abundance suggests that vegetation structure modulates microclimatic stability at the soil surface. Weed cover reduces sunlight penetration, lowers surface temperatures, and retains soil moisture conditions favorable for fungal conidia (Lubis et al., 2022; Swathy et al., 2024). Bunds with high coverage create thermally stable zones that protect propagules from rapid desiccation and microbial antagonism.

Furthermore, the presence of fibrous roots in dominant weeds enhances soil structure, porosity, and infiltration. Such effects reduce erosion and increase the duration of moisture retention after rainfall or irrigation. Fungal propagules, especially those of *Beauveria* and *Metarhizium*, are sensitive to short-term drought stress, and even small increases in moisture availability can extend their infective window (Ding et al., 2023; Du et al., 2022).

These microhabitat improvements contribute to fungal colonization success by increasing soil contact, reducing abiotic mortality, and fostering conditions for sporulation and hyphal growth. Thus, weed canopy acts not merely as physical cover but as a functional ecological filter that selects for microbial groups with specific survival traits in disturbed, peri-urban field margins.

The Role of Weed Diversity in Enhancing Biocontrol Potential

Weed diversity was found to significantly enhance larval infection rates, indicating a potential role in facilitating host-fungus interactions. Diverse weed assemblages promote belowground heterogeneity, resulting in complex rhizospheres that support greater microbial colonization and survival. These conditions enhance the probability of fungal contact with insect hosts, especially for EPF species that rely on passive dispersal.

Table 4. Summary of GLM Estimates for the Effects of Weed Cover, Diversity, and Abundance on EPF Colony Abundance (CFU) and Larval Infection Rates

Variable	EPF Abundance			Larval Infection Rates		
	Estimate	*SE*	*P*	*Estimate*	*SE*	*P*
Intercept	2.577	0.337	0.000***	36.331	0.187	0.000***
Weed cover	0.202	0.074	0.008**	0.014	0.041	0.740
Weed diversity	-0.021	0.035	0.559	0.043	0.020	0.038*
weed abundance	-0.003	0.002	0.097	0.001	0.001	0.430

Note: *P<0.05, SE: Std. Error.

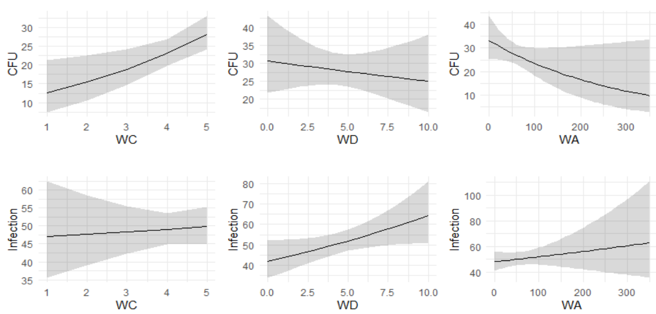

Figure 5. GLM Effect Plots Showing the Relationship Between Weed Parameters and EPF Persistence Indicators (CFU and Infection Rate)

Several weed species are known to form endophytic or associative symbioses with EPF, thus serving as alternative reservoirs for propagule maintenance during host scarcity (Head et al., 2022; Sharma et al., 2021; Vukicevich et al., 2019). By maintaining a high diversity of such plants, bund systems can function as in situ inoculum banks for season-long biological control.

In addition, the presence of multiple plant species creates a multilayered canopy and variable litter input, both of which support a rhizospheric mosaic that stabilizes fungal populations and increases microbial functional redundancy. This finding supports the hypothesis that structural and taxonomic diversity at the plant level translates into higher resilience and persistence of microbial biocontrol agents.

Species Specific Effects and Allelopathic Risks

Although several dominant weed species supported favorable microhabitat conditions for EPF, others may exert inhibitory effects through chemical interactions in the rhizosphere. Species such as *Cyperus rotundus* and *Ageratum conyzoides* are known to release allelochemicals including sesquiterpenes, phenolic acids, and alkaloids that can suppress microbial growth and alter soil pH (Li et al., 2022). These interactions may shift the soil microbial community composition, promoting antagonistic organisms and reducing the persistence or infectivity of EPF. This highlights a complex ecological balance in which the benefits of structural vegetation must be weighed against the biochemical interference exerted by certain plant species.

Notably, grass species such as *Digitaria ischaemum* and *Eleusine indica*, despite their structural contribution to bund cover and infiltration, are also reported to produce allelopathic compounds such as flavonoids, ferulic acid, and cinnamic acid. These substances, although potentially stimulatory at low concentrations by enhancing fungal enzymatic activity, are more often detrimental known to inhibit spore germination and mycelial growth of EPF (Bottrell & Weil, 1995; Zambelli et al., 2025). Supporting this, Vaicekonyte, (2011) found that secondary metabolites from *Alliaria petiolata* significantly reduced the abundance of soil dwelling EPF, while Lopez-Llorca & Olivares-Bernabeu, (1997) demonstrated that phenolics derived from leaf litter can hinder the development of both entomopathogenic and nematophagous fungi. These findings suggest that even commonly beneficial groundcover species may carry hidden biochemical risks for fungal biological control agents.

Given this dualistic role, future habitat-based pest management strategies must prioritize species-specific weed assessments rather than generalized suppression. While structurally dominant species may provide thermal and moisture buffering that favors EPF persistence, their allelopathic profiles may counteract these advantages. Thus, integrating ecological function and chemical ecology into weed management could enable selective conservation of compatible species that promote fungal viability without promoting antagonism or resource competition. Designing bund vegetation with both structural complexity and chemical compatibility in mind represents a promising avenue for optimizing native EPF persistence in peri-urban rice agroecosystems.

Limitation and Research Implications

While the present study provides compelling evidence that weed community structure influences the persistence of EPF, several limitations must be acknowledged. First, the observational and correlative nature of the design prevents direct inference of causality between weed traits and fungal dynamics. Although significant associations were observed, manipulative experiments such as selective weed removal or bund replanting are required to disentangle mechanistic pathways.

Second, all measurements were conducted during a single cropping season under relatively uniform climatic conditions in the peri-urban zone of Mulyoagung. Seasonal variations in rainfall, temperature, and bund vegetation dynamics may significantly influence EPF performance. Longitudinal studies that capture temporal changes and climatic interactions are needed to validate the consistency and generalizability of these findings.

Third, fungal identification in this study was limited to colony forming units and infection bioassays, without species level molecular confirmation. While the study targeted general persistence indicators, future research integrating molecular tools (e.g., qPCR, metagenomics) could offer deeper insights into species-specific interactions and detect cryptic EPF strains that are undetected via culture-based methods. Such advances would strengthen the ecological relevance and precision of biocontrol assessments in bund habitats.

Agroecological Perspectives and Management Recommendations

The findings of this study contribute to a growing body of knowledge highlighting the agroecological role of marginal field elements such as bunds as reservoirs for beneficial soil microbiota. In transitional peri-urban farming systems where biodiversity is fragmented and pest pressure is high, bunds serve as ecological buffers that can be harnessed to sustain native populations of EPF (Pérez-Méndez et al., 2025; Wang et al., 2025).

From a management perspective, maintaining structurally complex and diverse weed vegetation on bunds should be seen not as a constraint but as a strategic opportunity. Ecologically informed bund management, such as minimal disturbance, selective weeding, and conservation of functional species, could enhance the persistence and activity of EPF. This approach aligns with habitat management principles that favor conservation biological control over chemically intensive interventions (Baverstock et al., 2008; Head et al., 2022).

Furthermore, the bunds' role as microhabitats offers scalable potential. Because bunds occur pervasively in rice based systems, especially across Southeast Asia, adopting bund based EPF conservation could yield broad agroecological benefits without requiring structural changes to farming practices. Integrating bund vegetation management into broader land-use planning especially in peri-urban mosaics may represent a key innovation in sustainable pest control under climate and urbanization stressors.

Conclusion

This study reveals that weed community structure significantly influences the persistence of EPF in bund soils of peri-urban rice systems. Specifically, higher weed cover enhances fungal abundance, while greater species diversity increases larval infection rates underscoring the role of vegetation complexity in supporting microbial viability. These findings emphasize the ecological value of bund habitats as reservoirs for native EPF, offering a practical, habitat-based strategy to strengthen biological control in sustainable agroecosystems.

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Author Contributions
Conceptualization, F.A.F. and A.A.; methodology, F.A.F.; software, F.A.F.; validation, F.A.F., A.A. and A.M.; formal analysis, F.A.F.; investigation, F.A.F.; resources, A.A.; data curation, F.A.F.; writing original draft preparation, F.A.F.; writing review and editing, A.A. and A.M.; visualization, F.A.F.; supervision, A.A. and A.M.; project administration, F.A.F. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest
The authors declare no conflict of interest.

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