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Microbial consortia as biological phytomedicines: Activating plant secondary metabolism for insect resistance and sustainable rice (*Oryza sativa* L.) production

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Abstract

Plant microbe interactions can be harnessed as biological phytomedicines, wherein beneficial microbes activate endogenous plant secondary metabolism to confer pest resistance improve the nutritional quality and reduce insecticidal dependence. In this study, a core microbial consortium comprising nitrogen fixing (NFB), phosphorus solubilizing (PSB) and zinc solubilizing bacteria (ZSB) was combined with either silica solubilizing bacteria (SSB), potassium solubilizing bacteria (KSB) or arbuscular mycorrhizal fungi (AMF) to evaluate microbe induced phytomedicinal resistance against *Scirpophaga incertulas* and *Cnaphalocrocis medinalis* in rice during Rabi 2023 and 2024. Among the tested formulations, the SSB based consortium exhibited the strongest phytoprotective efficacy suppressing stem borer and leaf folder damage by 56.7% and 61.9%, respectively, followed by KSB (51.5% and 57.4%) and AMF based consortia (37.4% and 43.2%) over the untreated check. These effects were mediated through distinct but complementary phytomedicinal mechanisms: SSB primarily enhanced structural defenses *via* increased silica deposition (6.33% + 15.1%) and cell wall thickening (0.1860 µm + 113.8%), whereas KSB predominantly stimulated biochemical defenses by elevating phenolic accumulation (1.182 mg g-1 + 183.4%) metabolites known for antifeedant activity and herbivore induced oxidative stress. Concurrent improvements in nutrient acquisition, rhizosphere microbial activity and soil fertility supported sustained defense expression. As a result, grain yield and economic returns were maximized under SSB (5946 kg ha-1) and KSB (5915 kg ha-1) treatments. Overall, the findings demonstrate that microbial consortia act as plant delivered phytomedicines and plant probiotics integrating nutrient mobilization with secondary metabolite enrichment to suppress insect herbivory enhance crop nutritional quality and reduce dependence on synthetic pesticides, thereby promoting agro ecosystem resilience and human food safety in low-input rice production systems.

1. Introduction

Insect herbivory remains a major constraint to global rice productivity particularly in Asian agro ecosystems where lepidopteron pests such as the yellow stem borer (*Scirpophaga incertulas*) and rice leaf folder (*Cnaphalocrocis medinalis*) cause persistent yield losses. Conventional pest management relies heavily on synthetic insecticides which, despite short term efficacy have resulted in pest resistance, disruption of beneficial arthropods, contamination of food grains and adverse environmental and human health impacts. These limitations necessitate the development of ecologically sustainable strategies that reinforce plant intrinsic resistance while reducing chemical dependency.

Plants possess complex defense systems comprising constitutive and inducible mechanisms that deter herbivores through both structural and biochemical means. Structural defenses such as lignification and silica deposition reduce tissue palatability and feeding efficiency, whereas biochemical defenses involve the accumulation of secondary metabolites including phenolics, flavonoids, terpenoids and alkaloids that function as antifeedants, toxins or oxidative stress inducers in insect herbivores. These defenses are largely regulated by nutrient availability and phytohormonal signaling particularly jasmonic acid mediated pathways that play a central role in resistance against chewing insects (Howe and Jander, 2008). However, intensive cultivation practices and declining soil fertility often limit the plant's capacity to effectively deploy these defense mechanisms.

In recent years, plant associated beneficial microorganisms have emerged as critical modulators of plant nutrition, metabolism and

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immunity. Rhizosphere and symbiotic microbes not only enhance nutrient acquisition but also induce systemic resistance, a phenomenon widely recognized as microbe induced plant immunity. Importantly such microbes do not act as direct pesticides; instead they function as biological phytomedicines by activating endogenous plant defense pathways and secondary metabolism through microbial elicitors, signaling molecules and metabolic priming (Pieterse *et al*., 2014). This plant mediated mode of protection is environmentally benign, durable and compatible with food safety objectives.

Microbial consortia integrating complementary functional traits such as nitrogen fixation, phosphorus and micronutrient solubilization, potassium mobilization, silicon availability and mycorrhizal symbiosis are particularly effective in synchronizing plant nutrition with defense metabolism. Nitrogen supports the biosynthesis of nitrogen rich defensive compounds and proteinase inhibitors; phosphorus fuels ATP dependent phenylpropanoid pathways; zinc serves as a cofactor for defense related enzymes; potassium regulates carbohydrate partitioning and phenolic synthesis and silicon strengthens mechanical defenses while amplifying jasmonate mediated signaling against herbivores (Ma and Yamaji, 2006; Epstein, 2009). Arbuscular mycorrhizal fungi further enhance resistance by priming systemic defense responses and modifying plant volatile emissions that influence herbivore behavior (Pozo and Azcon-Aguilar, 2007).

Microbial consortia are defined here as *plant mediated phytomedicines* functionally coordinated assemblies of beneficial microorganisms that confer pest resistance primarily by activating endogenous plant defense machinery rather than through direct antagonism of herbivores. Following rhizosphere or endophytic establishment, these consortia reprogram host metabolic fluxes and signaling networks associated with nutrient mobilization and phytohormone homeostasis, thereby stimulating sustained production of defensive secondary metabolites (*e.g.,* phenolics, terpenoids, alkaloids) and reinforcing structural barriers such as lignification, silicification and cell wall thickening. This mode of action clearly distinguishes microbial consortia from conventional biopesticides, which depend on direct toxicity or pathogenicity toward pests and from classical induced systemic resistance, which is often triggered by single microbial strains and typically results in transient pathway priming without profound restructuring of plant metabolism or anatomy. In contrast, microbial consortia operate as integrated bioeffectors that convert plants into self regulating defense systems, offering durable and internally expressed protection.

Despite accumulating evidence for microbe mediated plant defense few studies have systematically evaluated multifunctional microbial consortia as phytomedicinal agents against major rice pests while simultaneously assessing their effects on soil health, crop productivity and economic viability. Understanding how distinct microbial assemblages differentially activate structural and biochemical defense components is essential for developing residue free, low-input pest management strategies aligned with sustainable agriculture and human food safety.

Against this background, the present study investigated the efficacy of a core microbial consortium comprising nitrogen fixing (NFB), phosphorus solubilizing (PSB) and zinc solubilizing bacteria (ZSB), supplemented with either silica solubilizing bacteria (SSB), potassium solubilizing bacteria (KSB) or arbuscular mycorrhizal fungi (AMF) in inducing plant mediated resistance against *S. incertulas* and *C. medinalis* in rice. By integrating pest suppression, plant defense traits, nutrient dynamics, soil microbial activity, yield performance and economic analysis. This work demonstrates that microbial consortia can function as plant delivered phytomedicines offering a sustainable pathway to enhance insect resistance, nutritional quality, agro ecosystem resilience and human food safety.

2. Materials and Methods

2.1 Study site and experimental conditions

Field experiments were conducted during the Rabi seasons of 2023 and 2024 at the Agricultural College and Research Institute, Madurai, Tamil Nadu, India (9.9712°N, 78.2070°E; 148 m above sea level). The experimental soil was clayey loam in texture. Climatic conditions during the cropping period were warm and predominantly dry with mean maximum temperatures ranging from 33.5 to 34.1°C and minimum temperatures from 19.2 to 28.8°C. These conditions are representative of rice growing environments where pest pressure is high and plant mediated defense activation is agronomically relevant.

2.2 Biological phytomedicine formulation: Microbial consortia

Microbial treatments were designed as biological phytomedicines intended to activate endogenous plant defense metabolism through nutrient mobilization and defense priming rather than direct pesticidal action. A core consortium comprising nitrogen fixing bacteria (NFB), *Azospirillum brasilense* (strain SP-7); phosphorus solubilizing bacteria (PSB), *Bacillus megaterium* var. *phosphaticum* (strain PSB-1) and zinc solubilizing bacteria (ZSB), *Pseudomonas chlororaphis* (strain ZSB-15) was used across all bioinoculated treatments.

To impart distinct phytomedicinal functions the core consortium was supplemented with one of the following functional microbial groups: silica solubilizing bacteria (SSB), *Bacillus altitudinus* (strain SSB-4); potassium solubilizing bacteria (KSB), *Bacillus aryabhattai* (strain KSB-1) or arbuscular mycorrhizal fungi (AMF), *Rhizophagus intraradices*. These microbial assemblages were formulated to synergistically enhance nutrient acquisition, prime defense signaling pathways and stimulate the accumulation of insect-deterrent secondary metabolites in rice.

2.3 Treatments and microbial application

Rice (*Oryza sativa* L. *var.* ADT 54) was subjected to five treatments, integrating microbial phytomedicine formulations with reduced or full inorganic fertilization:

T_1: Core consortium (NFB + PSB + ZSB) + SSB + 75% recommended NPK

T_2: Core consortium (NFB + PSB + ZSB) + KSB + 75% recommended NPK

T_3: Core consortium (NFB + PSB + ZSB) + AMF + 75% recommended NPK

T_4: Treated check - Core consortium (NFB + PSB + ZSB) + 75% recommended NPK

T_5: Untreated check - 100% recommended NPK

Seeds were treated with the respective microbial formulations at 1 kg ha^{-1}, followed by root dip application at transplanting at the same rate to facilitate early rhizosphere colonization and defense priming. Soil application was carried out at 20 and 35 days after transplanting

(DAT) at 2 kg ha^{-1} to sustain microbial activity and phytomedicinal effects. Bioinoculated treatments received 75% of the recommended NPK dose (75:37.5:37.5 kg ha^{-1}), whereas the untreated check received 100% NPK (100:50:50 kg ha^{-1}).

SSB, KSB and AMF were selected as complementary modules to the core consortium based on their distinct functional roles in plant defense activation. SSB enhance silicon bioavailability to promote structural defenses *via* silicification and cell wall reinforcement, whereas KSB primarily stimulate biochemical defenses by regulating potassium dependent enzymatic activity and phenylpropanoid metabolism. AMF contribute to systemic defense priming through improved nutrient acquisition and phytohormonal modulation, thereby integrating structural and metabolic resistance pathways.

2.4 Experimental design

The experiment was laid out in a randomized block design (RBD) with four replications. Individual plot size was 40 m² separated by buffer channels to prevent microbial cross contamination. Standard agronomic practices including irrigation and weed management were uniformly adopted across treatments to isolate phytomedicinal effects attributable to microbial consortia.

2.4.1 Assessment of insect herbivory

Incidence of yellow stem borer (*Scirpophaga incertulas*) and rice leaffolder (*Cnaphalocrocis medinalis*) was recorded at 30, 60 and 100 DAT. Plant mediated resistance was quantified through dead heart (DH), white ear (WE) and leaf damage (LD) percentages using standard protocols (Protocol 1 to 3):

Stem borer damage (% dead heart) (DH) on 30^{th} and 6^{th} DAT

$$= \frac{\text{Number of dead hearts hill}^{-1}}{\text{Total number of tillers hill}^{-1}} \times 100 \qquad \text{... (1)}$$

Stem borer damage (% white ear) (WE) on 100 DAT

$$= \frac{\text{Number of white ears hill}^{-1}}{\text{Total number of tillers hill}^{-1}} \times 100 \qquad \text{... (2)}$$

Leaf folder damage (% leaf damage) (LD) on 30^{th} and 60^{th} DAT

$$= \frac{\text{Number of leaves damaged by leaf folder hill}^{-1}}{\text{Total number of leaves hill}^{-1}} \times 100$$

These parameters reflect the functional outcome of microbe induced phytomedicinal defenses rather than direct pest toxicity.

2.4.2 Plant nutrient and phytochemical analyses

Leaf samples collected at 50 DAT were analyzed for total nitrogen (Kjeldahl method; Bremner, 1960), phosphorus (Vanadomolybdate yellow method; Jackson, 1973), potassium (Flame photometry; Jackson, 1973), and silicon (Alkaline extraction; Majumdar and Prakash, 2020). Total phenolic content, representing a key phytomedicinal trait associated with insect deterrence and antioxidant capacity was estimated in fresh leaf tissue using the Folin-Ciocalteu method (Baba and Malik, 2015) and expressed as mg catechol g^{-1} fresh weight.

2.4.3 Structural defense assessment

Leaf structural fortification was assessed by measuring cell wall thickness. Representative leaf sections collected at 50 DAT were examined under a scanning electron microscope (SEM; Hitachi 3030 Plus) at 1000 × magnification. Measurements were performed using Fiji image analysis software, exported as *.csv files and statistically analyzed using JASP software, enabling quantitative evaluation of microbe-induced mechanical defense traits.

2.4.4 Soil nutrient status and microbial population

Soil samples collected at 50 DAT (0 to 15 cm depth) were analyzed for available nitrogen (alkaline permanganate; Subbiah and Asija, 1956), phosphorus (Olsen's method; Olsen, 1954), potassium (neutral normal ammonium acetate; Stanford and English, 1949), organic carbon (Walkley and Black, 1934) and silicon (Majumdar and Prakash, 2020) along with pH and electrical conductivity. Culturable soil microbial populations bacteria, fungi and actinomycetes were enumerated using serial dilution and plate count methods to assess rhizosphere health and persistence of the phytomedicinal microbial consortia.

2.4.5 Growth, yield and economic analysis

Plant height, number of productive tillers, 1000 grain weight and grain yield (adjusted to 14% moisture) were recorded from five representative hills per plot. Economic performance was assessed by calculating gross returns, net returns and benefit cost ratio, thereby linking phytomedicine mediated pest suppression with farm level profitability.

2.5 Statistical analysis

All data were subjected to analysis of variance (ANOVA) appropriate for a randomized block design. Treatment means were separated using Duncan's Multiple Range Test (DMRT) at $p<0.05$. Statistical analyses were performed to determine the significance of biological phytomedicine effects on plant defense, pest suppression, productivity and soil health.

3. Results

3.1 Phytomedicine mediated pest suppression

Application of rhizosphere microbial consortia functioning as biological phytomedicines significantly suppressed lepidopteran herbivory in rice (Table 1). Among the treatments the silica solubilizing bacteria (SSB) enriched consortium conferred the strongest plant mediated resistance as reflected by the lowest incidence of stem borer injury at all observation stages. Dead heart incidence under the SSB based consortium was limited to 5.09% and 2.35% at 30 and 60 DAT, respectively, while white ear formation at 100 DAT was restricted to 1.04%. Relative to the untreated check, these values corresponded to reductions of 50.2%, 65.0% and 54.8%, respectively, indicating robust phytomedicinal protection. When compared with the treated check, reductions of 41.4%, 56.5% and 51.6% were recorded, confirming that microbial induction of plant defenses surpassed nutrient only management.

Table 1: Influence of microbial consortia on stem borer and leaf folder damage in Rice at different growth stages

Treatment	Stem borer damage (%)*			Leaf folder damage (%)*	
	Dead heart at 30 DAT	Dead heart at 60 DAT	White ear at 100 DAT	Leaf damage at 30 DAT	Leaf damage at 60 DAT
NFB + PSB + ZSB + SSB + 75% NPK	5.09 (13.02)[a]	2.35 (8.77)[a]	1.04 (5.72)[a]	5.10 (12.91)[a]	3.97 (11.45)[a]
NFB + PSB + ZSB + KSB + 75% NPK	4.88 (12.72)[a]	2.67 (9.38)[a]	1.31 (6.54)[b]	5.83 (13.78)[a]	4.40 (12.03)[a]
NFB + PSB + ZSB + VAM + 75% NPK	6.21 (14.39)[b]	4.28 (11.91)[b]	1.44 (6.86)[b]	7.31 (15.50)[b]	6.73 (14.98)[b]
Treated check: NFB + PSB + ZSB + 75% NPK	8.68 (17.13)[c]	5.41 (13.30)[c]	2.15 (8.43)[c]	9.33 (17.69)[c]	7.44 (15.80)[c]
Untreated check: 100% NPK	10.22 (18.62)[d]	6.71 (15.00)[d]	2.30 (8.70)[c]	11.34 (19.65)[d]	12.74 (20.89)[d]

Note: *Mean of two-year data (2023 and 2024); Mean of four replications; Values in parentheses are arcsine transformed values; In a column, mean followed by the same letter are not significantly different at p<0.05.

A similar trend was observed for rice leaf folder damage. The SSB based consortium restricted leaf damage to 5.10% at 30 DAT and 3.97% at 60 DAT, achieving reductions of 54.9% and 68.8% over the untreated check and 45.3% and 46.6% over the treated check, respectively. The potassium solubilizing bacteria (KSB) based consortium also exhibited strong phytomedicinal efficacy, producing pest suppression comparable to SSB treatments, whereas the AMF based consortium provided only moderate protection. Overall, consortia enriched with silica and potassium solubilizing microbes consistently achieved up to 65% suppression of stem borer damage and nearly 69% reduction in leaf folder injury, demonstrating the effectiveness of microbe activated plant defenses.

3.2 Activation of phytomedicinal nutritional, biochemical and structural traits

Microbial phytomedicine treatments significantly enhanced plant nutrient accumulation and defense associated traits (Table 2). The SSB based consortium induced the strongest integrative defense phenotype, recording the highest concentrations of nitrogen (3.59%), phosphorus (0.27%), potassium (0.27%) and silica (6.33%) all of which were significantly superior to the treated and untreated checks. This nutrient enrichment translated into pronounced structural fortification with the greatest cell wall thickness (0.1860 µm) reflecting enhanced mechanical resistance to chewing herbivores.

In contrast, the KSB based consortium preferentially stimulated biochemical phytomedicinal defenses recording the highest phenolic content (1.182 mg g^{-1}) representing a marked enhancement over all other treatments. Elevated phenolic accumulation is indicative of intensified secondary metabolite production associated with antifeedant activity and herbivore induced oxidative stress. The AMF based consortium resulted in moderate improvements in nutrient status, silica deposition, phenol concentration and cell wall thickness though consistently lower than the SSB and KSB based phytomedicine treatments.

Both the treated and untreated checks exhibited the weakest defense expression characterized by lower nutrient uptake (N: 3.17% and 3.02%; P: 0.19% and 0.16%; K: 0.20% and 0.19%), reduced silica accumulation (5.94% and 5.50%), minimal phenolic content (0.467 and 0.417 mg g^{-1}) and substantially thinner cell walls (0.0869 and 0.0872 µm) underscoring their limited capacity for endogenous defense activation (Figure 1). A significant negative correlations existed between pest damage and phenolic content, potassium concentration, silica accumulation and SEM derived cell wall thickness (Figures 2 and 3).

Table 2: Influence of microbial consortia on plant nutritional, biochemical and structural defense traits of Rice

Treatment	Plant nutritional/biochemical/structural defense traits*					
	N (%)**	P (%)**	K (%)**	Silica content (%)**	Phenol content (mg g^{-1})***	Cell wall thickness at 1000X in µm
NFB + PSB + ZSB + SSB + 75% NPK	3.59 (10.91)[a]	0.27 (2.95)[a]	0.27 (2.96)[a]	6.33 (14.57)[a]	0.580 (0.761)[b]	0.1860[a]
NFB + PSB + ZSB + KSB + 75% NPK	3.52 (10.80)[ab]	0.22 (2.69)[bc]	0.26 (2.90)[a]	6.19 (14.40)[a]	1.182 (1.087)[a]	0.1393[b]
NFB + PSB + ZSB + VAM + 75% NPK	3.37 (10.57)[b]	0.23 (2.72)[ab]	0.24 (2.79)[a]	6.00 (14.18)[b]	0.497 (0.705)[c]	0.1261[bc]
Treated check: NFB + PSB + ZSB + 75% NPK	3.17 (10.25)[c]	0.19 (2.47)[cd]	0.20 (2.56)[b]	5.94 (14.10)[b]	0.467 (0.684)[d]	0.0869[c]
Untreated check: 100% NPK	3.02 (10.01)[c]	0.16 (2.29)[d]	0.19 (2.51)[b]	5.50 (13.56)[c]	0.417 (0.646)[d]	0.0872[c]

Note: *Mean of two-year data (2023 and 2024); Mean of four replications; Values in parentheses are arcsine** and square root *** transformed values; In a column, mean followed by the same letter are not significantly different at p<0.05.

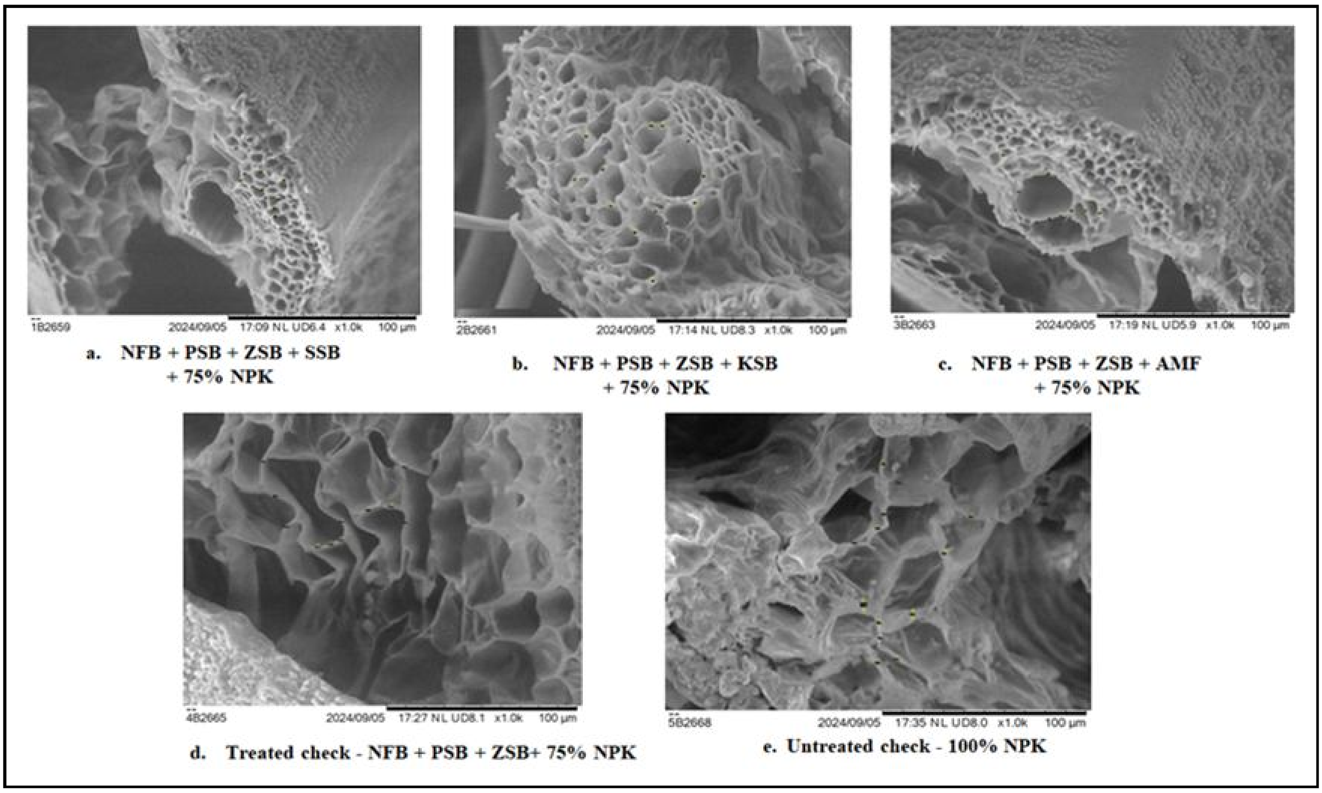

Figure 1: Scanning electron micrographs (1000X magnification) illustrating leaf cell wall thickness in rice under different microbial consortia (a-e).

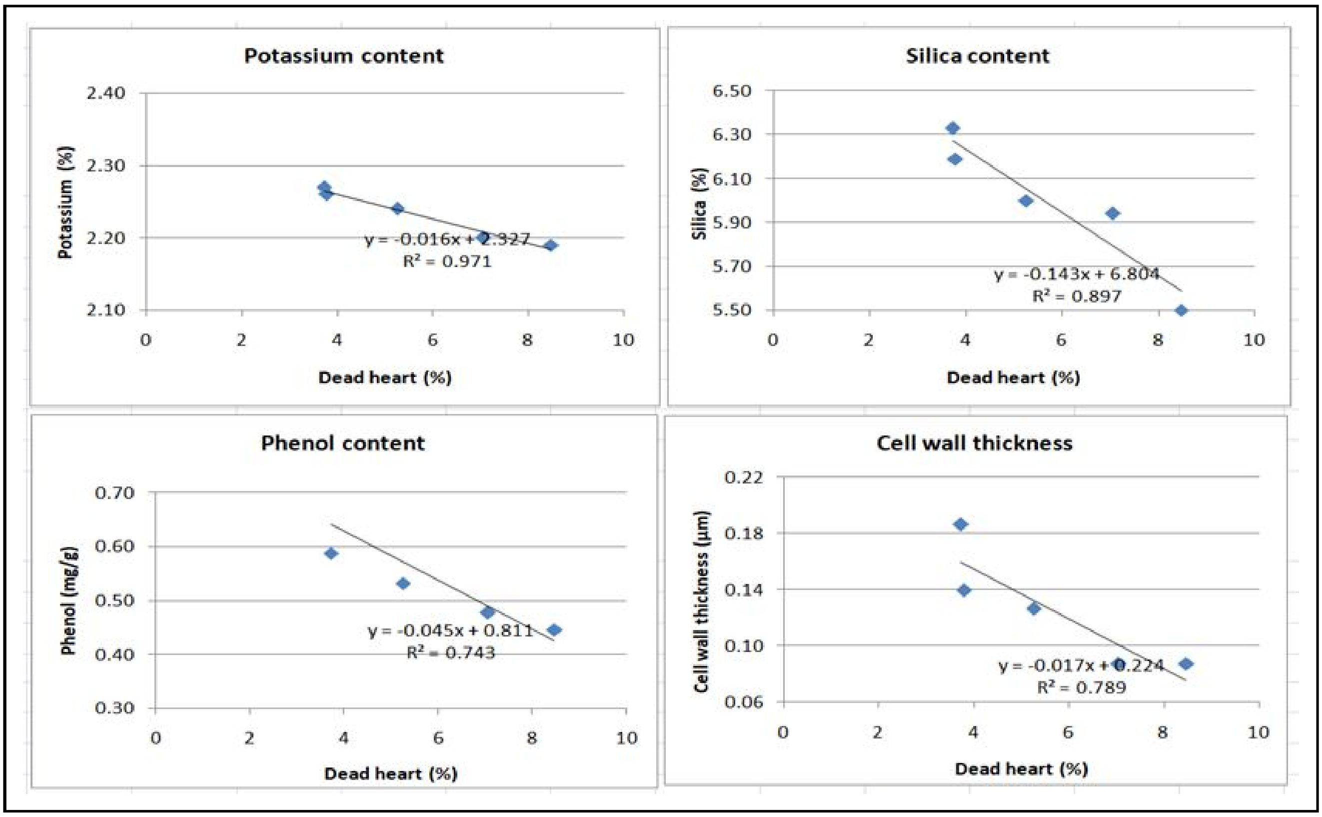

Figure 2: Relationship between plant biochemical/structural traits and stem borer damage across microbial consortia.

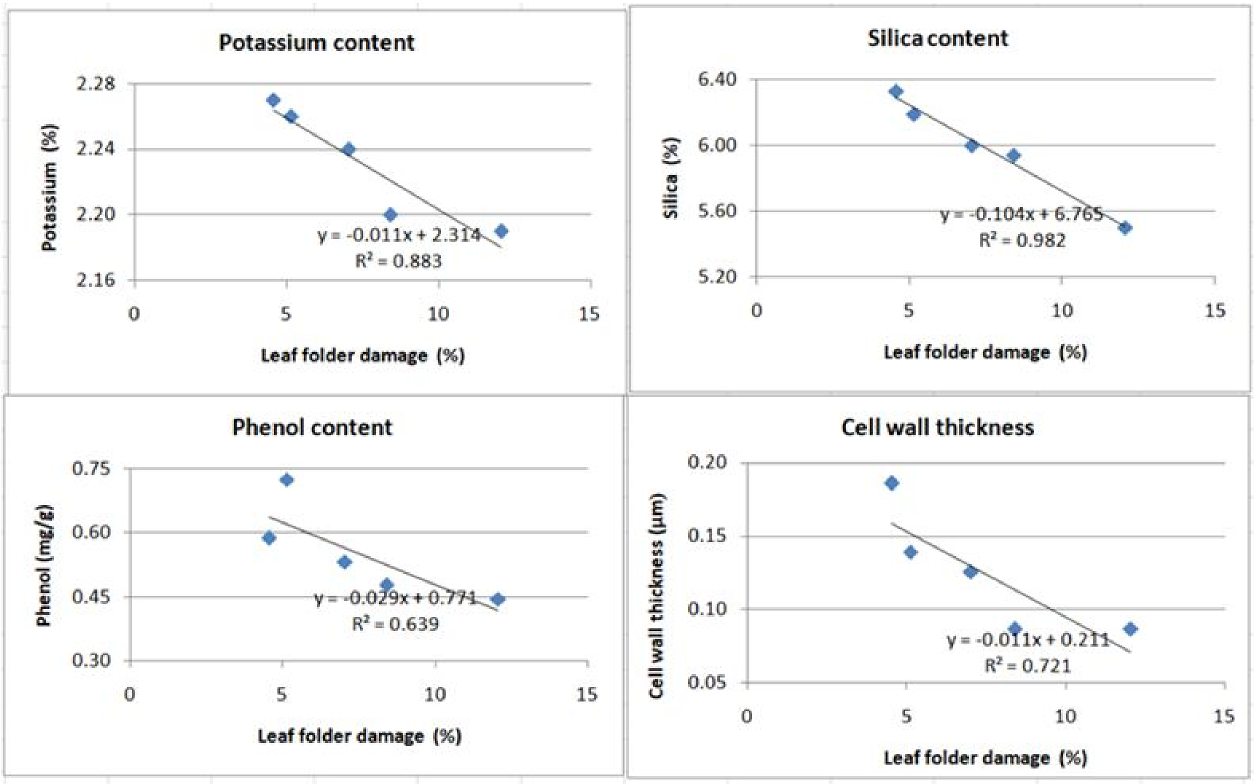

Figure 3: Relationship between plant biochemical/structural traits and leaf folder damage across microbial consortia.

3.3 Rhizosphere health and soil phytomedicine effects

Biological phytomedicine treatments significantly improved soil nutrient availability and rhizosphere quality (Table 3). The SSB based consortium recorded the highest levels of available nitrogen (148 kg ha^{-1}), phosphorus (92 kg ha^{-1}), silica (30.39 mg kg^{-1}) and organic carbon (4.67 g ha^{-1}), reflecting enhanced nutrient mobilization and soil health. The KSB based consortium performed comparably for nitrogen (147 kg ha^{-1}) and achieved the highest available potassium (791 kg ha^{-1}), reinforcing its role in sustaining potassium driven phytochemical defenses.

Table 3: Influence of microbial consortia on soil nutrient availability, organic carbon and physicochemical properties in Rice rhizosphere

Treatment	Soil nutrient availability, organic carbon and physicochemical properties*						
	Available N(kg ha^{-1})**	Available P(kg ha^{-1})**	Available K(kg ha^{-1})**	Available silica (mg/kg)**	Organic carbon (g ha^{-1})***	pH***	Electrical conductivity (dSm^{-1})***
NFB + PSB + ZSB + SSB + 75% NPK	148 (2.17)^{a}	92 (1.96)^{a}	785 (2.89)^{b}	30.39 (1.48)^{a}	4.67 (2.16)^{a}	6.45 (2.54)^{b}	0.48 (0.69)^{a}
NFB + PSB + ZSB + KSB + 75% NPK	147 (2.17)^{a}	84 (1.92)^{bc}	791 (2.90)^{a}	29.16 (1.47)^{ab}	4.41 (2.10)^{a}	6.43 (2.53)^{b}	0.48 (0.69)^{a}
NFB + PSB + ZSB + VAM + 75% NPK	145 (2.16)^{a}	86 (1.93)^{ab}	770 (2.89)^{c}	28.65 (1.46)^{ab}	4.41 (2.10)^{a}	6.96 (2.64)^{a}	0.52 (0.72)^{a}
NFB + PSB + ZSB + 75% NPK Treated check	143 (2.15)^{ab}	79 (1.90)^{cd}	764 (2.88)^{d}	27.56 (1.44)^{b}	4.22 (2.05)^{ab}	6.84 (2.62)^{ab}	0.51 (0.71)^{a}
Untreated check 100% NPK	140 (2.14)^{b}	73 (1.86)^{d}	759 (2.88)^{d}	26.63 (1.42)^{b}	3.89 (1.97)^{b}	7.06 (2.66)^{a}	0.51(0.71)^{a}

Note: *Mean of two-year data (2023 and 2024); Mean of four replications; Values in parentheses are log ** and square root*** transformed values; In a column, mean followed by the same letter are not significantly different at $p<0.05$.

The AMF based consortium improved soil nutrient status relative to both checks particularly for phosphorus (86 kg ha^{-1}) and silica (28.65 mg kg^{-1}) although values remained lower than those recorded under SSB and KSB treatments. Soil pH and electrical conductivity exhibited minimal variation across treatments with SSB and KSB consortia maintaining a slightly acidic pH (6.43 to 6.45) conducive to nutrient availability. The treated and untreated checks consistently exhibited the poorest soil fertility profiles including lower available nitrogen, phosphorus, silica and organic carbon indicative of reduced rhizosphere functionality.

3.4 Soil microbial dynamics supporting phytomedicinal function

Microbial consortia significantly enhanced soil microbial populations reinforcing the persistence and functionality of phytomedicine systems (Table 4 and Figure 4). The KSB based consortium supported the highest populations of bacteria (7.76 CFU g^{-1}), fungi (5.71 CFU g^{-1}) and actinomycetes (4.85 CFU g^{-1}) reflecting a diversified and active rhizosphere microbiome. The SSB based consortium also sustained high microbial abundance (7.54, 5.43 and 4.45 CFU g^{-1} for bacteria, fungi and actinomycetes, respectively), while the AMF based consortium produced moderate increases. In contrast, the untreated check recorded the lowest microbial counts across all groups indicating diminished soil biological health under conventional fertilization alone.

3.5 Phytomedicine driven growth, yield and economic returns

Microbial phytomedicine treatments significantly improved crop growth, yield attributes and farm level profitability (Table 5). The SSB based consortium recorded the highest plant height (116 cm), number of productive tillers (18 hill^{-1}), 1000 grain weight (26.49 g) and grain yield (5946 kg ha^{-1}), representing yield increases of 15.0% and 15.5% over the untreated and treated checks, respectively. The KSB based consortium achieved comparable yield performance (5915 kg ha^{-1}), while the AMF based consortium resulted in moderate yield enhancement (5523 kg ha^{-1}).

Table 4: Influence of microbial consortia on soil microbial population dynamics in Rice rhizosphere

Treatment	Microbial population (CFU/ g of soil) *		
	Bacteria	Fungi	Actinomycetes
NFB + PSB + ZSB + SSB + 75% NPK	7.54 ± 0.17^{b}	5.43 ± 0.04^{b}	4.45 ± 0.09^{b}
NFB + PSB + ZSB + KSB + 75% NPK	7.76 ± 0.04^{a}	5.71 ± 0.08^{a}	4.85 ± 0.03^{a}
NFB + PSB + ZSB + VAM + 75% NPK	7.30 ± 0.20^{c}	5.40 ± 0.05^{b}	4.52 ± 0.09^{b}
Treated check: NFB + PSB + ZSB + 75% NPK	7.26 ± 0.19^{d}	5.20 ± 0.19^{c}	4.49 ± 0.06^{b}
Untreated check: 100% NPK	6.90 ± 0.18^{e}	4.30 ± 0.05^{d}	3.60 ± 0.09^{c}

Note: *Mean of two-year data (2023 and 2024); Mean of four replications; In a column, mean followed by the same letter are not significantly different at p<0.05.

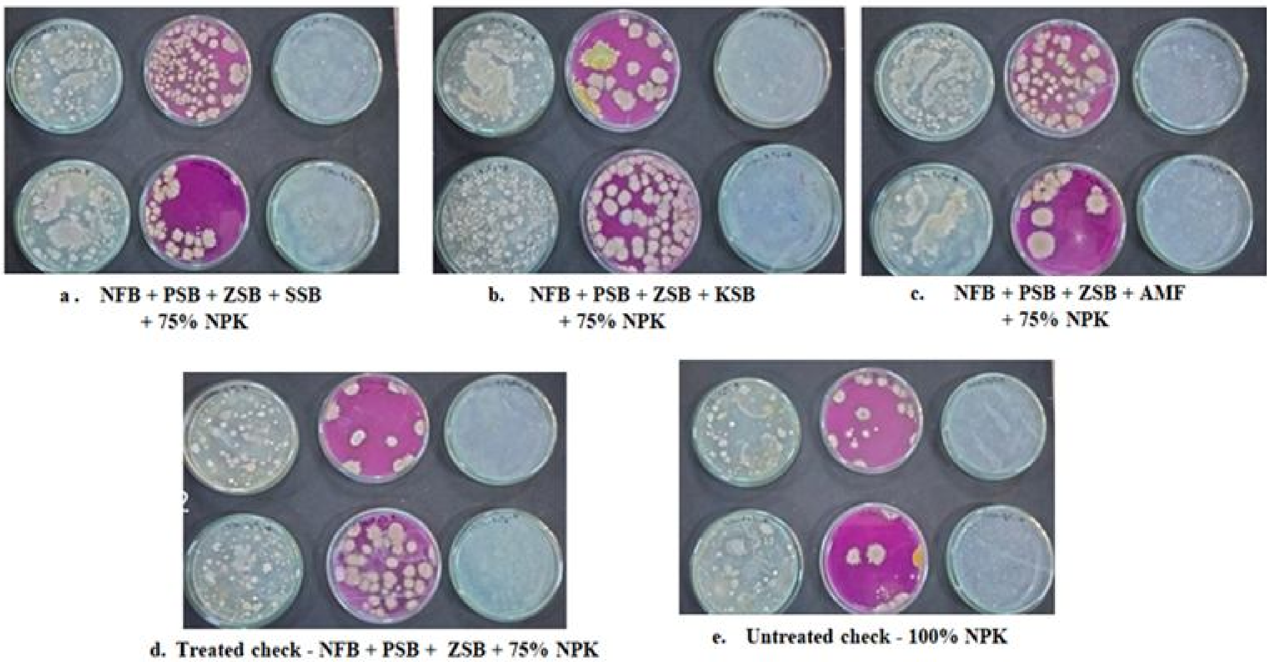

Figure 4: Influence of microbial consortia on rhizosphere microbial community structure in Rice (a-e).

Economic analysis further highlighted the superiority of silica and potassium based phytomedicines. The SSB based consortium generated the highest gross (Rs. 1,36,758 ha^{-1}) and net returns (Rs. 82,583 ha^{-1}) with a benefit cost ratio of 2.52, closely followed by the

KSB based consortium (B ratio: 2.51). In contrast, the untreated check recorded the lowest economic efficiency (B ratio: 2.09). These results demonstrate that biological phytomedicines not only suppress insect herbivory but also enhance profitability under reduced chemical input regimes. Overall, the results establish that microbial consortia function as effective biological phytomedicines by activating plant derived structural and biochemical defenses improving rhizosphere health and delivering sustainable gains in productivity and economic returns.

Table 5: Influence of microbial consortia on growth, yield attributes and economic performance of Rice

Treatment	Growth, yield attributes and economic performance*							
	Plant height (cm)	Productive tillers (nos. $hill^{-1}$)	1000 grain weight (g)	Grain yield (kg ha^{-1})	Gross return (Rs. ha^{-1})	Cost of cultivation (Rs. ha^{-1})	Net return (Rs.ha^{-1})	B:C ratio
NFB + PSB + ZSB + SSB + 75% NPK	116 (2.06)^{a}	18 (1.25)^{a}	26.49 (1.42)^{a}	5946 (3.77)^{a}	136758	54175	82583	2.52
NFB + PSB + ZSB + KSB + 75% NPK	115 (2.06)^{a}	18 (1.25)^{a}	25.77 (1.41)^{a}	5915 (3.77)^{a}	136068	54175	81893	2.51
NFB + PSB + ZSB + VAM + 75% NPK	114 (2.06)^{b}	17 (1.23)^{a}	23.33 (1.37)^{b}	5523 (3.74)^{b}	127029	54175	72854	2.34
Treated check: NFB + PSB + ZSB + 75% NPK	113 (2.05)^{bc}	16 (1.20)^{a}	23.16 (1.36)^{b}	5148 (3.71)^{c}	118404	54175	64229	2.19
Untreated check: 100% NPK	112 (2.05)^{c}	15 (1.18)^{a}	20.67 (1.31)^{c}	5091 (3.71)^{c}	117093	55975	61118	2.09

Note: Farm-gate price: Rs. 23 kg^{-1}; *Mean of two-year data (2023 and 2024); Mean of four replications; Values in parentheses are log transformed values; In a column, mean followed by the same letter are not significantly different at $p<0.05$.

4. Discussion

The pronounced suppression of stem borer and leaffolder damage under SSB and KSB based microbial consortia clearly demonstrates that rhizosphere microbiomes can function as biological phytomedicines activating endogenous plant defense systems rather than exerting direct pesticidal effects. By stimulating plant derived structural and biochemical defenses, these consortia convert rice plants into self protective systems capable of deterring herbivory through innate resistance mechanisms.

Enhanced silica accumulation in SSB treated plants represents a primary phytomedicinal mode of action based on physical fortification. Increased silica deposition strengthens epidermal and sclerenchymatous tissues, thickens cell walls and reduces tissue palatability, thereby limiting feeding and penetration by chewing insects such as stem borers. These findings are consistent with earlier reports demonstrating that silica fortifies cell walls and enhances resistance to herbivores in rice (Jeer *et al*., 2016; Han *et al*., 2016). In this context, silica functions as a plant derived defensive compound whose accumulation is biologically induced by microbial activity, exemplifying a non-toxic, phytomedicine based resistance strategy. Simultaneously, KSB based consortia predominantly activated chemical phytomedicinal defenses as evidenced by significantly elevated phenolic concentrations. Phenolic compounds are well established secondary metabolites with antifeedant properties and the ability to induce oxidative stress and digestive inhibition in herbivores (Wallis and Galarneau, 2020; Singh *et al*., 2021).

The significant negative correlations between pest damage and phenolic content, potassium concentration, silica accumulation and SEM derived cell wall thickness provide clear mechanistic evidence that microbial consortia suppress stem borer and leaffolder injury through coordinated enhancement of both biochemical and structural defenses. Correlation analyses demonstrate that increases in phenolics and potassium are closely associated with reduced feeding damage indicating activation of metabolically mediated resistance *via* phenylpropanoid enrichment and potassium regulated enzymatic and redox processes. Concurrently, strong inverse relationships between silica content, cell wall thickness and pest injury, supported by SEM measurements establish that microbial treatments particularly SSB and AMF enriched consortia induce tangible anatomical reinforcement that directly constrains larval penetration and feeding efficiency. Together, these statistically robust associations delineate a cause effect continuum in which microbial treatments first modulate nutrient availability and signaling, subsequently enhance defense traits at biochemical and ultrastructural levels and ultimately translate into effective insect suppression, confirming the synergistic and plant mediated nature of resistance. Similar associations between phenolic enrichment and reduced herbivory have been reported earlier (Meena *et al*., 2014) reinforcing the role of microbe induced secondary metabolism in plant mediated insect deterrence.

Improved uptake of nitrogen, phosphorus, potassium and silica under microbial consortia further highlights their role as nutrient enabled phytomedicines. The combined action of NFB, PSB, ZSB, SSB and KSB enhanced nutrient solubilization and assimilation, thereby supporting vigorous growth and strengthening plant immune capacity. Nutrient sufficient plants possess greater metabolic flexibility to allocate resources toward defensive secondary metabolite production and structural reinforcement, enhancing tolerance to herbivore attack. These observations align with earlier reports that plant associated microbes enhance nutrient acquisition and physiological resilience (Backer *et al*., 2018; Meena *et al*., 2017), underscoring nutrient mediated conditioning as a critical determinant of plant herbivore interactions.

Structural and biochemical modulation was further confirmed through increased cell wall thickness and silica deposition in SSB treated plants, as revealed by SEM observations. Such anatomical reinforcement represents a durable phytomedicinal barrier against boring insects. Silica deposition integrates physical and biochemical defense by interfacing with key signaling pathways that govern endogenous resistance phenotypes. Accumulation of amorphous silica in cell walls not only increases tissue rigidity and abrasion against herbivores but also modulates plant phytohormonal networks, particularly jasmonic acid (JA) signaling, which orchestrates oxidative stress responses and the activation of downstream defensive pathways. Silicon supplemented plants exhibit primed JA responses upon herbivory leading to elevated expression of JA responsive genes and defense enzymes that channel metabolic flux through the phenylpropanoid pathway resulting in enhanced biosynthesis and accumulation of phenolic compounds, flavonoids and lignin that bolster both antioxidative capacity and structural integrity. These phenolics also act as pharmacologically relevant phytochemicals with antioxidant and deterrent properties reinforcing the coordinated defense phenotype involving silica deposition, JA signaling, oxidative stress induction and secondary metabolism. This integrated mechanism positions silicon as a modulator of multi layered plant defense rather than a mere physical barrier (Ye *et al.,* 2013).

In contrast, KSB mediated stimulation of phenolic compounds highlights the role of microbial signaling in redirecting plant metabolic pathways toward defense related secondary metabolism. AMF based consortia induced moderate enhancement of these traits, consistent with previous evidence that mycorrhizal fungi prime systemic plant defenses and modulate host defense pathways (Perez-de-Luque *et al.,* 2017). These findings illustrate that microbial consortia can be selectively designed to activate distinct phytomedicinal defense modalities.

The significant enrichment of bacterial, fungal and actinomycete populations particularly under KSB based consortia demonstrates the strong rhizosphere modulating effects of nutrient solubilizing microbes. Enhanced microbial diversity promotes nutrient mineralization, organic carbon stabilization and soil biochemical functioning, thereby reinforcing soil ecological health (Vessey, 2003; Heinen *et al*., 2018). Such improvements in soil health are integral to the sustained efficacy of biological phytomedicines, ensuring continuous stimulation of plant defense responses under reduced chemical inputs.

The substantial improvements in growth, yield attributes and economic returns observed under SSB and KSB based consortia further validate the agronomic relevance of the phytomedicine concept. Achieving higher yields and superior benefit cost ratios with only 75% NPK fertilization demonstrates improved nutrient use efficiency and reduced dependency on synthetic inputs. Unlike chemical pesticides that act externally and may disrupt ecological balance, microbial phytomedicines enhance productivity by strengthening intrinsic plant defense and soil health, thereby supporting safer food production and agroecosystem sustainability.

Overall, the study provides compelling evidence that multifunctional microbial consortia act as biological phytomedicines, simultaneously enhancing soil fertility, nutrient acquisition, structural fortification and secondary metabolite production to suppress major rice pests. The complementary strengths of SSB and KSB based consortia highlight the scope for strategic microbiome assembly to achieve targeted phytomedicinal outcomes. By reducing reliance on chemical pesticides and fertilizers, these consortia offer a biologically grounded pathway toward sustainable, resilient and health conscious rice production systems. Microbial consortia functioning as plant mediated phytomedicines substantially reduce pesticide dependence by activating durable, endogenous defense mechanisms rather than relying on external toxic inputs. The coordinated enhancement of structural barriers (silicification and cell wall thickening) and biochemical defenses (phenolic enrichment and redox regulation) provides sustained suppression of lepidopteran pests, thereby lowering the need for repeated insecticide applications. This host centered mode of protection directly contributes to improved food safety by minimizing pesticide residues in rice grains and reducing off target contamination of agro ecosystems. Simultaneously, the microbial mobilization of silicon, potassium and other nutrients improves nutrient-use efficiency by channeling absorbed resources toward defense linked metabolic pathways without compromising crop productivity even under reduced fertilizer regimes. Owing to their ecological compatibility, preventive action and non-disruptive effects on natural enemies, these consortia integrate seamlessly into integrated pest management frameworks and are particularly suited to low-input rice production systems, where resilience, input efficiency and environmental safety are paramount.

5. Conclusion

The present study demonstrates that rhizosphere microbial consortia function as biological phytomedicines activating plant derived structural and biochemical defenses to suppress major rice pests. Silica and potassium solubilizing consortia enhanced silica deposition, cell wall fortification and phenolic accumulation resulting in effective, plant mediated insect deterrence under reduced fertilizer inputs. This phytomedicinal defense translated into improved soil health, nutrient use efficiency, yield stability and economic returns without reliance on chemical pesticides. The findings highlight microbiome assisted defense priming as a sustainable alternative to conventional pest management. Microbial consortia deployed as plant mediated phytomedicines represent a shift from chemical dependent pest suppression toward reinforcement of the plant's own defense capacity. By concurrently promoting silicification, cell wall fortification and defense linked secondary metabolism these consortia provide stable protection against lepidopteran pests while substantially curtailing the need for repeated insecticide use. The resulting reduction in chemical inputs contributes to safer grain production and diminished environmental burden, alongside improved efficiency in the utilization of silicon, potassium and associated nutrients under reduced fertilizer regimes. Their compatibility with beneficial arthropods and alignment with preventive, ecosystem based management underscore their suitability for incorporation into IPM frameworks and low-input rice production systems aimed at long term sustainability. Future research should focus on elucidating molecular defense signaling, identifying phytomedicinal biomarkers and validating consortium performance across diverse agro ecosystems to enable scalable adoption.

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Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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