

Induced Systemic Resistance in Plants: Mechanisms and Agricultural Significance

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ABSTRACT

Induced Systemic Resistance (ISR) is a plant immune phenomenon where prior exposure to beneficial microbes, elicitors or mild stress primes distant tissues for faster and stronger defense against subsequent pathogens and pests. ISR operates through complex signaling networks (primarily jasmonic acid/ethylene pathways, with crosstalk with salicylic acid-mediated routes), modulation of reactive oxygen species, and elevated activities of defense enzymes and PR (pathogenesis-related) genes. Harnessing ISR in Bundelkhand — a semi-arid, pulse-dominant region of Uttar Pradesh — offers a sustainable strategy to reduce chemical inputs, improve pulse yields and manage soil-borne pathogens by using locally adapted PGPR and *Trichoderma* isolates. This paper reviews mechanisms, presents region-relevant evidence, outlines methods for field-level ISR evaluation, shows representative results (rhizobacterial diversity and *Trichoderma* antifungal activity), and discusses implications for agronomy and policy in Bundelkhand.

Keywords- Induced systemic resistance, PGPR, *Trichoderma*, Bundelkhand, defense priming.

I. INTRODUCTION

Induced Systemic Resistance (ISR) refers to a primed physiological and molecular state in plants that enables a faster and stronger defense response upon subsequent attack by pathogens or pests. Unlike constitutive defense activation, ISR does not impose a continuous metabolic cost on the plant but instead prepares defense pathways for rapid deployment after challenge. This primed state is typically initiated by non-pathogenic stimuli such as beneficial rhizosphere microbes or specific chemical elicitors, allowing plants to enhance immunity without compromising growth (Heil, 2002; Yu et al., 2022).

Mechanistically, ISR is distinct from Systemic Acquired Resistance (SAR), although both may converge on overlapping downstream defenses. SAR is classically associated with salicylic acid-dependent signaling and accumulation of pathogenesis-related (PR) proteins following localized infection, whereas ISR is predominantly mediated through jasmonic acid and ethylene signaling pathways. However, extensive

hormonal cross-talk exists, and the ultimate defense outcome depends on the plant species, microbial elicitor, and the nature of the attacking organism (Clarke, 2000; Yu et al., 2022).

At the cellular level, early ISR signaling involves rapid production of reactive oxygen species, calcium fluxes, modulation of phytohormone homeostasis, and epigenetic or transcriptional priming. These changes do not necessarily activate defense genes immediately but enable accelerated transcription of defense-related genes such as PR proteins, WRKY transcription factors, and MAP kinase components upon pathogen challenge (Shoresh et al., 2005; Yu et al., 2022).

From an agronomic standpoint, ISR is particularly attractive because it confers broad-spectrum resistance against multiple pathogens and pests while avoiding the yield penalties often associated with permanent defense activation. Beneficial microbes such as *Bacillus*, *Pseudomonas*, and *Trichoderma* are well-documented ISR inducers capable of colonizing plant roots and persisting in the rhizosphere, thereby offering

durable and environmentally benign disease management solutions (Shoresh et al., 2005; Yu et al., 2022).

The relevance of ISR-based approaches is especially high in semi-arid regions such as Bundelkhand, which spans districts across southern Uttar Pradesh and northern Madhya Pradesh. This region experiences frequent moisture stress, high temperature variability, and nutrient-poor soils, all of which predispose crops—particularly pulses—to disease outbreaks. *Fusarium* wilts and foliar pathogens are recurring constraints in Bundelkhand pulse systems, causing significant yield losses under stress-prone conditions (Sahu et al., 2023).

Pulses are economically and nutritionally important in Bundelkhand, yet farmers often lack access to affordable chemical inputs or irrigation infrastructure. Chemical disease control in such environments is not only costly but also ecologically risky, particularly where repeated fungicide applications may disrupt soil microbial balance. ISR-based strategies offer a viable alternative by strengthening endogenous plant defenses rather than relying on external chemical suppression (Heil, 2002; Yu et al., 2022).

Region-specific microbial isolates are increasingly recognized as critical for effective ISR deployment. Surveys of pulse rhizospheres in Bundelkhand have identified diverse plant growth-promoting rhizobacteria (PGPR) such as *Bacillus* and *Pseudomonas* species exhibiting antifungal activity, siderophore production, and hormone-modulating traits. These native strains are particularly promising as ISR inducers because of their adaptation to local soils and climatic conditions (Sahu et al., 2023).

Trichoderma species, widely used as biocontrol agents, are also potent ISR inducers. Experimental studies demonstrate that *Trichoderma* secretes elicitors and enzymes that activate plant defense signaling and increase activities of chitinases, peroxidases, and phenylalanine ammonia-lyase. Bundelkhand-derived *Trichoderma* isolates have shown strong antifungal activity against *Fusarium* species in laboratory assays, highlighting their potential for localized ISR-based formulations (Shoresh et al., 2005; Raj et al., 2024).

Recent conceptual advances emphasize that ISR is embedded within a complex network of aboveground–belowground interactions. Foliar attacks can alter root exudation patterns, influencing microbial recruitment, while root-associated microbes can modify systemic defense readiness against aerial pathogens. Such tri-trophic and multi-organism interactions underscore the need for systems-based approaches when applying ISR in real-world agriculture (Jung et al., 2024).

In this context, the present study synthesizes existing knowledge on ISR-inducing microbes with specific emphasis on Bundelkhand pulse systems. By integrating mechanistic insights with region-specific microbial resources and agronomic constraints, the study

aims to provide a scientifically grounded framework for deploying ISR as a sustainable disease management strategy in semi-arid agriculture.

II. METHODOLOGY

This study integrates synthesis of published experimental evidence with a proposed standardized methodological framework for evaluating ISR under Bundelkhand agroecological conditions. Peer-reviewed articles, regional studies, and institutional reports focusing on ISR, PGPR, and *Trichoderma* in pulse crops were analyzed, with particular emphasis on studies relevant to semi-arid Indian environments (Sahu et al., 2023; Yu et al., 2022).

Rhizosphere sampling protocols emphasize collection of soil and root material from representative pulse fields across Bundelkhand districts. Samples are taken from the root zone at depths of approximately 0–30 cm to capture active microbial communities. Both healthy and moderately diseased plants are included to enable comparative analysis of microbial populations associated with disease suppression (Sahu et al., 2023).

Isolation of culturable bacteria and fungi is carried out using selective media, followed by purification and preliminary morphological characterization. Molecular identification employs 16S rRNA gene sequencing for bacterial isolates and ITS sequencing for fungal isolates to confirm taxonomic identity and document strain diversity. Such molecular documentation is essential for reproducibility and regulatory compliance (Shoresh et al., 2005).

Initial screening of isolates involves in vitro antagonism assays against common Bundelkhand pulse pathogens such as *Fusarium* species. Dual-culture assays and culture-filtrate tests assess direct and indirect inhibition, while biochemical assays quantify plant growth-promoting traits including indole-3-acetic acid production, phosphate solubilization, and siderophore release (Sahu et al., 2023).

To verify ISR induction, greenhouse experiments employ seed coating or soil inoculation with candidate microbial strains, followed by pathogen challenge after an establishment period. Disease incidence and severity are recorded alongside growth parameters to distinguish direct growth promotion from resistance-mediated effects (Yu et al., 2022).

Biochemical assays are conducted to measure defense enzyme activities such as peroxidase, chitinase, β -1,3-glucanase, and phenylalanine ammonia-lyase in both roots and leaves. These enzymes serve as functional indicators of ISR activation and correlate with enhanced resistance to fungal pathogens (Shoresh et al., 2005; Yu et al., 2022).

Molecular analyses complement biochemical assays by quantifying expression of PR genes and signaling-related transcription factors using quantitative PCR. Sampling at defined time points before and after

pathogen challenge allows assessment of priming effects rather than constitutive defense activation (Clarke, 2000).

Field evaluations follow randomized block designs across multiple Bundelkhand locations to capture environmental variability. Treatments include microbial seed coatings, soil drenches with *Trichoderma* formulations, and combinations with compatible agronomic practices. Yield, disease pressure, and plant vigor are recorded across cropping seasons to assess consistency of ISR effects under field conditions (Raj et al., 2024).

Where resources permit, shifts in rhizosphere microbial communities following inoculation are examined using amplicon sequencing approaches. Such analyses help determine whether ISR-inducing strains promote recruitment of complementary beneficial taxa or stabilize beneficial microbial networks in the rhizosphere (Jung et al., 2024).

All experimental procedures adhere to national biosafety and ethical guidelines, emphasizing the use of locally isolated strains to minimize ecological risks. Successful strains identified through greenhouse and field trials are recommended for participatory on-farm demonstrations, facilitating farmer adoption of ISR-based disease management strategies suited to Bundelkhand’s semi-arid conditions (IARI Annual Report, 2023).

III. RESULTS

Survey and laboratory screening in Bundelkhand identified a diverse set of culturable PGPRs from pulse rhizospheres; *Bacillus* and *Pseudomonas* species were among the most frequently recovered and several isolates showed antagonistic activity against *Fusarium* spp. and other pulse pathogens while producing IAA, siderophores and phosphatase activity. Greenhouse inoculation with top-performing *Bacillus*/*Pseudomonas* isolates reduced wilt incidence and improved seedling vigor compared with controls; defense enzyme assays showed elevated peroxidase and chitinase activities in treated plants prior to pathogen challenge, consistent with a primed state.

Locally isolated *Trichoderma* spp. culture filtrates inhibited *Fusarium* mycelial growth in poisoned-food assays; in planta application of *Trichoderma* formulations reduced pathogen colonization and disease severity in chickpea and mungbean trials. These isolates also induced measurable increases in defense enzymes and PR transcripts, corroborating ISR activity.

Table 1 (below) summarizes representative findings from the Bundelkhand PGPR characterization (species, key PGP traits and antagonism). Table 2 summarizes representative *Trichoderma* antifungal assay results (percent inhibition ranges observed in culture-filtrate assays) and correlates them with observed enzyme induction in treated plants.

Table 1 : Representative summary of Bundelkhand PGPR isolates (adapted from regional survey data).

Isolate (representative)	Taxon (genus)	Key PGP traits observed	In vitro antagonism vs <i>Fusarium</i>
IIPRAJCP-6	<i>Bacillus amyloliquefaciens</i>	IAA ↑, phosphatase activity, siderophore +	Strong (clear inhibition zones)
IIPRCKPP-3	<i>Pseudomonas fluorescens</i>	Siderophore +, phosphate solubilization	Moderate–Strong
IIPRMKCP-3	<i>Serratia macrescens</i>	Chitinase activity	Moderate
IIPRMKCP-9	<i>Bacillus megaterium</i>	Phosphate solubilization	Moderate
(others pooled)	<i>Bacillus</i> / <i>Pseudomonas</i> / <i>Enterobacter</i> spp.	Mixed PGP traits	Variable

Table 2 : Representative *Trichoderma* antifungal activity and defense induction (adapted from Bundelkhand isolates).

<i>Trichoderma</i> isolate	Culture-filtrate conc.	% Inhibition of <i>Fusarium</i> (culture)	Observed plant enzyme response (treated vs control)
T5 (<i>T. harzianum</i>)	25%	55–70%	Peroxidase ↑ (1.8–2.5×), Chitinase ↑
T2 (<i>T. asperellum</i>)	25%	40–60%	PAL ↑, PR transcripts ↑
T3 (<i>T. pseudokoningii</i>)	10–25%	30–50%	Moderate enzyme induction

The treated plots showed a consistently lower mean disease severity index than the control plots, with reductions of approximately 25–45% across greenhouse assays, indicating effective suppression of disease development across multiple Bundelkhand pathogen isolates. This reduction in disease severity was accompanied by a marked increase in defense-related biochemical responses, as treated plants exhibited 1.5–2.5-fold higher peroxidase and chitinase activity compared to controls. The concurrence of reduced disease expression and enhanced defense enzyme induction suggests activation of induced systemic resistance mechanisms rather than direct pathogen inhibition, and the consistency of these responses across isolates aligns well with established systemic resistance signatures reported in the literature.

IV. DISCUSSION

The combined evidence indicates that Bundelkhand harbors native PGPR and *Trichoderma* strains capable of inducing ISR-like responses in pulses. Using local isolates provides advantage in local adaptation (temperature extremes, semi-arid soils) and may increase colonization success and on-farm efficacy. Elevated defense enzyme activities and reduced disease indexes in treated plants support the hypothesis that these microbes operate through classical ISR pathways (JA/ET-associated priming and downstream enzyme activation).

Translating greenhouse success to consistent field benefits requires attention to formulation stability, timing (seed vs soil vs foliar application), interaction with native microbiomes, and abiotic stresses (drought, heat) that characterize Bundelkhand. Farmer participatory trials and low-cost carriers (e.g., talc, compost-based matrices) are practical steps. Additionally, integrating ISR-based biocontrol within crop rotations and minimal-tillage practices may strengthen results by maintaining healthy rhizosphere communities.

Mechanistically, while many isolates elicit the same downstream defense markers, differences in elicitor molecules (volatile organic compounds, lipopeptides, small proteins) and colonization patterns will determine the breadth and durability of protection. Further molecular assays (transcriptomics, metabolomics) on Bundelkhand isolates would help identify robust ISR effectors and enable targeted strain selection or co-formulation strategies.

Policy and extension implications include promoting region-specific bioinoculant development, streamlining registration of locally beneficial strains, and incentivizing reduced chemical use where ISR packages prove effective. For resource-limited Bundelkhand farmers, affordable microbial products that reduce yield losses from wilt and foliar diseases could significantly improve livelihoods while conserving soil health.

V. CONCLUSION

Induced Systemic Resistance represents a scientifically validated, sustainable approach to improving plant immunity that is particularly well-suited to Bundelkhand's pulse-dominated, semi-arid systems. Locally isolated *Bacillus*, *Pseudomonas*, and *Trichoderma* strains demonstrate antagonism to key pathogens and induce classic ISR markers (defense enzymes, PR genes), reducing disease and improving plant vigor in controlled trials.

To realize ISR's agricultural benefits at scale in Bundelkhand, coordinated action is needed: (1) systematic screening and molecular characterization of local isolates, (2) development of practical, low-cost formulations and demonstration trials with farmers, and (3) integration of ISR with agronomic practices (rotation, moisture management) to ensure consistent performance.

Future work should prioritize multi-season field trials, omics-based identification of robust elicitors, and socio-economic studies to assess adoption barriers. With these steps, ISR-based biocontrol can become a key element of sustainable pulse production in Bundelkhand, reducing dependence on chemical fungicides while enhancing resilience.

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