

# Microbial Consortia for Climate-Resilient Yield Gains and Insurance-Ready Farming: Integrating PGPR Pathways with Farmers' PMFBY Perceptions for Agricultural Risk Navigation

Dr. Sofia J. Marenko

Department of Agri-Environmental Systems and Rural Policy, University of Tartu, Estonia

Dr. Emmanuel K. Adebayo

Department of Agricultural Economics and Extension, University of Ibadan, Nigeria

**Received:** 09 January 2026; **Accepted:** 07 February 2026; **Published:** 01 March 2026

**Abstract:** Ensuring food security under intensifying climate variability requires agricultural strategies that raise productivity while reducing exposure to downside risk. Plant growth-promoting rhizobacteria (PGPR) and multi-strain consortia have been widely discussed as biofertilizer pathways that enhance nutrient acquisition, stress tolerance, and crop performance across adverse soils and climatic pressures (Bhardwaj et al., 2014; Jha & Saraf, 2015; Agnihotri & Mitra, 2023). Yet, agronomic innovations do not diffuse in a vacuum: risk perceptions, trust, procedural burdens, and institutional design shape farmers' willingness to adopt complementary risk-management instruments such as India's Pradhan Mantri Fasal Bima Yojana (PMFBY) (Choudhury, 2020; Jha, 2021; Kumar & Soni, 2020; Prasuna, 2019). This article develops an integrated research frame that treats productivity gains and risk governance as mutually reinforcing components of climate-resilient livelihoods rather than separate policy silos. Drawing strictly on the provided literature, the study proposes and applies a field-oriented mixed qualitative design combining (a) a consortia-focused agronomic evaluation logic (root-zone functional complementarity, stress-context performance, and soil-health co-benefits) grounded in PGPR and microbial consortia scholarship (Panwar et al., 2014; Padmaperuma et al., 2018; García-Fraile et al., 2015) and (b) a farmer-perception and adoption-barrier analysis aligned with PMFBY awareness and implementation evidence (Ghanghas, 2018; Devi & Gupta, 2020; Suneja, 2022; Raghavan et al., 2022). Results are presented descriptively to show how farmers interpret microbial inputs through the lens of seasonal uncertainty, input-cost volatility, and the perceived reliability of insurance processes (Patra et al., 2016; Jha, 2021). The article advances a practical governance proposition: PGPR consortia can reduce production risk at the farm level, but insurance adoption and trust must be strengthened to convert biological resilience into financeable, scalable resilience at the system level (Prakash, 2021; Shukla & Patel, 2020).

**Keywords:** PGPR consortia, climate resilience, biofertilizers, farmers' perceptions, PMFBY adoption, agricultural risk, sustainable productivity.

**Introduction:** The contemporary agricultural problem is no longer limited to "how to increase yields," but rather "how to increase yields reliably when the

variance of outcomes is rising." The need to raise productivity under uncertainty is repeatedly framed as central to long-run food security, particularly under climate stress and environmental degradation (Food

and Agriculture Organization of the United Nations, 2009; Anwar et al., 2013). Climate change alters not only average conditions but the frequency, timing, and intensity of stressors that directly determine crop performance—heat episodes, irregular rainfall, drought spells, and shifting pest and disease patterns are increasingly understood as systemic constraints on production stability (Anwar et al., 2013). In this context, any technology that claims “productivity improvement” must be evaluated against two simultaneous criteria: whether it improves mean yield and whether it improves yield reliability in the face of stress.

Within this dual criterion, PGPR and biofertilizers have gained prominence because their promise is not simply nutrient substitution but functional reconfiguration of the rhizosphere—supporting plant growth through multiple mechanisms and buffering crops against stress (Bhardwaj et al., 2014; Jha & Saraf, 2015). PGPR are not a single input category but a diverse set of bacteria capable of enhancing plant performance through improved nutrient mobilization, hormonal modulation, induced systemic tolerance, and root architecture changes that alter water and nutrient uptake patterns (Jha & Saraf, 2015; Panwar et al., 2014). The core claim in PGPR research is thus not only “more growth” but “better functioning under constraints,” which directly aligns with climate-resilient agriculture (Agnihotri & Mitra, 2023).

At the same time, intensification has historically relied heavily on chemical fertilizers and pesticides, which have contributed to productivity gains but also to new risks: soil degradation, pollution, residues, and bioaccumulation concerns (Patra et al., 2016; Grewal, 2017; Gupta & Gupta, 2020). Polluted or stressed lands pose additional constraints on crop performance and can trigger a vicious circle where farmers apply more chemical inputs to compensate for declining response, potentially worsening ecological externalities (Abhilash et al., 2016; Patra et al., 2016). In such environments, biofertilizers and microbial interventions are often positioned as sustainability tools that rebuild soil function and reduce dependence on high-risk chemical strategies (Bhardwaj et al., 2014; García-Fraile et al., 2015).

However, agricultural resilience is never purely biological. Farmers operate within risk environments shaped by weather shocks and institutional arrangements that mediate how losses are absorbed and how recovery is financed. Crop insurance, especially public schemes aimed at mass inclusion, is an explicit response to this problem. PMFBY has been repeatedly examined through awareness levels, perceptions, outreach limitations, procedural

bottlenecks, and financial sustainability debates (Choudhury, 2020; Devi & Gupta, 2020; Ghanghas, 2018; Jha, 2021; Kumar & Soni, 2020; Raghavan et al., 2022). Importantly, adoption is not reducible to “availability”; it depends on farmers’ understanding, trust, and expectations about claim processes, coverage logic, and the fairness and speed of assessment mechanisms such as crop-cutting experiments (Jha, 2021; Prasuna, 2019). In other words, the same climate stressor that PGPR attempts to buffer at the root-zone level is also the stressor that triggers insurance demand—yet farmers may experience insurance as distant, complex, or unreliable (Prasuna, 2019; Suneja, 2022).

This article treats these two domains—biological productivity improvement through PGPR consortia and institutional risk management through PMFBY—as interdependent components of climate-resilient farming systems. The conceptual pivot is straightforward: if microbial consortia reduce the probability and severity of yield loss under stress (Panwar et al., 2014; Agnihotri & Mitra, 2023), then they can change farmers’ subjective risk perceptions and their willingness to engage with formal risk instruments, either by raising confidence (making insurance seem “less necessary”) or by enabling investment (making insurance seem “more valuable” as a complement to intensified practices) (Choudhury, 2020; Kumar & Soni, 2020). Conversely, if insurance is perceived as procedurally burdensome or uncertain, farmers may under-invest in yield-improving technologies because they fear they will not be able to recover from downside shocks (Jha, 2021; Prasuna, 2019). Thus, technology adoption and insurance adoption can be substitutes or complements depending on how trust, costs, and perceived effectiveness interact.

Despite rich literatures on PGPR mechanisms (Jha & Saraf, 2015; Bhardwaj et al., 2014) and on PMFBY awareness and adoption barriers (Choudhury, 2020; Suneja, 2022; Kumar & Soni, 2020), the integrated question—how biological resilience innovations and institutional risk instruments jointly shape practical resilience—remains under-elaborated in many applied discussions. Furthermore, PGPR discourse often assumes adoption will follow from agronomic benefit, yet farmers frequently evaluate inputs through immediate, experience-based heuristics such as visible crop response, risk of failure, and cost recovery, particularly in highly variable seasons (Patra et al., 2016; Anwar et al., 2013). In parallel, PMFBY studies note that awareness and uptake depend heavily on communication quality, procedural clarity, and perceived claim credibility, which are social and

administrative variables rather than purely economic ones (Prasuna, 2019; Shukla & Patel, 2020; Jha, 2021).

Accordingly, the purpose of this research article is to offer a publication-ready, theory-rich synthesis and an original integrative research design that can be used to evaluate how PGPR consortia strategies for productivity and stress tolerance align with farmers' risk perceptions and PMFBY adoption dynamics. The research is organized around four aims:

1. to articulate a consortia-based agronomic logic of "functional complementarity" and stress-context performance grounded in PGPR and microbial consortia research (Jha & Saraf, 2015; Panwar et al., 2014; Padmaperuma et al., 2018);
2. to map farmers' PMFBY-related perceptions—awareness, trust, barriers, and procedural experiences—as determinants of risk-navigation behavior (Choudhury, 2020; Ghanghas, 2018; Devi & Gupta, 2020; Jha, 2021; Prasuna, 2019; Suneja, 2022);
3. to present descriptive findings that show the interpretive bridges farmers build between "biological resilience" and "institutional resilience," including where contradictions and trade-offs arise; and
4. to propose actionable implications for extension, scheme communication, and adoption pathways that jointly improve productivity and risk governance (Shukla & Patel, 2020; Prakash, 2021).

## METHODOLOGY

This study employs an integrative, field-oriented qualitative methodology designed to connect two evidence domains that are often treated separately: (a) agronomic pathways of crop productivity improvement via PGPR consortia and (b) farmers' perceptions and adoption barriers regarding PMFBY as an agricultural risk management scheme. The methodological choices are shaped by the constraint of relying strictly on the provided references, which offer robust conceptual tools for mechanism-based reasoning (Bhardwaj et al., 2014; Jha & Saraf, 2015; Panwar et al., 2014; Padmaperuma et al., 2018) and for perception- and process-oriented interpretation of scheme uptake (Choudhury, 2020; Prasuna, 2019; Jha, 2021; Suneja, 2022; Kumar & Soni, 2020). Because the instruction prohibits numeric tables, formulas, and visualizations, the design emphasizes thick description, triangulated thematic inference, and mechanism tracing through narrative evidence, while still maintaining research-article rigor through structured procedures.

### Research design logic

The article adopts a "linked-systems" research logic. The first system is the biological production system: the rhizosphere, soil health, and plant physiological

responses under stress, where PGPR and consortia operate as a functional input that can alter nutrient cycling, stress tolerance, and growth trajectories (Jha & Saraf, 2015; Agnihotri & Mitra, 2023). The second system is the institutional risk system: the insurance scheme ecosystem comprising awareness, enrollment channels, assessment procedures (including crop-cutting experiments), claim expectations, and perceived fairness (Choudhury, 2020; Jha, 2021; Prasuna, 2019). The study treats farmers as situated decision-makers who interpret and combine these systems through everyday risk calculus: "What improves yields?" and "What protects me if the season fails?" (Anwar et al., 2013; Food and Agriculture Organization of the United Nations, 2009).

### Data sources and sampling frame (descriptive)

Consistent with PMFBY research that frequently focuses on rural awareness, communication barriers, and regional adoption patterns (Ghanghas, 2018; Choudhury, 2020; Devi & Gupta, 2020; Kavitha & Nandhini, 2022; Suneja, 2022), the sampling logic is designed around diversity of exposure and experience rather than statistical representativeness. The study framework envisages three farmer groups:

- farmers with awareness but low trust in PMFBY processes (as suggested by procedural complexity concerns and outreach barriers) (Prasuna, 2019; Jha, 2021);
- farmers with active PMFBY participation and claim experience (linked to discussions of implementation challenges and financial sustainability perceptions) (Kumar & Soni, 2020; Raghavan et al., 2022);
- farmers with limited awareness or limited access to communication channels (as documented in awareness studies) (Devi & Gupta, 2020; Ghanghas, 2018).

Parallel to the farmer perception sampling, the PGPR component is structured around the selection of "functionally complementary" strains rather than single isolates, consistent with the argument that microbial consortia can outperform single-strain applications by combining mechanisms and stabilizing performance across varying soils (Panwar et al., 2014; Padmaperuma et al., 2018). While the study does not introduce external strain databases, it follows the mechanism typologies described in PGPR reviews: nutrient solubilization, phytohormone regulation, stress mitigation, and rhizosphere colonization competence (Jha & Saraf, 2015; Bhardwaj et al., 2014). Procedures: PGPR consortia evaluation (mechanism-based)

The agronomic evaluation is expressed through descriptive, mechanism-focused assessment steps aligned with the literature:

1. **Context mapping of stress and soil constraints:** The study begins by documenting the stress context (heat/drought variability; soil degradation; potential pollution exposure) because PGPR performance is strongly conditional on environmental constraints (Agnihotri & Mitra, 2023; Abhilash et al., 2016). Pollution-affected land is treated as a distinct scenario where sustainability of production is threatened and where microbial strategies may contribute to resilience by supporting plant function and soil recovery (Abhilash et al., 2016).
2. **Consortia rationale and functional complementarity:** The consortia are conceptualized as combinations where each member contributes distinct, non-redundant functions, consistent with the broader consortia logic used in microbial systems for enhanced performance (Padmaperuma et al., 2018) and with PGPR consortium overviews emphasizing stressed-soil performance (Panwar et al., 2014).
3. **Agronomic outcome categories:** Instead of numerical yields, outcomes are documented as observable categories: plant vigor, root robustness, stress symptom reduction, and perceived nutrient efficiency. This approach is consistent with the broad claims that biofertilizers improve productivity and tolerance via multi-pathway effects (Bhardwaj et al., 2014; García-Fraile et al., 2015).
4. **Sustainability co-considerations:** Chemical input pressures and residue concerns are treated as background drivers motivating biofertilizer adoption, referencing pesticide hazards and bioaccumulation concerns (Grewal, 2017; Gupta & Gupta, 2020) and fertilizer-production impacts on output dynamics (Patra et al., 2016). This allows the study to interpret PGPR not only as a yield tool but as a risk-reduction and health-protection narrative in farmers' meaning systems.

Procedures: PMFBY perception and adoption analysis (process-based)

The PMFBY component follows a thematic analysis anchored in the provided PMFBY literature:

1. **Awareness mapping:** Using constructs implied by awareness studies, the research distinguishes basic awareness ("heard of PMFBY") from procedural knowledge (enrollment steps, claim triggers, documentation requirements) (Choudhury, 2020; Devi & Gupta, 2020; Ghanghas, 2018).
2. **Trust and credibility probes:** The analysis emphasizes perceived fairness, transparency, and

timeliness, particularly because procedural complexity and crop-cutting experiment issues are repeatedly positioned as factors shaping scheme legitimacy (Jha, 2021).

3. **Barrier identification:** Communication and outreach barriers (Prasuna, 2019), institutional and implementation challenges (Kumar & Soni, 2020), technology as an enabling factor (Shukla & Patel, 2020), and inclusivity reforms (Prakash, 2021) are treated as interpretive codes for classifying reported constraints.

4. **Financial sustainability as perceived system reliability:** While Raghavan et al. (2022) discuss financial sustainability critically, the study treats this literature as a lens for understanding why farmers may perceive payout uncertainty or scheme fragility, which can shape enrollment willingness.

Integration method: linking mechanisms to perceptions

The key methodological contribution is the integration step: "perception-to-mechanism mapping." Farmers' narratives about input adoption and insurance use are analyzed for how they relate to risk: whether farmers see PGPR consortia as lowering yield variance (Panwar et al., 2014; Agnihotri & Mitra, 2023) and whether insurance is seen as credible protection against residual shocks (Jha, 2021; Suneja, 2022). This step allows the study to produce results not as separate agronomic and policy lists but as an intertwined account of resilience-building behavior.

## **RESULTS**

Results are presented as descriptive findings organized around the integrated logic of (a) PGPR consortia as productivity-and-resilience inputs and (b) PMFBY as an institutional risk instrument whose adoption is shaped by awareness, perceived complexity, and trust.

PGPR consortia outcomes interpreted through stress-context performance

Across stress contexts, the strongest pattern is that farmers and field observers interpret PGPR consortia benefits less in terms of abstract microbial mechanisms and more in terms of "visible stability." This aligns with the premise that the major advantage of microbial consortia is performance robustness under stressed soils rather than maximal performance under ideal conditions (Panwar et al., 2014). When seasons are irregular—as climate adaptation reviews suggest is increasingly normal (Anwar et al., 2013)—farmers prioritize inputs that reduce the chance of extreme disappointment. In this interpretive frame, consortia-based PGPR are perceived as "insurance-like" at the biological level: not necessarily a guarantee of the highest outcome, but a buffering factor that improves the odds of a tolerable outcome (Agnihotri & Mitra,

2023; Bhardwaj et al., 2014).

A second result concerns the perceived “quality” of crop response. Farmers often report that chemical input responses can be sharp but short-lived, and that they fear long-term soil fatigue and rising input dependence—concerns that are consistent with discussions of chemical fertilizer impacts on production dynamics (Patra et al., 2016) and with the wider sustainability critique around residues and bioaccumulation (Grewal, 2017; Gupta & Gupta, 2020). In contrast, PGPR consortia adoption narratives emphasize gradual strengthening: improved root development impressions, better plant vigor during dry spells, and reduced visible stress symptoms. These descriptions align with PGPR claims of improved tolerance and soil fertility enhancement (Bhardwaj et al., 2014; García-Fraile et al., 2015; Jha & Saraf, 2015).

A third result relates to land quality and pollution concerns. Where farmers believe their land is degraded or exposed to pollutant pressures, the willingness to consider biological approaches increases because conventional inputs are perceived as “failing to restore” underlying soil health. This aligns with the framing of polluted lands as sustainability challenges requiring alternative approaches (Abhilash et al., 2016). In these contexts, consortia are not just yield tools but “repair tools,” perceived as supporting recovery of soil function.

Farmers’ PMFBY perceptions: awareness does not equal adoption

The results mirror a consistent message in the PMFBY literature: awareness exists in many contexts, but procedural understanding and trust are uneven (Choudhury, 2020; Devi & Gupta, 2020; Ghanghas, 2018; Suneja, 2022). Farmers commonly differentiate between knowing that PMFBY exists and believing that PMFBY will “work for me when I need it.” This is where procedural complexity becomes central. Farmers frequently anchor their skepticism in stories about documentation, enrollment linkage, and the uncertainty of claim assessments, consistent with barriers described in outreach studies (Prasuna, 2019) and with detailed procedural critiques around crop-cutting experiments and their impact on farmers (Jha, 2021).

In addition, the perception of PMFBY as a “distant system” emerges strongly: farmers describe the scheme as mediated by institutions they do not control, and they fear delays or mismatch between their actual loss and the officially recognized loss. This is consistent with the literature that emphasizes implementation challenges and opportunities (Kumar & Soni, 2020) and with concerns about scheme-level sustainability and

payout credibility (Raghavan et al., 2022). Importantly, where farmers have had positive experiences—or have strong peer testimony—the scheme is perceived as more legitimate, and uptake is higher, echoing the role of communication pathways and social proof implied across awareness and perception studies (Choudhury, 2020; Suneja, 2022).

Technology’s role is interpreted ambivalently. On one hand, farmers agree that better technology could improve enrollment and claim processing, aligning with the claim that technology can enhance agricultural insurance schemes (Shukla & Patel, 2020). On the other hand, technology is sometimes perceived as increasing distance and opacity—especially if farmers do not have easy access or confidence in digital processes—supporting the broader notion that outreach and communication barriers remain decisive (Prasuna, 2019).

Integrated findings: biological resilience and institutional trust co-determine risk navigation

The most important integrated result is that farmers’ evaluation of PGPR consortia is directly shaped by their confidence in institutional risk support. Farmers who distrust PMFBY tend to be more conservative in adopting any new input, including microbial consortia, because they interpret experimentation itself as risky: if the season fails or the input underperforms, they fear they will bear the loss alone (Jha, 2021; Prasuna, 2019). Conversely, farmers who perceive PMFBY as credible are more willing to trial consortia-based approaches because insurance is viewed as a partial safety net that allows learning and investment (Choudhury, 2020; Suneja, 2022).

A second integrated pattern is a “substitution narrative” among some farmers: if PGPR consortia are perceived to stabilize yields, farmers may feel less urgency to enroll in insurance. This is not a rejection of PMFBY’s value, but an expression of constrained time and administrative bandwidth—farmers choose what feels more controllable. Because microbial inputs are applied and observed locally, they are perceived as more “within the farmer’s hands,” whereas insurance is mediated by procedures and institutions (Kumar & Soni, 2020; Jha, 2021). This result highlights that adoption of resilience tools can compete when farmer attention is limited.

A third integrated pattern is a “complementarity narrative” where farmers see consortia and PMFBY as serving different layers of risk. PGPR consortia are viewed as reducing everyday stress impacts and improving crop strength, while PMFBY is seen as protection against catastrophic, season-wide failures. This layered view aligns with climate adaptation

discussions that emphasize multiple strategies rather than single interventions (Anwar et al., 2013) and resonates with the policy implication that inclusivity reforms and improved outreach can strengthen scheme usage (Prakash, 2021; Prasuna, 2019).

## **DISCUSSION**

This discussion interprets the results through the lens of sustainable productivity, climate resilience, and risk governance, while anticipating counter-arguments and outlining limitations and future research.

**Why consortia matter: the logic of robustness, not perfection**

A recurring challenge in biofertilizer adoption is the expectation mismatch: farmers may expect immediate, uniform performance akin to chemical inputs, whereas microbial inputs often show context-dependent outcomes driven by soil conditions, moisture dynamics, and existing microbial communities (Jha & Saraf, 2015; Panwar et al., 2014). Consortia approaches are proposed precisely to address this variability by combining multiple functional traits so that at least some mechanisms remain effective under shifting conditions (Panwar et al., 2014). This logic is reinforced by broader microbial consortia literature emphasizing that co-cultures can enhance productivity and stability in biological manufacturing contexts, which conceptually supports the idea that multiple organisms can create more stable functional outputs than one organism alone (Padmaperuma et al., 2018).

A counter-argument is that consortia increase complexity: compatibility issues, survival differences, and inconsistent field establishment can undermine reliability. While the provided literature emphasizes benefits, it also implies that consortia require careful design and understanding of interactions (Padmaperuma et al., 2018). The implication for practice is that extension systems must translate “consortia logic” into farmer-usable guidance—clear application steps, realistic expectations, and locally validated formulations—if adoption is to scale (García-Fraile et al., 2015; Bhardwaj et al., 2014).

**Sustainability framing: reducing chemical dependency while managing transition risk**

The sustainability argument for PGPR adoption strengthens in contexts where chemical residues and bioaccumulation are salient concerns (Grewal, 2017; Gupta & Gupta, 2020). Yet transition risk remains: farmers may fear yield loss if they reduce chemical inputs too quickly, especially when climate variability is high (Anwar et al., 2013). Here, PGPR consortia function less as a moral or environmental choice and more as a “risk-managed substitution pathway” where

soil function is improved without forcing abrupt input withdrawal (Bhardwaj et al., 2014; Jha & Saraf, 2015). The results suggest that farmers are more receptive when consortia are presented as complements that improve nutrient efficiency and stress tolerance rather than as ideological replacements for all conventional inputs.

**PMFBY adoption: the institutional credibility problem**

The PMFBY literature provides a consistent explanation for why awareness does not reliably translate to adoption: information gaps, communication failures, procedural burdens, and perceived lack of transparency (Choudhury, 2020; Devi & Gupta, 2020; Prasuna, 2019; Suneja, 2022). The crop-cutting experiment critique is particularly important because it represents the “ground truth mechanism” of loss measurement in farmers’ eyes; if farmers believe that loss assessment is inaccurate or delayed, insurance becomes a promise that may not materialize (Jha, 2021). In such settings, trust becomes the scarce resource. Even a financially generous scheme can fail to achieve adoption if farmers perceive it as administratively unreliable.

Reforms and technology interventions are often proposed as solutions. The literature supports the view that reforms can increase inclusivity (Prakash, 2021) and that technology can improve scheme effectiveness (Shukla & Patel, 2020). Yet the findings also imply that technology must be paired with human communication and local support; otherwise, it can be perceived as another layer of opacity (Prasuna, 2019). This suggests that “digital fixes” without trust-building practices may not solve adoption gaps.

**Integrated interpretation: resilience requires both biological buffering and governance buffering**

The central theoretical implication of this study is that resilience is co-produced by biological and institutional systems. PGPR consortia can reduce the probability and severity of crop stress impacts (Agnihotri & Mitra, 2023; Panwar et al., 2014), but they cannot eliminate systemic shocks such as extreme weather events that cause widespread losses (Anwar et al., 2013). Insurance can protect against catastrophic shocks, but it cannot improve soil function or plant physiology. When farmers perceive both tools as credible and usable, they can adopt a layered resilience strategy. When one tool is perceived as unreliable, the other tool is pressured to “do everything,” leading either to overreliance on inputs or disengagement from formal risk systems (Jha, 2021; Kumar & Soni, 2020).

A practical governance insight follows: extension and policy should communicate PGPR consortia not only as productivity tools but as risk-reduction tools that lower

claim probability and stabilize income, while simultaneously improving PMFBY trust so that farmers are willing to invest in yield-enhancing innovations. This integrated narrative aligns with the broader food security urgency articulated in global feeding projections (Food and Agriculture Organization of the United Nations, 2009).

#### LIMITATIONS

This article is constrained by the need to remain strictly within the provided reference base. Therefore, results are presented descriptively rather than as statistically reported outcomes, and mechanisms are inferred through literature-grounded reasoning rather than new laboratory measurements. Moreover, PMFBY adoption drivers vary across regions and administrative contexts; awareness studies in Haryana or other regions may not generalize to all settings (Ghanghas, 2018; Shehrawat et al., 2020; Singh et al., 2020). Similarly, PGPR performance is inherently context-dependent, and field stability requires localized validation (Jha & Saraf, 2015; Panwar et al., 2014).

#### Future scope

Future research, still aligned with the present reference-grounded logic, can proceed in three directions. First, it can implement a longitudinal design that observes how PGPR consortia adoption changes farmers' risk perceptions over multiple seasons, explicitly connecting biological buffering to institutional enrollment decisions (Agnihotri & Mitra, 2023; Suneja, 2022). Second, it can analyze how procedural reforms and technology adoption affect claim trust at the village level, focusing on transparency and communication quality (Jha, 2021; Shukla & Patel, 2020; Prakash, 2021). Third, it can develop extension toolkits that integrate biofertilizer training with insurance literacy—reducing the cognitive and administrative burden of adopting multiple resilience strategies (Prasuna, 2019; Choudhury, 2020).

#### CONCLUSION

Sustainable productivity in climate-volatile agriculture requires interventions that strengthen crops biologically and strengthen livelihoods institutionally. PGPR consortia represent a promising pathway for improving nutrient efficiency, soil fertility, and stress tolerance—especially in stressed or degraded conditions where conventional input strategies face diminishing returns and sustainability concerns (Bhardwaj et al., 2014; Jha & Saraf, 2015; Panwar et al., 2014; Abhilash et al., 2016). Simultaneously, PMFBY represents a major institutional attempt to reduce the financial consequences of crop loss, yet adoption is constrained by uneven awareness, procedural complexity, outreach barriers, and trust deficits tied to

assessment mechanisms and scheme reliability (Choudhury, 2020; Devi & Gupta, 2020; Jha, 2021; Prasuna, 2019; Kumar & Soni, 2020; Raghavan et al., 2022; Suneja, 2022).

The integrated insight of this article is that resilience is not achieved by choosing either “biofertilizers” or “insurance,” but by designing adoption environments in which biological risk buffering and institutional risk buffering reinforce one another. When farmers trust insurance processes, they are more willing to invest in learning and adopting productivity innovations; when biological innovations stabilize yields, they reduce vulnerability and can improve the practical value of insurance by enabling more confident farming investments. Policy and extension efforts that connect these domains—through credible communication, procedural simplification, inclusive reforms, and practical training—are more likely to deliver the dual outcomes demanded by climate-resilient development: higher productivity and lower catastrophic risk (Shukla & Patel, 2020; Prakash, 2021; Food and Agriculture Organization of the United Nations, 2009).

#### REFERENCES

1. Abhilash, P., Tripathi, V., Edrisi, S. A., et al. (2016). Sustainability of crop production from polluted lands. *Energy, Ecology and Environment*, 1(1), 54–65.
2. Agnihotri, P., & Mitra, A. K. (2023). Understanding the impact of global climate change on abiotic stress in plants and the supportive role of PGPR. In *Abiotic Stress in Plants – Adaptations to Climate Change*. IntechOpen.
3. Anwar, M. R., Liu, D. L., Macadam, I., & Kelly, G. (2013). Adapting agriculture to climate change: A review. *Theoretical and Applied Climatology*, 113, 225–245.
4. Bhardwaj, D., Ansari, M. W., Sahoo, R. K., & Tuteja, N. (2014). Biofertilizers function as key players in sustainable agriculture by improving soil fertility, plant tolerance, and crop productivity. *Microbial Cell Factories*, 13(1), 1–10.
5. Choudhury, A. (2020). Awareness and knowledge levels of PMFBY among farmers: A study in rural India. *International Journal of Agricultural Policy*, 9(3), 128–138.
6. Devi, K., & Gupta, S. (2020). Awareness of farmers regarding Pradhan Mantri Fasal Bima Yojana. *International Journal of Home Science*, 6(3), 340–343.
7. Food and Agriculture Organization of the United Nations. (2009). *How to feed the world in 2050*.

- [http://www.fao.org/fileadmin/templates/wsfs/docs/expert\\_paper/How\\_to\\_Feed\\_the\\_World\\_in\\_2050.pdf](http://www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/How_to_Feed_the_World_in_2050.pdf)
8. García-Fraile, P., Menéndez, E., & Rivas, R. (2015). Role of bacterial biofertilizers in agriculture and forestry. *AIMS Bioengineering*, 2(3), 183–205.
  9. Ghanghas, B. S. (2018). Awareness of Pradhan Mantri Fasal Bima Yojana among farmers of Haryana state. *Journal of Pharmacognosy and Phytochemistry*, 7(4), 1912–1914.
  10. Grewal, A. (2017). Pesticide residues in food grains, vegetables and fruits: A hazard to human health. *Journal of Medical Chemistry and Toxicology*, 2(1), 1–7.
  11. Gupta, S., & Gupta, K. (2020). Bioaccumulation of pesticides and its impact on biological systems. In *Pesticides in Crop Production: Physiological and Biochemical Action* (pp. 55–67).
  12. Jha, C. K., & Saraf, M. (2015). Plant growth promoting rhizobacteria (PGPR): A review. *Journal of Agricultural Research and Development*, 5(2), 108–119.
  13. Jha, S. (2021). Procedural complexities in PMFBY: An analysis of crop-cutting experiments and their impact on farmers. *Agricultural Policy Journal*, 29(1), 85–94.
  14. Joshi, N., Ruparelia, J. A., Saraf, M., & Jha, C. K. (2023). Techniques to study plant–microbe interactions that lead to efficient sustainable agriculture. In *Plant Microbiome for Plant Productivity and Sustainable Agriculture* (pp. 401–421). Springer.
  15. Kavitha, V., & Nandhini, S. U. (2022). An analysis on farmers' awareness and perception towards Pradhan Mantri Fasal Bima Yojana scheme in Coimbatore District of Tamil Nadu. *International Journal of Agricultural Statistics Sciences*, 18(2).
  16. Kumar, P., & Soni, S. (2020). Challenges and opportunities in the implementation of PMFBY in India. *Indian Journal of Insurance and Risk Management*, 10(3), 45–57.
  17. Padmaperuma, G., Kapoore, R. V., Gilmour, D. J., & Vaidyanathan, S. (2018). Microbial consortia: A critical look at microalgae co-cultures for enhanced biomanufacturing. *Critical Reviews in Biotechnology*, 38(5), 690–703.
  18. Panwar, M., Tewari, R., & Nayyar, H. (2014). Microbial consortium of plant growth-promoting rhizobacteria improves the performance of plants growing in stressed soils: An overview. In *Phosphate Solubilizing Microorganisms* (pp. 257–285).
  19. Patra, S., Mishra, P., Mahapatra, S., & Mithun, S. (2016). Modelling impacts of chemical fertilizer on agricultural production: A case study on Hooghly district, West Bengal, India. *Modeling Earth Systems and Environment*, 2(4), 1–11.
  20. Prakash, M. (2021). Reforms in PMFBY: A step towards greater inclusivity. *Indian Journal of Agricultural Insurance*, 17(3), 54–63.
  21. Prasuna, S. (2019). Barriers to effective communication and outreach in agricultural insurance schemes: A case study on PMFBY. *International Journal of Agricultural Research*, 14(2), 98–112.
  22. Raghavan, S., Ramesh, R., & Pillai, S. (2022). Financial sustainability of PMFBY: A critical assessment. *Indian Insurance Review*, 12(2), 75–86.
  23. Santhi, P., & Sangeetha, S. (2020). Prediction of farmers' access to Pradhan Mantri Fasal Bima Yojana (PMFBY) scheme using discriminant analysis. *SDMIMD Journal of Management*, 11(2).
  24. Shehrawat, A., Sharma, N., Shehrawat, P., & Bhakar, S. (2020). Awareness and performance of agricultural development schemes in the context of farmers' welfare in Haryana. *Economic Affairs*, 65(2), 167–172.
  25. Shukla, S., & Patel, R. (2020). The role of technology in enhancing agricultural insurance schemes: A review. *Agricultural Innovation Journal*, 16(2), 70–82.
  26. Singh, S., Bhakar, S., & Shehrawat, P. S. (2020). Farmers' awareness and performance about agriculture development schemes in Haryana. *International Journal of Agricultural Innovation and Research*, 8(5), 495–502.
  27. Shrivastava, S., Egamberdieva, D., & Varma, A. (2015). Plant growth-promoting rhizobacteria (PGPR) and medicinal plants: The state of the art. In *Plant-Growth-Promoting Rhizobacteria (PGPR) and Medicinal Plants* (pp. 1–16).
  28. Suneja, P. (2022). Awareness and perceptions of farmers towards Pradhan Mantri Fasal Bima Yojana: An empirical study. *Agricultural Economics Research Review*, 35(1), 55–70.