Biofilm biofertilizer for climate-resilient rice cultivation: A strategic review of emerging Indonesia–Australia collaboration

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Abstract. Rice farming in Asia is under mounting pressure from drought, salinity, and declining soil health, all of which are intensified by climate change. Biofilm biofertilizer (BB), a microbial technology that embeds beneficial bacteria within biofilm structures, offers a promising solution to enhance plant growth and resilience in paddy fields. This literature review is based on references accessed through Science Direct, Google Scholar, Scopus, and other academic sources. Findings reveal that biofilm biofertilizers can increase rice yields while improving crop performance under water-limited conditions. Beyond yield gains, adoption of BB is strengthened when farmers are actively involved, supported by bilingual training materials and institutional backing. Practical strategies such as farmer field schools and policy-aligned proposals are recommended to ensure effective implementation. In Indonesia, efforts to build climate-resilient agriculture highlight the importance of international collaboration. Emerging partnerships with Australia are identified as strategic opportunities, combining shared scientific goals with community-based approaches. This article underscores the potential of biofilm biofertilizers not only to improve rice production but also to foster long-term cooperation for sustainable agricultural development across the region.

1 Introduction

Rice serves as the primary food source for billions of people across Asia, including a large population in Indonesia. Demand for this crop is expected to rise sharply in the coming years. Yet, rice cultivation in the region is increasingly challenged by the impacts of climate change. Environmental stresses such as drought, flooding, soil salinity, and declining fertility, along

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with new biological pressures from evolving pests and pathogens, pose serious risks to stable production. Agricultural systems throughout Asia are under mounting strain from climate shifts and resource depletion, which could lead to significant drops in output over the next decades. In some areas, such as Java, rice yields are projected to decline dramatically. Given rice's central role in food security, these trends underscore the urgent need for sustainable farming strategies that can boost productivity while strengthening resilience to climate change.

Biofilm biofertilizer is an environmentally friendly plant nutrition technology that harnesses beneficial microbes to improve nutrient availability and stimulate the production of growth-promoting phytohormones. These microbes, such as *Azospirillum, Bacillus, Rhizobium*, Plant Growth Promoting Rhizobacteria (PGPR), and *Cyanobacteria* form resilient colonies within a biofilm matrix. This structure not only shields them from environmental stresses but also supports nitrogen fixation, phosphate solubilization, and the secretion of phytohormones that enhance plant growth and root development. Applications of biofilm biofertilizers have been shown to boost rice yields and increase nitrogen fertilizer efficiency compared with conventional practices. Beyond yield gains, they strengthen soil health by stimulating microbial activity and nutrient cycling, which sustains long-term productivity while reducing greenhouse gas emissions from excessive chemical fertilizer use. As a result, biofilm biofertilizer stands out as a sustainable agricultural innovation and a vital strategy for climate mitigation and adaptation in the food sector [1].

Advancing biofilm-based biofertilizers calls for integrated, cross-regional collaboration that unites microbial diversity, advanced formulation technologies, and rigorous field validation. Indonesia and Australia illustrate a complementary partnership model in this effort. Indonesia contributes abundant tropical microbial resources and extensive rice cultivation systems that serve as practical testing grounds, while Australia offers expertise in molecular biotechnology, biofilm engineering, and globally recognized research infrastructure [2]. Although rice is not a dominant crop in Australia, its agricultural regions face challenges such as drought, salinity, and nutrient deficiencies, making biofilm biofertilizers equally relevant for key commodities like wheat, barley, and pulses in water-limited environments. Joint development initiatives create mutual advantages: Indonesia gains access to advanced tools for optimizing microbial formulations, while Australia benefits from expanded commercialization pathways and strengthened food security cooperation across the Indo-Pacific. Together, these assets enable the creation and scaling of adaptive biofertilizers that enhance climate resilience in both tropical and semi-arid farming systems [3].

This paper presents a comprehensive and systematic review of biofilm biofertilizer research, with a particular focus on enhancing climate resilience in rice cultivation and examining opportunities for scientific collaboration between Indonesia and Australia. It introduces a conceptual framework that integrates microbiological science, sustainable agricultural policy, the mechanisms by which biofilm biofertilizers contribute to climate resilience, and strategies for strengthening research capacity to accelerate translational innovation. The findings aim to guide policymakers, researchers, and practitioners in advancing biofertilizer research and promoting its adoption for climate-resilient rice production across the Asia–Pacific region

2 Materials and Methods

The foundation of this paper's content and methodology lies in an extensive review of relevant literature. The research was carried out comprehensively by examining numerous studies and review articles published in reputable international journals. Reference materials were gathered using databases such as Google Scholar, ScienceDirect, Scopus, and other online journal repositories, employing keywords including “biofilm biofertilizer,” “climate resilience,” “paddy fields,” and “biofilm”, etc.

3 Result and Discussion

3.1 Fundamental Concept Biofilm in Australia and Biofertilizer in Indonesia

In Indonesia, biofertilizer development is closely aligned with national agricultural priorities, particularly the need to sustain productivity in tropical ecosystems while reducing reliance on chemical inputs [4]. Derived from microbial innovations, biofertilizers harness the country’s rich soil biodiversity to enhance nutrient cycling, plant growth, and soil health. Beyond substituting chemical fertilizers, they function as strategic tools to mitigate land degradation, lower greenhouse gas emissions, and promote sustainable farming. Recent studies also show that integrating microbial fuel cells with fertilization can boost soil nitrogen and suppress denitrification in lowland rice fields [5].

Evidence from Indonesia demonstrates that biofertilizers improve rice growth and yield while fostering environmentally sustainable practices [4]. By utilizing native microbial consortia, including biofilm-forming bacteria, they are tailored to diverse tropical agroecosystems and help crops withstand stresses such as drought, flooding, and salinity [6]. Research and development efforts aim to embed biofertilizers into national agricultural programs, reducing dependence on imported chemical fertilizers and advancing food security and climate resilience. This framework reflects Indonesia’s commitment to positioning biofertilizers as a sustainable innovation that bridges microbial biodiversity with practical agricultural applications.

In contrast, Australia’s biofilm research is primarily rooted in health sciences, where biofilms are often viewed as problematic due to their role in shielding pathogenic microorganisms from immune responses and antimicrobial treatments [7]. This has driven intensive molecular and clinical investigations into biofilm formation, quorum sensing, and microbial resistance. Biofilms are recognized as major contributors to chronic infections and hospital-acquired diseases, particularly in association with medical devices such as catheters and implants. Consequently, Australian research emphasizes antibiofilm strategies, including novel biomaterials, nanotechnology, and therapeutic agents designed to disrupt biofilm integrity.

Supported by advanced biotechnology platforms and internationally standardized infrastructure, Australia has developed robust in vitro and in vivo models to study pathogenic biofilms, strengthening translational research in medical microbiology. While biofilms are largely framed as a health challenge in Australia, this orientation underscores the country’s strength in molecular biotechnology and biomedical innovation. Together with Indonesia’s agricultural focus, these complementary perspectives provide a strong foundation for interdisciplinary collaboration. Integrating Australia’s biomedical expertise with Indonesia’s agroecological applications can generate adaptive biofilm technologies that address both clinical and agricultural challenges across the Asia–Pacific region.

3.2 Fundamental Concept and Development of Biofilm Biofertilizer

The concept of biofilm biofertilizers represents a breakthrough in agricultural biotechnology, employing microbial communities embedded within an extracellular polymeric substance (EPS) matrix rather than relying on single-cell inoculants. These multicellular consortia are more resilient to environmental stresses such as drought, temperature extremes, and pH fluctuations, while the biofilm structure itself creates a stable microenvironment that supports microbial communication and protection. Within rice-based systems of Southeast Asia, this structural advantage enhances durability and adaptability under variable climatic conditions.

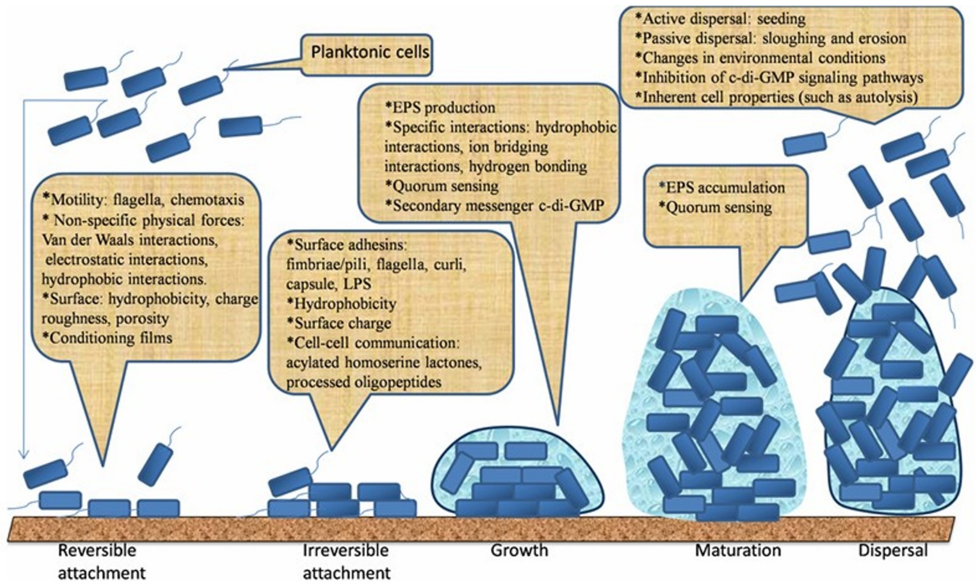

Fig. 1. The developmental stages of bacterial biofilm formation [8].

This schematic illustrates the five-step lifecycle of a biofilm, transitioning from planktonic cells to a mature community and finally to dispersal (Fig. 1). The process initiates with reversible attachment, where free-floating planktonic cells approach a surface, facilitated by motility (flagella) and non-specific physical forces such as Van der Waals and electrostatic interactions. This stage progresses to irreversible attachment, characterized by strong adhesion via surface structures (fimbriae, pili, and capsules) and the onset of cell-cell communication.

Subsequent phases involve growth and maturation, driven by the production of Extracellular Polymeric Substances (EPS) and regulated by signaling mechanisms like Quorum Sensing and the secondary messenger c-di-GMP. These processes result in a structured, multi-layered biofilm matrix. The cycle concludes with dispersal, where bacteria detach from the biofilm through active seeding or passive erosion, reverting to the planktonic state to colonize new environments [8].

Biofilm formation arises from synergistic interactions among diverse microbial groups: *Azospirillum* contributes nitrogen fixation and phytohormone production; Plant Growth-Promoting Rhizobacteria (PGPR) like *Bacillus, Pseudomonas, and Rhizobium* strengthen the biofilm matrix through polysaccharides and adhesive proteins; *Arbuscular Mycorrhizal Fungi* (AMF) expand hyphal networks for nutrient uptake; and *cyanobacteria* provide nitrogen fixation and exopolysaccharides that stabilize flooded paddy soils. Together, these organisms form a multifunctional consortium that sustains efficiency across diverse conditions.

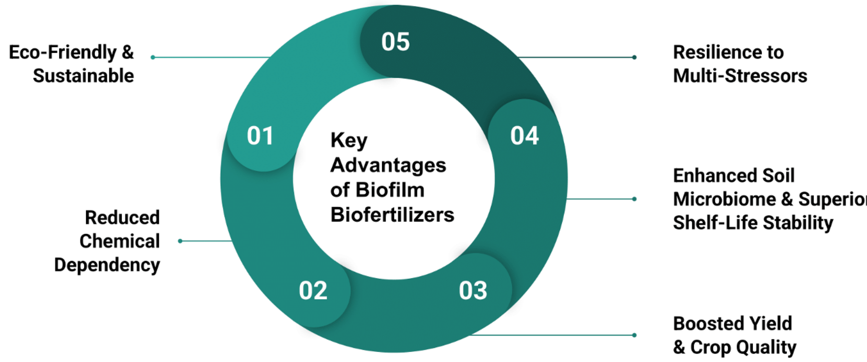

Fig. 2. Illustrates the multifaceted benefits of Biofilm Biofertilizers in sustainable agriculture. Central to its application is its role as an environmentally friendly alternative that significantly reduces the dependency on synthetic chemical fertilizers.

Functionally, biofilm biofertilizers operate through biostimulation (enhancing growth via hormones and enzymes), biofertilization (improving nutrient bioavailability), and bioprotection (shielding plants from pathogens and abiotic stress) (Fig. 2). The EPS matrix further aids soil aggregation and water retention. Importantly, empirical studies show that biofilm biofertilizers can boost rice yields by 10–30% while reducing synthetic nitrogen fertilizer use by up to 50%, making them a cornerstone of climate-smart agriculture. This innovation is particularly strategic for Indonesia and Australia, where microbial diversity and biotechnological expertise converge to develop sustainable, adaptive solutions for climate-resilient rice production across the Asia–Pacific.

Beyond environmental safety, these biofertilizers improve the agronomic potential of crops by enhancing plant growth and overall crop quality. Simultaneously, they bolster the plant's defense mechanisms, offering increased resistance against multi-stress conditions (such as drought, salinity, or pathogens). At the rhizosphere level, the application serves to increase soil microbial activity, restoring soil health. Furthermore, due to the protective nature of biofilms, these products exhibit a longer shelf life compared to conventional liquid biofertilizers, ensuring better stability and viability during storage.

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3.3 Biofilm Biofertilizer in the Climate Resilience

Empirical studies confirm that biofilm biofertilizers significantly optimize rice productivity and water efficiency by retaining root-zone moisture. In Asia, formulations utilizing bacteria like *Azospirillum* have successfully boosted yields by 15–35% while curbing irrigation needs by 20–30%. This surge in productivity is underpinned by microbial activity within the biofilm, which accelerates Nitrogen and Phosphorus availability, stimulates root branching, and prolongs the photosynthetic period. Consequently, this enhanced natural nutrient supply reduces the need for synthetic inputs, as evidenced in Sri Lanka, where biofilm treatments allowed for a 34% reduction in chemical fertilizer use compared to standard recommendations [9,10].

Beyond yield gains, biofilm biofertilizers serve as both adaptation and mitigation tools. They bolster plant tolerance to heat, drought, and salinity through microbial production of osmoprotectants and antioxidants, while simultaneously reducing reliance on synthetic nitrogen fertilizers. This dual role enhances soil organic carbon stability, curbs greenhouse gas emissions such as N_2O and CO_2, and improves soil health. Biological nitrogen fixation combined with greater nutrient-use efficiency helps lower the carbon footprint while simultaneously enhancing soil health through increased organic carbon content. Once incorporated into microbial biomass, this organic carbon becomes more stable, leading to reduced soil respiration and lower CO_2 emissions.

Case studies across Asia highlight their adaptability: in Indonesia, a Bacillus subtilis–*Azospirillum brasilense* consortium raised rice yields by 28%; in China, Cyanobacteria–PGPR biofilms increased soil nitrogen and reduced methane emissions; in Vietnam, endophytic biofilms improved flood and salinity tolerance; and in Japan, biofilm–biochar integration boosted nitrogen-use efficiency by 40%.These examples demonstrate that biofilm biofertilizers can be tailored to diverse agroecological conditions, making them a versatile solution for sustainable rice production.

Applications are particularly promising for marginal and coastal lands affected by salinity. Salt-tolerant microbes such as *Halomonas* and *Azotobacter chroococcum* maintain nitrogen uptake under saline stress, with exopolysaccharide (EPS) production helping retain hydration and protect microbial cells. In Indonesia and northern Australia, biofilm systems are being explored to rehabilitate coastal agroecosystems, restore soil fertility, and strengthen community resilience. Collectively, biofilm biofertilizers represent a sustainable innovation that boosts rice productivity and resource efficiency while supporting climate-resilient agriculture across tropical regions of the Asia–Pacific.

3.4 Biofilm Biofertilizer for Sustainable Development Goals

Biofilm-based biofertilizers represent an innovative pathway for advancing global goals such as ending hunger and promoting sustainable agriculture (SGDs point 2). Ensuring food security requires sustained improvements in crop productivity to meet future demand, and biofilm biofertilizers provide an environmentally sound solution. By employing microbial consortia capable of forming biofilms, these formulations enhance nutrient availability, enrich soil fertility, and strengthen crop resilience to stresses such as drought and salinity. Their application reduces dependence on chemical fertilizers, lowering production costs and supporting smallholder farmers in tropical regions. Ultimately, biofilm biofertilizers stabilize yields and promote sustainable agricultural productivity, contributing directly to efforts to secure adequate and nutritious food supplies.

Beyond food security, biofilm biofertilizers also advance climate action (SGDs point 13). By minimizing excessive chemical inputs, they mitigate greenhouse gas emissions—including carbon dioxide, methane, and nitrous oxide—linked to fertilizer production and use, while simultaneously reducing soil degradation and biodiversity loss [11]. These biofertilizers foster beneficial microbial communities around plant roots, improving nutrient uptake, soil structure, and water retention. Such benefits strengthen plant resilience to drought, flooding, and temperature fluctuations, thereby reducing climate change impacts on crop productivity [12]. In addition to stabilizing yields, they lessen reliance on synthetic fertilizers, lower emissions, and contribute to global climate action.

They also support the protection of terrestrial ecosystems by safeguarding soil health and limiting degradation caused by intensive tillage and heavy chemical inputs (SGDs point 15). By reducing agricultural waste, they minimize the ecological footprint of conventional practices, particularly their adverse effects on soil and water systems. Microbial biofilms play a central role in sustainable agriculture by enhancing plant health and improving soil quality. Their application optimizes microbial communities, shifting them toward functional groups that assemble into multispecies biofilms beneficial to crops. Through the formation of stable soil aggregates, biofilms reinforce soil structure, regulate nutrient availability, stabilize organic matter, and improve water retention [13]. These interactions not only boost crop productivity but also secure long-term soil fertility and ecosystem stability.

The biofilm matrix further protects beneficial microbes, enabling effective colonization of plant roots and restoration of ecological balance in degraded soils. This dual role enhances ecosystem services, conserves microbial and soil biodiversity, and strengthens the adaptive capacity of agroecosystems under climate stress. Thus, biofilm biofertilizers serve as a strategic innovation that integrates agricultural productivity with climate resilience and environmental conservation, contributing holistically to sustainable development.

3.5 Farmer Involvement and Technology Transfer

The success of biofilm biofertilizers in climate-resilient agriculture depends not only on technological innovation but also on farmer engagement and acceptance. Adoption is influenced by factors such as technical training, effective communication, and strong local partnerships. Field-based, hands-on training has proven more effective than traditional extension methods, as it allows farmers to directly observe improvements in crop growth and yield. Clear communication is particularly important in Indonesia–Australia collaborations, where translating scientific concepts into accessible local language enhances knowledge transfer. Partnerships with farmer cooperatives, women's farming groups, and village agricultural extension centres are also vital for ensuring widespread distribution and use within communities.

The Climate Field School model offers a practical approach to strengthening farmers' capacity to adopt biofilm biofertilizers. Through participatory learning, farmers evolve from users to co-innovators, adapting technologies to local conditions. Integrated with Participatory Technology Development initiatives led by CSIRO and Indonesian universities, this model encourages simple field trials, supports monitoring of outcomes, and promotes peer-to-peer dissemination. Beyond technical skills, participatory programmes foster ownership, confidence, and trust in new technologies, which are essential for long-term adoption at the grassroots level.

Embedding biofilm biofertilizers into national agricultural policies represents a strategic step toward advancing green innovation in the food sector [13]. In Indonesia, the technology aligns with the National Action Plan for Sustainable Agriculture and the Climate Change Adaptation Strategy, both of which emphasize reducing chemical fertilizer use and improving nutrient efficiency. It also contributes to the Low Carbon Development Initiative by lowering nitrous oxide emissions from paddy fields. In Australia, programmes such as the Future Drought Fund and the Sustainable Agriculture Strategy 2025 support the integration of tropical biofertilizer research through collaboration with Indonesian institutions. Establishing a bilateral Biofertilizer Innovation Centre would provide a hub for research and farmer support in implementing low-emission technologies. Together, inclusive policies, collaborative research, and participatory technology transfer empower farmers as agents of change in building sustainable and climate-resilient agriculture, particularly across tropical regions of Indonesia and northern Australia.

3.6 Opportunities and Challenges in Indonesia–Australia Collaboration

The collaboration between Indonesia and Australia in developing biofilm biofertilizers holds strategic importance across ecological, scientific, and economic dimensions. Both countries share tropical and subtropical ecosystems that face similar challenges, including soil degradation, rainfall variability, and the impacts of climate change on food production. Indonesia, with its agrarian economy and high food demand, requires biotechnological innovations to enhance productivity in its extensive rice fields while ensuring environmental sustainability. Biofilm biofertilizers can be applied not only to paddy but also to other staple crops such as maize and wheat, offering adaptability to Australian conditions. Notably, maize recorded the highest yield increase of 43.11% when inorganic fertilizer was combined with biochar, organic fertilizer, and phosphate-solubilizing bacteria, an integrated approach that also boosted bacterial populations and soil respiration, highlighting the broader benefits of biofilm biofertilizers for soil health and crop productivity [14]. Australia contributes advanced expertise in microbial technology, industrial bioprocessing, and molecular biofilm research, providing a strong scientific foundation for adaptive biofertilizer formulations. The integration of Indonesia's microbial diversity with Australia's technological capabilities creates opportunities for context-specific solutions tailored to Asia–Pacific agroecological conditions.

Bilateral cooperation enables the development of adaptive microbial consortia incorporating tropical strains alongside nano-biofilm technologies and controlled-release systems. Joint funding initiatives from institutions in both countries can support sustainable production models suited to regional climates. Collaborative activities—including scientist exchanges, technician training, and joint field trials in Indonesia's tropical lowlands and Australia's semi-arid zones—facilitate reciprocal technology transfer and promote innovation. This partnership also supports research-based commercialization, encouraging adoption of biofilm innovations by eco-friendly fertilizer industries and agritech start-ups.

A major opportunity lies in establishing an Asia–Pacific Biofertilizer Research Network to promote cross-country knowledge exchange. Institutions such as IPB University and CSIRO Agriculture & Food, supported by international organizations, are well positioned to lead this initiativeM. Such a network would strengthen Indonesia–Australia research outcomes, enhance climate-resilient agriculture in tropical and subtropical regions, and reinforce science diplomacy and regional food security. Persistent barriers include differences in research infrastructure, biosafety regulations, and funding mechanisms, as well as limited skilled personnel in microbial biotechnology and biofilm formulation. Addressing these challenges requires long-term capacity-building and effective translation of laboratory research into policy and field applications through participatory engagement with farmers and private stakeholders.

3.7 Future Research Direction

Future research on biofilm biofertilizers should prioritize the development of multi-strain, site-specific microbial formulations tailored to tropical and subtropical agroecosystems. These formulations integrate functional microorganisms such as Azospirillum, Rhizobium, Bacillus, and cyanobacteria, which work synergistically within a unified biofilm matrix. Research must also advance eco-physiological and adaptive genomic strategies to ensure microbial compatibility with diverse soil types, climatic conditions, and rice varieties. Collaboration between Indonesia and Australia can strengthen biodiversity-based formulations by applying microencapsulation and biofilm engineering technologies, leading to durable, stable, and efficient biofertilizer products suited to varied agroclimatic zones.

Another promising direction involves the integration of nano-biofilm biofertilizers into organic farming and sustainable agroforestry systems. Nanomaterials are increasingly utilized in the fields of health, industry, environment, and agriculture, where nanotechnology is applied in fertilizers, pesticides, seed treatments, as well as more efficient detection and delivery systems [15]. This technology supports agricultural mechanization, economic growth, and environmental sustainability, while nanoparticles hold potential for controlling plant pathogens, thereby promoting organic farming and soil sustainability. Nano-biofilm biofertilizers combine the controlled-release and efficiency advantages of nanotechnology with the ecological benefits of microbial biofilms, enhancing nutrient availability, improving soil structure, minimizing pollution, and fostering synergistic interactions in agroforestry systems. Long-term field trials across Indonesia and Australia will provide empirical evidence on ecological and economic impacts, including contributions to carbon credits and environmental incentives in low-emission agricultural systems. Future research must adopt transdisciplinary approaches that integrate microbiology, nanotechnology, agrotechnology, socioeconomics, and policy frameworks to accelerate the transition toward microbe-based sustainable agriculture.

Artificial intelligence can be applied to analyze publication patterns, international collaborations, and research gaps, while knowledge mapping systems can support policy formulation through shared data platforms between Indonesian and Australian institutions. This initiative will enhance the global visibility of Indonesia–Australia research and accelerate evidence-based innovation in sustainable agriculture. Ultimately, the future research landscape of biofilm biofertilizers requires interdisciplinary collaboration across nations and ecosystems. By integrating microbial biotechnology, adaptive agricultural systems, and transformative policy frameworks, Indonesia and Australia can position themselves as global leaders in tropical biofertilizer development, strengthening climate-resilient agriculture and food security across the Asia–Pacific region.

4 Conclusion

Scientifically, biofilm biofertilizers have demonstrated strong potential as adaptive solutions to climate change in rice cultivation and broader tropical agriculture. They enhance nutrient efficiency, biological nitrogen fixation, and plant tolerance to environmental stress, while also supporting climate change mitigation by lowering N_2O emissions, improving soil structure, and promoting low-carbon farming systems. Collaboration between Indonesia and Australia integrating Indonesia's microbial diversity with Australia's biotechnology expertise, offers a strategic pathway to develop adaptive and competitive biofilm formulations suited to tropical and subtropical agroecosystems. Such cooperation can drive innovation, strengthen regional food security, and advance climate adaptation. To accelerate progress, supportive green innovation policies, farmer-centered training, and interdisciplinary research integration are essential. Strengthening these areas will help transform agriculture into a productive, efficient, and sustainable system capable of meeting global challenges posed by climate change.

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