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Revealing the Crucial Role and Future Prospects of Biofertilizers for Improving Soil Health and Crop Productivity in Eco-Friendly Sustainable Agriculture in Indonesia

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ABSTRACT

Agricultural intensification in Indonesia has largely depended on inorganic fertilizers to meet the food demands of its rapidly growing population. However, this reliance has resulted in severe environmental challenges including soil degradation, diminished soil fertility, and pollution from chemical fertilizers. Biofertilizers, which utilize beneficial microorganisms to promote plant growth and soil health, offer a sustainable alternative for agriculture. This article presents a comprehensive overview of biofertilizers in Indonesia, through bibliometric analysis and literature review examining their development, current status, and effectiveness. It categorizes different types of biofertilizers, such as nitrogen-fixing bacteria, phosphate-solubilizing microorganisms, mycorrhizal fungi, water fern Azolla, plant growth promoting rhizobacteria, and biofertilizers, based on local knowledge, assessing their role in improving soil health and crop productivity. The review highlights that biofertilizers enhance soil properties by increasing nutrient availability, organic matter content, and microbial activity. Studies show that crops treated with biofertilizers demonstrate better growth, higher yields, and greater resilience to stress compared to those reliant on chemical fertilizers. The use of microorganisms like Azospirillum, Rhizobium, Bacillus, and Pseudomonas has significantly improved soil nitrogen and phosphorus levels, contributing to better root development and plant health. Despite these advantages, the adoption of biofertilizers in Indonesia is hindered by challenges such as inconsistent results in the field, limited farmer awareness, and inadequate infrastructure for production and distribution. To address these barriers, the article suggests strategies including farmer education, the development of region-specific strains, and inclusive government policies. It also underscores the importance of enhancing research and development as well as improving distribution networks to ensure the quality and accessibility. In conclusion, biofertilizers have substantial role to support eco-friendly sustainable agriculture in Indonesia. By addressing current obstacles through targeted interventions,widespread adoption can be achieved, leading to improved soil health, higher crop productivity, and reduced environmental impact,—the key factors for ensuring long-term agricultural sustainability and food security in Indonesia.

Keywords: bibliometric, biofertilizers, future prospect, policy, soil health

INTRODUCTION

Increasing food production through intensification that relies on the use of inorganic fertilizers and various chemicals has become a solution to meet the rising food demands in Indonesia. Since the Green Revolution in the 1960s, intensification programs have significantly increased crop productivity. However, they have also led to a decline in soil health and fertility. Agricultural intensification continues to be driven by the need to meet the increasing food demands of the growing population (Simarmata 2013). Indonesia's population in 2024 has reached approximately 280 million people, with a growth rate of about 1.28 % per year and a doubling time of around 35-40 years. This means that by 2050, Indonesia's population is projected to reach 400-450 million people, with a rice consumption rate of about 100-125 kg per capita per year (UNFPA Indonesia 2018). On the other hand, agricultural land is experiencing a gradual reduction due to the conversion of farmland for other uses (roads, housing, and other infrastructure), estimated at around 125,000-150,000 hectares per year, which makes agriculture even more intensive. The rate of agricultural land conversion to non-agricultural uses, based on data from the Central Statistics Agency of Indonesia, for the period 1998-2002, was 110,000 hectares per year (Mulyani *et al*., 2016; UNFPA Indonesia 2018).

Intensive agricultural fertilization relying on chemical fertilizers accelerates the decomposition of soil organic matter, reduces organic carbon content, and diminishes soil health and quality. Recent research indicates that agricultural soils worldwide are becoming exhausted and are classified as "sick soils," with organic carbon content less than 1.5%. Approximately 90% of the 70 million hectares of agricultural land has significantly degraded and is categorized as sick and fatigued soils (Goud *et al*., 2022). Additionally, around 70% of paddy fields (about 7.4 million hectares) have low organic carbon content, 22% have moderate organic carbon content, and 4% have high organic carbon content (Simarmata *et al*., 2018). As a result, the decline in soil health and quality threatens food availability and poses a potential disaster for human life. Furthermore, global warming has exacerbated these issues, leading to decreased agricultural productivity, increased pest and disease outbreaks, shifting seasons, salinization, and the loss of agricultural land due to rising sea levels (The World Bank Group and Asian Development Bank 2021; Simarmata *et al*., 2023).

The adoption of eco-friendly and sustainable agriculture based on biofertilizers and organic fertilizers is essential for the recovery and sustainable enhancement of soil and agricultural productivity (Simarmata *et al.,* 2023). The key characteristics include efficient resource management, environmentally friendly agricultural practices, minimizing chemical use, sustainable soil management, renewable energy and energy efficiency, and social and economic well-being (Simarmata *et al*., 2023).

Biofertilizers play a crucial role in (1) enhancing and facilitating nutrient availability, (2) improving and increasing soil health, (3) reducing or substituting the use of inorganic fertilizers, and (4) boosting plant health and productivity. Biofertilizers can generally be defined as preparations containing live or latent cells capable of efficient nitrogen-fixation, phosphate-solubilization, or cellulolytic mechanisms for application to seeds, soil, or composting areas with the objective of increasing the number of such microorganisms and accelerating those microbial processes that augment the availability of nutrients that can be easily assimilated by plants (Simarmata 2013; Abioye *et al*., 2024). Biofertilizers in liquid or solid form can mobilize, facilitate, and increase the availability of nutrients (Simarmata 2013; Barin *et al*., 2022). Biofertilizers that have high potential for integrated organic-based agriculture include: N-fixers, P-solubilizing microbes, K-solubilizing microbes, phytohormone-producing microbes (plant growth-promoting rhizobacteria), organic matter decomposers, mycorrhizal fungi and microbes acting as biocontrol agents (Haryantini *et al*., 2019; Ji *et al*., 2020; Shi *et al*., 2023)**.**

The latest studies reveal that the use of nitrogen-fixing biofertilizers can supply 25-75% of a plant's nitrogen needs (Rehmaan *et al*., 2022). Symbiotic nitrogen-fixing bacteria that form nodules can reduce the use of inorganic fertilizers by approximately 75-90%, while non-symbiotic ones generally reduce it by around 25% (Langenfeld *et al*., 2021). Phosphate-solubilizing microbes can enhance fertilizer efficiency by about 25% (Khumairah *et al*., 2022). Plant growth promoting rhizobacteria (PGPR) biofertilizers not only increase nutrient availability for plants but also act as bioprotectors, improving both soil and plant health (Kloepper *et al*., 1980; Vessey 2003; Harahap *et al*., 2023). The use of biofertilizers can significantly increase nitrogen availability and reduce the use of nitrogen fertilizers**.** Additionally, Azolla is an inexpensive green manure that is widely available and can be used in large quantities. Azolla extract can be produced and enriched using beneficial microbes (biofertilizers agent or bioagent) and applied as liquid foliar biofertilizers (Setiawati *et al.*, 2018; Prayoga *et al*., 2021).

The primary aims of this systematic literature review (SLR) and bibliometric analysis are to comprehensively assess and reveal: (1) the history of biofertilizer development, current status of biofertilizer technology, and various groups of biofertilizers in Indonesia, (2) the performance of biofertilizers in improving soil health, plant growth, and productivity, (3) strategies for mainstreaming biofertilizers, and (4) the challenges and prospects of biofertilizers in promoting eco-friendly sustainable agriculture.

METHODOLOGY

Data retrieval for bibliometric analysis

Data for this bibliometric analysis F were collected from Scopus database. The search terms and combinations used were "biofertilizer”, “soil”, “plant”, “sustainable”, “agriculture”, “bacteria”, “fungi”, “azolla”, “algae”, “pgpr”, “local”, and “microorganism”. The search was limited to research articles published from 2020-2024. Language of publication was limited to English. The detailed search strategy is outlined in Table 1. The bibliographic information from the search results was exported in RIS format and analyzed using VOSviewer 1.6.19. The occurrence term was set to 50 obtaining 128 terms for visualization.

Table 1. Search strategies used to retrieve relevant research articles

Search Strategies	Scopus
biofertilizer AND soil	716
biofertilizer AND plant	970
biofertilizer AND sustainable AND agriculture	146
biofertilizer AND bacteria	397
biofertilizer AND fungi	240
biofertilizer AND azolla	11
biofertilizer AND algae	38
biofertilizer AND pgpr	118
biofertilizer AND local AND microorganism	8
Total data retrieved from Scopus database	2,644

Systematic literature review using PRISMA

Data obtained from Scopus were evaluated following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow guidelines or through a Systematic Literature Review (see Figure 1). Duplicates were removed using Mendeley Reference Manager version 2.107.0. The eligibility of the included documents was determined based on the relevance of their abstracts to the article's topic. Irrelevant documents were classified as ineligible and excluded from further content analysis.

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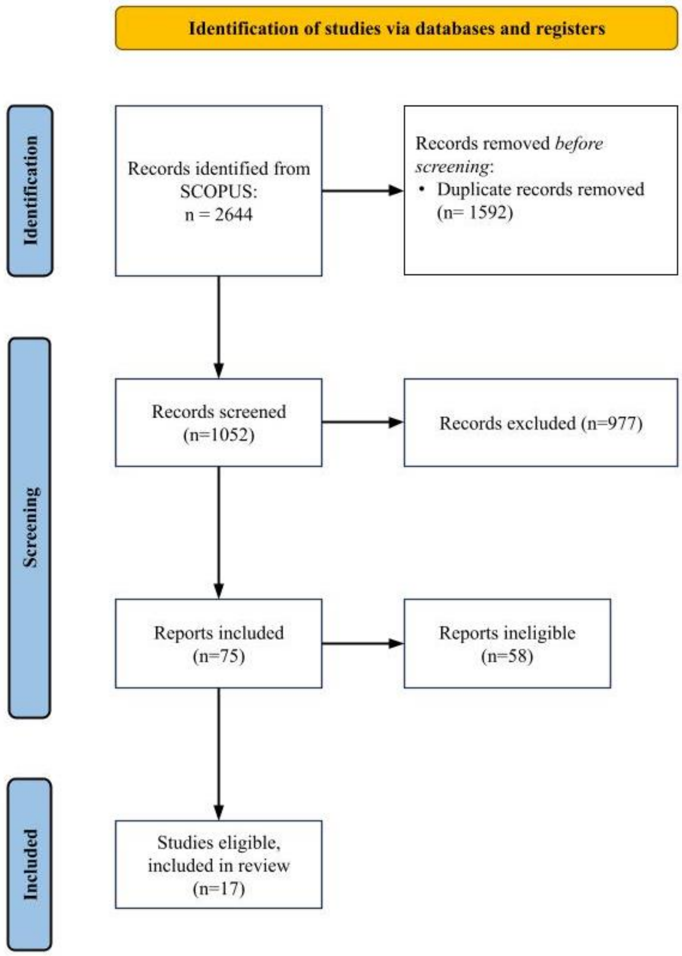

Figure 1. PRISMA flowchart reporting the article selection process for the systematic literature review

RESULTS AND DISCUSSION

Bibliometric analysis by VOSviewer

Bibliometric data analysis was done using VOSviewer to assign developing themes of study and research trends during the last five years. The mapping of document keywords through visual aids, such as binary counting, to show their co-occurrence. To find 128 key keywords using a variety of search techniques, the minimum co-occurrence of the document keywords in the research articles was set at 50. These important terms paint a fairly accurate picture of the paths taken by scientists studying biofertilizers for sustainable agriculture.

A stark distinction exists between research associated with plant growth affected by rhizobacteria and experiments using fertilizers, yet research about stress tolerance and microbial abundance is still limited. Figure 2 presents the four clusters formed by all connected terms. Four clusters were formed with red, green, blue, and yellow colors indicating the number of topics published from the most to the least. Cluster 1, indicated in red color, reflected all reports related to plant growth affected by rhizobacteria consisting of terms such as acetic acid, ammonia, *Bacillus*, bacterial strain, beneficial effect, biocontrol agent, endophytic bacterium, formulation, gene, germination, growth promotion, inoculant, microorganism, pgpr, and plant growth promotion. Cluster 2, indicated in green color, reflected all reports related to experiments using fertilizer consisting of terms such as biofertilizers, dose, experiment, fertilization, field experiment, foliar application, grain yield, randomized block design, inorganic fertilizers and soil health. Cluster 3, indicated in blue color, reflected all reports related to stress tolerance consisting of terms such as drought, salt stress, tolerance, catalase, root colonization, proline, and heavy metals. Cluster 4, indicated in yellow color, reflected all reports related to microbial abundance consisting of terms such as abundance, diversity, function, greenhouse experiment, and microbial community. These results showed a critical area of interest and research about biofertilizers for sustainable agriculture based on VOSviewer analysis that has been done. Research in biofertilizers, driven by the need to address the negative impacts of chemical fertilizers on soil health, water quality, and the environment, aims to mitigate agricultural environmental impacts by reducing synthetic inputs and promoting more sustainable practices (Allouzi *et al*., 2022; Jacob and Paranthaman 2023). Additionally, research into stress tolerance and microbial abundance remains a burgeoning area of interest in the study of biofertilizers. This is driven by the need to understand how plants adapt to and cope with various environmental stresses, such as drought, salinity, and extreme temperatures. This research is crucial for developing sustainable agricultural practices that can ensure crop resilience and productivity under changing environmental conditions (Ali *et al.*, 2023; Khan *et al*., 2023).

Figure 3 shows a representation of the publication year mapping. Degradation of the color from dark blue to light yellow means the time of publication from the oldest (2021) to the latest (2022). It can be seen that research relating to plant stress tolerance and microbial diversity can be found mostly beyond 2022 (yellow color). This reinforces the previous observation in Figure 2 that research on these topics is limited because they are still relatively new and emerging. However, interest in these areas is growing. In contrast, research on plant growth affected by rhizobacteria and experiments using fertilizers, as shown in Figure 4, is more prevalent and denser compared to other topics. These findings indicate that biofertilizer is still a hot topic to be researched and used for sustainable agriculture.

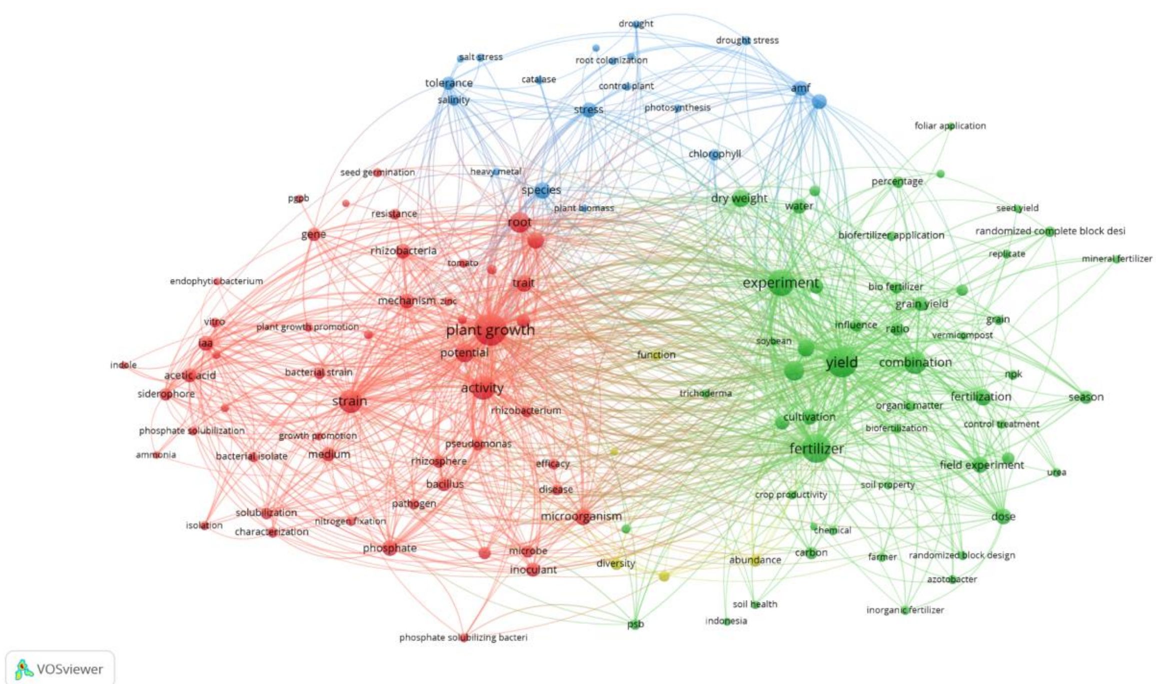

Figure 2. A network visualization of the co-occurrence mapping of pertinent keywords related to research on biofertilizers.

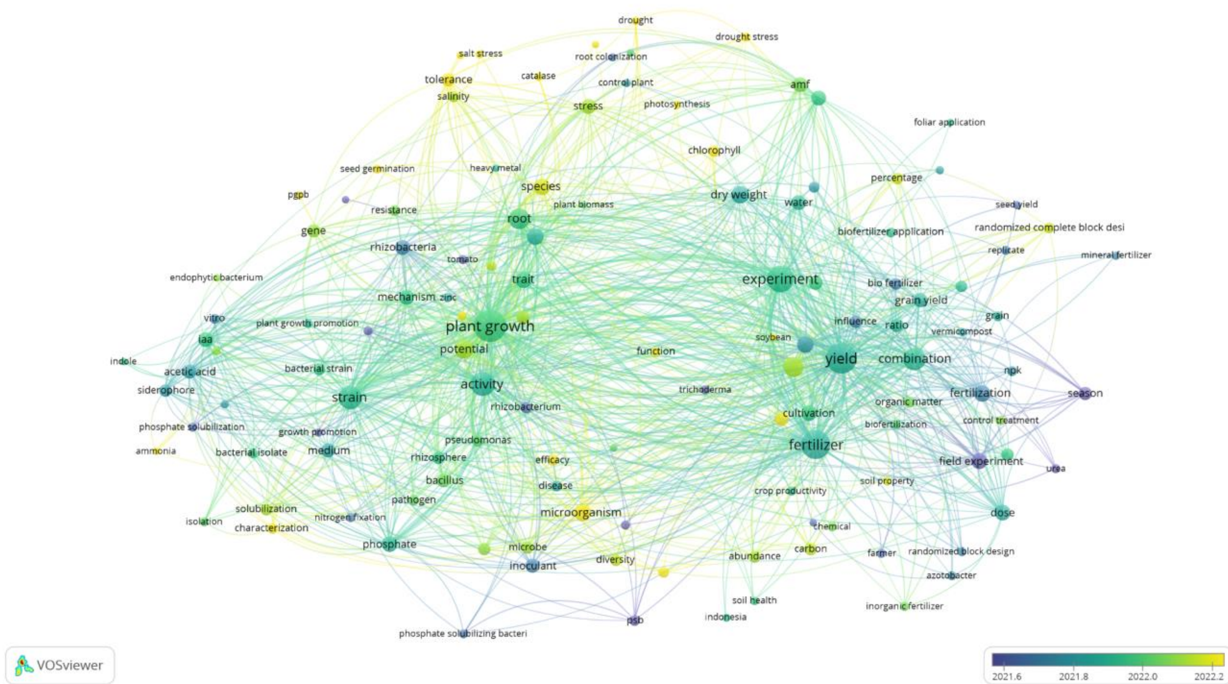

Figure 3. An overlay visualization of the publication year mapping related to research on biofertilizers.

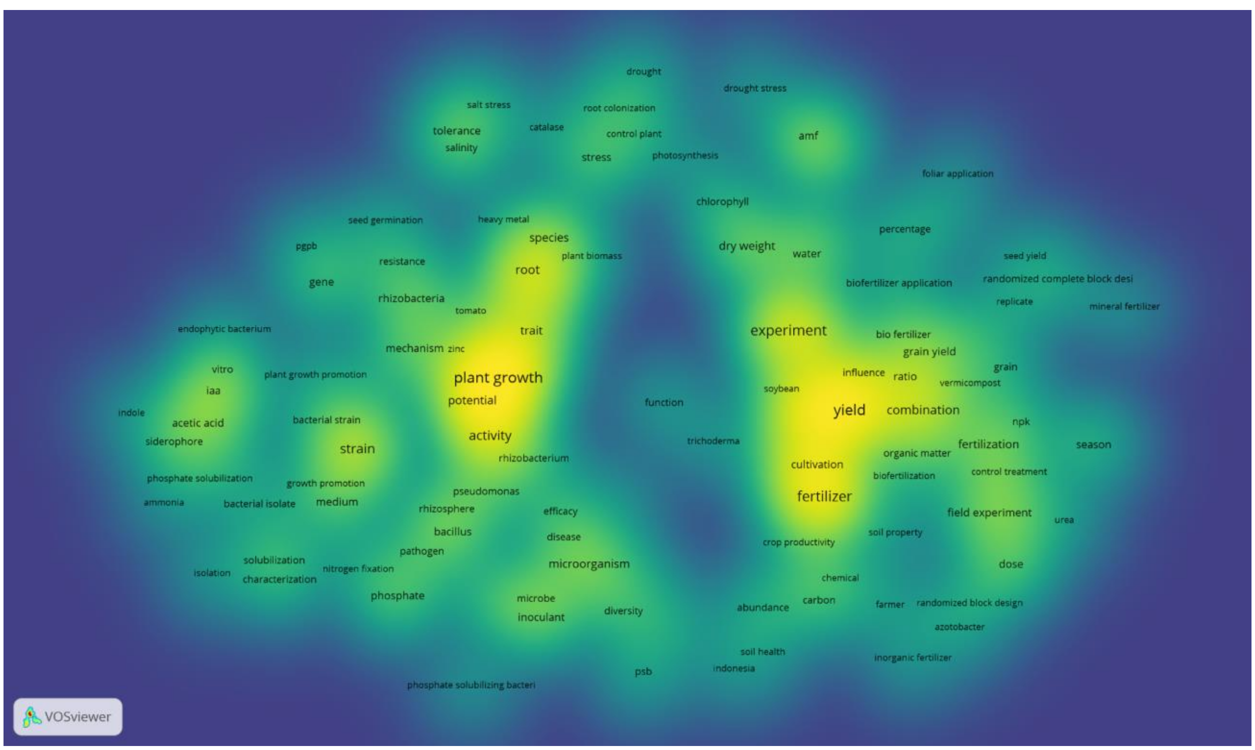

Figure 4. A density visualization of the co-occurrence mapping of pertinent keywords related to research on biofertilizers.

Trends and development of biofertilizers

Trends in biofertilizer research

Based on the bibliometric results, an investigation into biofertilizer research trends using Scopus data from 1982 to 2024 (Figure 5.).

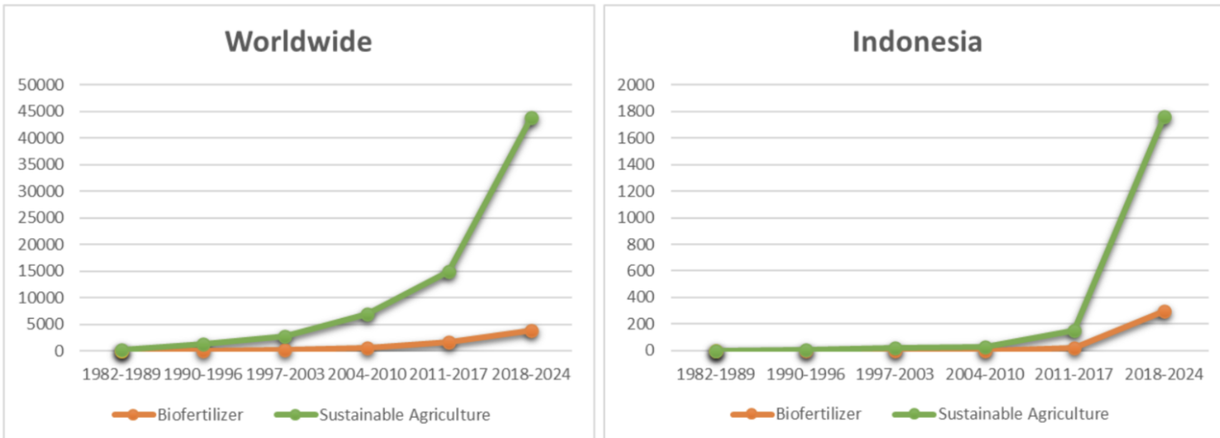

Figure 5. Trends in Biofertilizer Research Worldwide (left) and Indonesia only (right)

Figure 5 shows a significant increase in the number of journals indexed in Scopus with the keywords "biofertilizer" and "sustainable agriculture" from 1982 to 2024, both globally and in Indonesia. The number of journals for both topics has steadily increased each period, with a sharp rise seen from 2018 to 2024. This trend indicates growing interest and attention towards research in the fields of biofertilizers and sustainable agriculture.

Indonesia needs to conduct more research on biofertilizers because the country has extremely high biodiversity, which can be utilized to develop environmentally friendly and sustainable fertilizers. The high microbial diversity in Indonesia is driven by a stable tropical climate, the variety of plants that provide root exudates, and the symbiotic relationships between microbes and plants (Umukoro, 2020). The use of biofertilizers can naturally enhance soil fertility, reduce dependence on chemical fertilizers, and improve agricultural yields (Macik *et al*., 2020). The use of biofertilizers can also enhance the health of marginal soils in Indonesia by improving soil structure, increasing organic matter content, and supporting beneficial microbial activity, making previously less fertile soils more productive for agriculture (Fitriatin *et al*., 2021). Some microbes found in various soils across Indonesia have the potential to become biofertilizers that can enhance biodiversity in marginal soils (Ambarita *et al*., 2024). Additionally, this research is crucial for supporting sustainable agriculture and maintaining ecosystem balance, aligning with global efforts to mitigate climate change impacts. With its significant potential in the agricultural sector, Indonesia can leverage biofertilizers to boost agricultural productivity, improve farmers' welfare, and ensure national food security.

History and development of biofertilizer utilization in Indonesia

Research on biofertilizers in Indonesia has been continuously evolving since the 1980s. Various types of biofertilizers, including PGPR, Azolla, and phosphate-solubilizing microorganisms, have played a crucial role in supporting environmentally friendly agriculture in Indonesia, from the initial stages of basic research to their widespread adoption by farmers. Roadmap of the history of biofertilizer usage in Indonesia is shown in Figure 6.

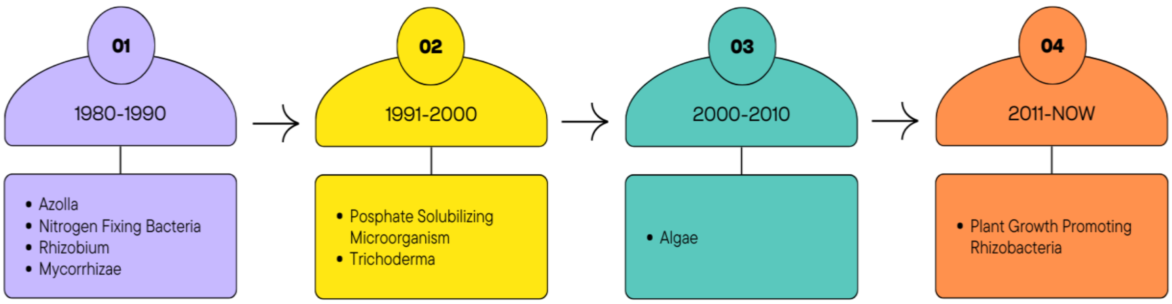

Figure 6. Roadmap of biofertilizer utilization in Indonesia

Biofertilizers in Indonesia were first researched by Badan Penelitian Tanah (BPT) from 1960 to 1980, characterizing beneficial soil bacteria and testing their effectiveness in soil to enhance soil fertility and plant productivity. In the early 1990s, BPT successfully isolated Rhizobium, which proved effective in increasing the production of leguminous plants. This bacterium was then commercialized with the private sector, resulting in the production of Rhizo-plus (Irmawanty *et al*., 2021). Rhizo-plus is one of the pioneering biofertilizers introduced in Indonesia.

Rhizo-plus is a biofertilizer composed of several superior strains, carefully selected and used as key components in biofertilizers. The addition of phosphorus-solubilizing microbes and growth-promoting bacteria to soybean plants inoculated with Rhizobium has been shown to increase phosphorus availability in the soil, stimulate root growth, and enhance the uptake of nitrogen and phosphorus by plants. This biofertilizer enhances the efficiency of nitrogen and phosphorus fertilizer usage for soybean plants by improving the effectiveness of nitrogen fixation symbiosis and phosphorus solubilization capabilities. As a result, it reduces the need for nitrogen and phosphate fertilizers while increasing yields by 20-40%. During the 1997-1998 planting season, the Rhizo-plus compound biofertilizer was applied to 330,790 hectares of soybeans across 26 provinces (Harsono *et al*., 2021). Additionally, since 1990, extensive research has been conducted on the use of phosphorus-solubilizing microbes. This research has successfully identified isolates that are highly effective in solubilizing phosphate from insoluble sources, with the potential to improve the growth and nutrient uptake of maize plants.

In the 2000s, research on mycorrhiza and PGPR in Indonesia experienced significant growth, focusing on understanding the roles and potentials of both types of microbes in enhancing agricultural productivity and environmental sustainability. This research included the identification of potential mycorrhizal and PGPR species, understanding their mechanisms of action and interactions with plants and the surrounding environment, as well as the development of practical application technologies such as effective biofertilizer formulations and application methods. It is hoped that this knowledge can be widely implemented in agricultural practices, supported by farmer education and cooperation between the government, research institutions, and the private sector.

With an increasing awareness of the importance of using biofertilizers, the government supports the use of organic fertilizers or biofertilizers in Indonesia to improve soil health and minimize the use of chemical fertilizers. In 2000, the Indonesian government initiated the "Go Organic 2000" movement to promote biofertilizers and reduce dependence on chemical fertilizers. Since 2000, Indonesia has been continuously conducting research on biofertilizers, demonstrating its commitment to advancing agricultural practices and sustainability.

Types of biofertilizers in Indonesia

Currently, in Indonesia, various types of biofertilizers are being utilized to support and enhance plant growth. Figure 7 illustrates the interaction of different beneficial microorganisms with plant roots, highlighting their roles in promoting plant growth and improving soil health. The types of biofertilizers presently used in Indonesia include nitrogen-fixing bacteria, phosphate-solubilizing bacteria, plant growth-promoting rhizobacteria, azolla, and arbuscular mycorrhizal fungi.

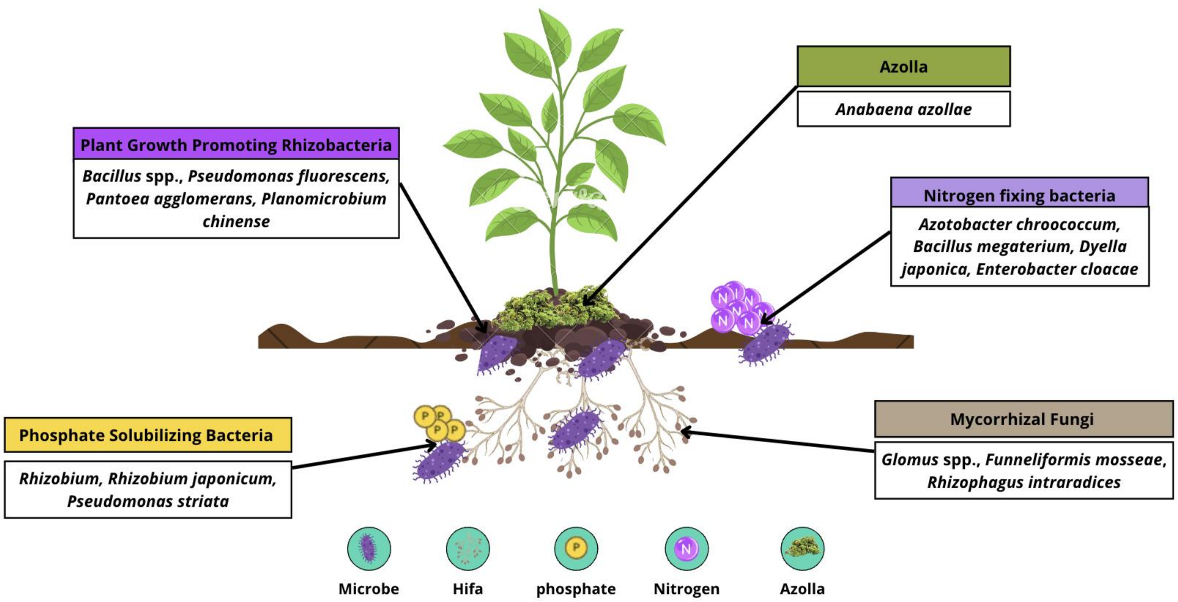

Figure 7. Illustration of the Role of Microbes as Biofertilizers

Nitrogen fixing bacteria

A nitrogen-fixing biofertilizer contains nitrogen-fixing bacteria (NFB) that can colonize the plant rhizosphere, promoting plant growth by increasing the availability of essential nutrients (Khumairah *et al*., 2022). NFB can inhabit plant roots and convert atmospheric nitrogen into a form plants use, enriching the soil (Basu *et al*,. 2021). These natural NFB are categorized into symbiotic and non-symbiotic N-fixing bacteria. Symbiotic N-fixing bacteria form a mutualistic relationship with plants, such as Rhizobium species (*Rhizobium* sp. and *Bradyrhizobium* sp.), which live in the roots of legumes and create nodules (Manasikana *et al*., 2019).

Non-symbiotic bacteria, such as *Azotobacter* species are NFB that live independently and can convert atmospheric nitrogen into compounds usable by plants (Reed *et al*., 2011). *Azotobacter* fixes nitrogen and produces growth-enhancing substances, vitamins, and antifungal metabolites that promote seed germination and boost plant growth (Khandare *et al*., 2020). These growth-enhancing substances include indole acetic acid and gibberellins, which help increase chlorophyll content and accumulate photosynthates, improving plant health (Arifin *et al.*, 2021). As shown in Table 2, applying *Azotobacter* to wheat can boost yields by 10.5-10.9% (Khandare *et al*., 2020). Additionally, using *Dyella japonica* and *Enterobacter cloacae* on maize has increased yield by 40.8% (Sembiring and Sabrina, 2022).

Phosphate solubilizing bacteria

Phosphate solubilizing bacteria (PSB) play a crucial role in making phosphorus (P) more accessible to plants by speeding up the breakdown of organic P compounds and the dissolution of inorganic P in the soil

(Khandare *et al*., 2020). PSB utilizes various mechanisms to enhance phosphorus availability, including producing organic acids, acidification, chelation, enzymatic processes, ion exchange, and improving soil structure. Through the secretion of organic acids and proton release, PSB dissolves inorganic P (Abderrazak *et al.*, 2014). The organic acids produced by PSB, such as acetic acid, lactic acid, fumaric acid, glycolic acid, and succinic acid (Bargaz *et al*., 2021), lower the soil pH around them, facilitating the conversion of insoluble phosphate compounds like calcium phosphate into soluble forms like dihydrogen phosphate ($H_2PO_4^-$) and hydrogen phosphate (HPO_4^{2-}), which plants can absorb (Rodríguez and Fraga, 1999). Additionally, PSB can produce inorganic acids, such as hydrochloric acid, which further acidify the soil, enhancing phosphate solubility by protonation of phosphate ions and aiding in their release from mineral complexes (Tian *et al.*, 2021).

The chelation of metal ions occurs because some phosphate-solubilizing bacteria (PSB) can produce siderophores and other chelating agents that bind to metal ions like Fe^{3+}, Al^{3+}, and Ca^{2+}, associated with phosphate minerals. This chelation frees phosphate ions into the soil solution, making them accessible for plant absorption (Sharma *et al*., 2013). Moreover, PSB in the soil can release various enzymes such as phosphatase, phytase, phosphodiesterase, phosphomonoesterase, phospholipase, and phosphoesterase (Richardson and Simpson, 2011). These enzymes break down complex organic phosphates into simpler inorganic forms, thus enhancing the phosphorus availability to plants (Sharma and Sharma, 2022). Additionally, the activity of PSB can improve soil structure by producing polysaccharides that promote soil aggregation. Better soil structure facilitates root growth and increases the root surface area in contact with soil particles, improving phosphorus uptake by plants (Backer *et al*., 2018). According to a study by Beltran-Medina *et al*. (2022), the use of Rhizobium can lead to a 17% increase in crop yields, while research by Shome *et al*. (2022) indicates that using *Rhizobium japonicum* and *Pseudomonas striata* as biofertilizers on soybean can boost yields by 60%.

Plant Growth Promoting Rhizobacteria (PGPR)

Plant growth-promoting rhizobacteria (PGPR) are a diverse group of root-associated bacteria that can directly or indirectly enhance plant growth (Cavite *et al.*, 2021). PGPR is increasingly popular because it can reduce the need for fertilizers, improve fertilization efficiency, and decrease the reliance on synthetic pesticides and agrochemicals (Rana *et al*., 2012). PGPR contributes to plant nutrient availability through nitrogen fixation, nutrient solubilization, and exopolysaccharide production (Rouphael and Colla, 2020; Ahmad *et al*., 2023). Moreover, PGPR produces plant growth-promoting substances like IAA, gibberellin, and ACC deaminase (Cavite *et al*., 2021).

Under biotic stress, PGPR can inhibit soil pathogens through mechanisms such as the production of hydrogen cyanide (HCN), siderophores, antibiotics, antifungal activity, and volatile organic compounds (Bhattacharyya *et al.,* 2016). In the face of abiotic stress, PGPR application can improve plant tolerance to challenges like drought, salinity, and metal toxicity (Harahap *et al*., 2023). The effectiveness of PGPR is influenced by factors such as soil pH, organic matter, environmental conditions, and its interactions with other microorganisms in the rhizosphere (Billah *et al*., 2019). Research has led to commercializing various biofertilizers, including species like *Pseudomonas*, nitrogen-fixing *Azospirillum*, and *Bacillus* (Timmusk *et al*., 2017). Studies by Ortega Pérez *et al.* (2023) indicate that *Azotobacter* spp. and *Bacillus* spp. can increase tomato yields by 20–32%. Similarly, Khan *et al*. (2023) reported that a biofertilizer containing *Planomicrobium chinense* and *Azotobacter chroococcum* can boost maize yields by 81% (Table 2).

Azolla

Azolla serves as an essential biofertilizer, playing a significant role in enhancing plant growth and development. This small aquatic fern establishes a symbiotic relationship with the nitrogen-fixing cyanobacterium *Anabaena azollae*. As a biofertilizer, Azolla contributes to soil fertility through various processes, including nitrogen fixation, adding organic matter, phosphorus solubilization, and allelopathic interactions. *A. azollae* converts atmospheric nitrogen (N_2) into ammonia (NH_3) through nitrogen fixation.

This ammonia is then integrated into amino acids and proteins, enriching the nitrogen content in biomass of Azolla. When Azolla is incorporated into the soil, it decomposes and releases nitrogen, making it accessible to plants (Khan *et al*., 2021).

Using Azolla as a biofertilizer introduces organic material into the soil, which, as it decomposes, enhances soil structure, boosts microbial activity, and improves water retention. This organic material also provides nutrients for soil microorganisms, impacting nutrient cycling and plant availability. Azolla can solubilize insoluble phosphate compounds by secreting organic acids, making these nutrients accessible to plants. Furthermore, Azolla produces allelopathic compounds that inhibit the growth of weeds and harmful microorganisms in the soil, reducing competition for nutrients and creating better conditions for plant growth. The symbiotic relationship between Azolla and Anabaena can fix 30–60 kg of nitrogen per hectare within 30 days, enough to meet crop nitrogen needs for several weeks (Yadav *et al*., 2023). Annually, Azolla species can fix up to 1,000 kg of atmospheric nitrogen per hectare (Carrapiço 2010).

Arbuscular mycorrhizal fungi

Arbuscular mycorrhizal fungi (AMF) are a key functional group that significantly enhances plant growth, nutrition, and productivity (Adeyemi *et al*., 2021). AMF application is highly effective in improving plant assimilation, uptake, and transport of essential macro and micronutrients (Sharma and Sharma, 2022). These fungi establish a symbiotic relationship with plant roots, facilitating water uptake and nutrient acquisition through an extensive hyphal network (Berruti *et al.*, 2016). The hyphae produced by AMF penetrate root cells, increasing root surface area and enhancing nutrient absorption (Feng *et al*., 2022). AMF are particularly adept at improving plant phosphorus (P) availability, with P acquisition facilitated by extraradical hyphae and fungal P transporters (De Nardi *et al*., 2024). The extraradical mycelium of AMF acts as an extension of plant roots, exploring large soil volumes for nutrients, especially P, in exchange for carbohydrates (Adeyemi *et al*., 2022). In addition to plant nutrition, AMF contributes to crucial ecosystem functions and processes, including nutrient cycling, plant resilience to biotic and abiotic stresses, and soil aggregate stability (Verbruggen *et al*., 2013). Research by Adeyemi *et al*. (2021), summarized in Table 2, demonstrates that the use of *Funneliformis mosseae*, *Rhizophagus intraradices*, and *Claroideoglomus etunicatum* can increase soybean yields by 44.2% to 46.5%.

Table 2. The Impact of biofertilizer application on crop productivity enhancement

No	Type of biofertilizer	Species	Crop	Persentase of productivity	Reference
1	Consortium of decomposer fungi, P Solubilizing bacteria, N-fixing bacteria	*Trichoderma* sp., *Bacillus* sp., *Azospirillum* sp.	Soybean	The highest soybean yields were obtained by applying biofertilizer phytohormone-producing bacteria (*Methylobacterium* sp.) with 150% NPK is 1.6 t ha^{-1}.	(Maftu'Ah *et al.*, 2023)
2	AMF	*Glomus* spp.	Rice	The impact on grain yield was observed in soil water potential, with reductions ranging from 38–50% for wet direct-seeded plants and 38–53% for transplanted plants.	(Das *et al.*, 2022)
3	AMF	*Funneliformis mosseae, Rhizophagus*	Soybean	The studies indicated that inoculating with R. *intraradices* and F. *mosseae* resulted in the	(Adeyemi *et al.*, 2021)

		intraradices, and *Claroideoglomus etunicatum*		highest yield increases, ranging from 44.2% to 45.4% and 44.9% to 46.5% over the control in both soybean cultivars.	
4	PGPR	*Azotobacter* spp, *Bacillus* spp	Tomato	The findings indicated that regularly supplying biofertilizers containing PGPB increased crop yield by 20–32%.	(Ortega Pérez *et al.*, 2023)
5	PGPR	*Bacillus megaterium, Pseudomonas fluorescens,* and *Pantoea agglomerans*	Lettuce and Broccoli	Chemical and biofertilizer combinations resulted in total and marketable lettuce yields ranging from 6.50 to 8.08 kg m^{-2}.	(Demir *et al.*, 2023)
6	PGPR	*Planomicrobium chinense andAzotobacter chroococum*	Maize	The enhancement of hormonal activity and the activity of plant-defense-related antioxidant enzymes contributed to a boost in yield, with an observed increase in grain yield of 81%.	(Khan *et al.*, 2023)
7	PGPR	*Acidovorax delafieldii*	Rice	A notable rise of 34% in grain yield per plant was recorded in plants cultivated in sterilized soil compared to those grown in natural soil conditions.	(Cavite *et al.*, 2021)
8	PGPR	*Burkholderia ubonensis, Burkholderia vietnamiensis,* and *Citrobacter bitternis*	Rice	Grain yield increased by 2.5% to 13.5% in the inoculated treatments that received either 75% or 100% (150 kg N ha−1) of the nitrogen fertilizer dose.	(Ríos-Ruiz *et al.*, 2020)
9	PGPR	*Pseudomonas syringae*	Maize	The highest grain yield was achieved by applying P. syringae combined with 50% NPK and urea, resulting in a 30.64% increase.	(Amogou *et al.,* 2021)
10	PGPR	*Bacillus subtilis, Bacillus aryabhattai andBacillus aryabhatta*	Maize	The grain yield was significantly higher by 17% and 12%, respectively, with consortium application compared to the control.	(Ahmad *et al.*, 2023)
11	NFB	*Azotobacter*	Wheat	Applying carrier-based biofertilizer to the soil at 10 kg ha^{-1}, and liquid-based biofertilizers at 625 and 1250 mL ha^{-1}, combined with 75% NP, was comparable to using 100% NP, resulting in a significant increase in grain yield by 10.9%, 10.5%, and 10.8%, respectively.	(Khandare *et al.*, 2020)

12	NFB	*Dyella japonica* and *Enterobacter cloacae*	Maize	The N3U1 treatment could boost plant production by as much as 40.8% compared to the control.	(Sembiring and Sabrina, 2022)
13	NFB	*Azotobacter chroococcum*	Rice	The grain yield of TPR on bare soil was increased by 31.9%.	(Meena *et al.*, 2023)
14	NFB	*Azotobacter*	Sorgum	The sorghum variety Bohuth-70, treated with F0, achieved an impressive grain yield of 7.157 mg ha^{-1}.	(Alaarage and Alamery, 2023)
15	PSB	*Rhizobium*	Maize	17% increase in grain yield, equivalent to 20 g per plant, was achieved by using 50% diammonium phosphate (DAP) compared to the control treatment with the same amount.	(Beltran-Medina *et al.*, 2022)
16	PSB	*Rhizobium japonicum* and *Pseudomonas striata*	Soybean	A combination of 50% N+R. *japonicum* and 75% P + P. *striata* produced a 60% higher yield than control.	(Shome *et al.*, 2022)
17	NFB and PSB	*Bacillus megaterium*	Maize	The maize yield was significantly enhanced by 54.7% and 48.1% in both seasons when using a combination of B. *megaterium* and micro-dosed NPK 2:3:2 fertilizer, compared to the control.	(Kubheka *et al.*, 2020)

Benefits and performance of biofertilizers

Soil health and fertility improvement

Biofertilizers are live, ready-to-use mixtures of helpful microbes that can be applied to seed, root, or soil, increasing the microbe's availability and utility. Biofertilizers are pivotal in bolstering soil health and fertility through their multifaceted benefits and performance. Biofertilizers improve soil fertility by fixing atmospheric nitrogen in conjunction with plant roots and the absence of plant roots (Khumairah *et al*., 2018). In the soil, some chemicals help plants develop. They are being monitored and encouraged to utilize the existing biological system to mobilize nutrients naturally (Ghosh *et al.*, 2020). Moreover, biofertilizers improve soil structure by promoting aggregation and stability, which enhances water retention and aeration, facilitating optimal root growth and overall plant vigor (Akram *et al*., 2020). Embracing biofertilizers underscores a commitment to sustainability, as they mitigate environmental impact by reducing reliance on chemical inputs and minimizing nutrient runoff (Alnaass *et al*., 2023; Haroun *et al*., 2023). Biofertilizers can improve water-holding capacity of soil, reduce soil erosion, and enhance the overall biodiversity of the soil ecosystem (Baldi *et al*., 2021; Wang *et al*., 2023). This is particularly important in areas where soil degradation is a significant concern, as biofertilizers can help mitigate the negative impacts of erosion and nutrient depletion. This eco-friendly approach conserves biodiversity and translates into long-term cost savings for farmers. Additionally, biofertilizers have been demonstrated to boost crop yields and improve produce quality by fortifying plants against diseases and pests. Their adaptability to diverse cropping systems and compatibility with other fertilizers make them versatile for enhancing agricultural productivity while nurturing soil vitality for future generations.

Nutrient pptake enhancement

Biofertilizers are the formulation of living or latent microbes' cells, providing an additional advantage in nutrient uptake and plant performance in the rhizosphere. The biofertilizer formulation technique is simple and has a low installation cost. The former can be composed of a single or a mix of two or more diverse microbial strains, including *Acetobacter*, *Azotobacter*, *Bacillus*, *Pseudomonas*, *Rhizobium*, PGPB, and AM (Basu *et al*., 2021; Fasusi *et al*., 2021; Mohanty *et al.*, 2021). Biofertilizers have been found to significantly enhance plant nutrient uptake by promoting beneficial microbial activity in the soil. The application of nutrient-mobilizing microbial inoculants has been found to stimulate the root and shoot growth, enhance nutrient uptake, and increase seed yield of different crops under pot experiment as well as in the field under different agro-environmental conditions (Etesami *et al.*, 2021). These microorganisms, such as rhizobia, mycorrhizal fungi, and bacteria, form symbiotic relationships with plant roots, increasing the availability of essential nutrients like nitrogen, phosphorus, and potassium (Herdiyantoro *et al.*, 2018; Khumairah *et al*., 2020; Setiawati *et al*., 2022). This enhanced nutrient uptake can lead to improved plant growth, increased crop yields, and enhanced plant quality. Additionally, biofertilizers can also solubilize minerals, making them more accessible to plants, and produce plant growth-promoting substances that stimulate root development and nutrient uptake (Kumutha *et al*., 2023). This natural process of nutrient uptake enhancement through biofertilizers can reduce the reliance on synthetic fertilizers which can have negative environmental impacts, and promote a more sustainable and environmentally friendly approach to agriculture.

Strategies for promoting biofertilizers

Awareness campaigns

Several key strategies can be used to promote biofertilizers effectively in awareness campaigns. Education is crucial, and campaigns should emphasize the advantages of biofertilizers in improving soil health, boosting crop yields, and reducing environmental impact. It is important to encourage the adoption of biofertilizers among farmers through voluntary awareness initiatives and surveys that assess their knowledge and highlight the benefits of biofertilizers compared to chemical fertilizers. This approach should especially target agricultural areas still in their natural state, supporting micro-innovative projects based on entrepreneurship to create essential local fertilizers from local resources. These projects can provide cost-effective solutions for farmers, including microbial biostimulants and biofilm-based biofertilizers (Ammar *et al.*, 2023).

Farmers need training and extension services to understand how to use biofertilizers effectively and the benefits they offer. These services can be provided through agricultural cooperatives, government programs, or non-governmental organizations. Governments have a crucial role in encouraging biofertilizer use and should streamline the regulatory process to make these products more accessible. Public awareness campaigns and educational initiatives can help consumers learn about biofertilizers, the value of sustainable agriculture, and the environmental impact of their food choices (Ahmed *et al*., 2023b). Additionally, offering incentives such as subsidies, training, and certification can promote the adoption of biofertilizers. Engaging local communities and stakeholders to address their concerns and support implementation is key to fostering acceptance and ensuring sustainability. By adopting these strategies, awareness campaigns can effectively drive the widespread use of biofertilizers, supporting sustainable agricultural practices and environmental care.

Research and development initiatives

Promoting biofertilizers in research and development requires a comprehensive approach that includes innovation, collaboration, and the spread of knowledge. First, it is essential to invest in research to understand biofertilizer effectiveness better, improve production methods, and investigate new microbial strains. This should involve partnerships between academia, industry, and government agencies to utilize expertise and resources effectively. Encouraging interdisciplinary research that combines microbiology, agronomy, and soil science can foster innovation and tackle complex issues (Jacob and Paranthaman, 2023). Additionally, sharing research results through publications, conferences, and outreach helps keep the scientific community and policymakers informed and involved. By focusing on these strategies, adopting biofertilizers can be accelerated, promoting sustainable agricultural practices and environmental benefits.

Another approach involves leveraging advanced technologies in smart agriculture, such as simulation systems tailored for different crops. This includes using IoT applications, big data, cloud computing, and artificial intelligence to analyze plant diversity across regions. These technologies help identify the necessary biofertilizers for promoting growth and determine the most effective organisms for biofertilizer extraction (Ammar *et al*., 2023). Ongoing research is crucial to assess the effectiveness and compatibility of various biofertilizer strains with different crops. Collaboration among scientists and agricultural experts is essential for biofertilizer technologies' continuous refinement and innovation (Ahmed *et al*., 2023a).

Policy recommendations

To effectively promote the use of biofertilizers, governments can adopt several strategic policy measures. They should establish a regulatory framework to ensure the quality and safety of biofertilizers and run public awareness campaigns to educate farmers, agro-dealers, and extension agents about their benefits, proper handling, storage, and usage (Malusá and Vassilev, 2014). Governments might also consider offering subsidies or incentives for biofertilizer adoption, supporting research institutions to innovate in biofertilizer production, and providing extension services to farmers (Raimi *et al*., 2021). Additionally, establishing a certification process for biofertilizers, fostering market development, and collaborating with private companies to enhance and promote biofertilizers could be beneficial. By implementing these recommendations, governments can foster an environment conducive to adopting and using biofertilizers, ultimately promoting more sustainable and eco-friendly agricultural practices.

Challenges and future prospects of biofertilizers

Potential impact on sustainable agriculture

The potential impact of biofertilizers on sustainable agriculture is enormous because biofertilizers offer a more environmentally friendly alternative to chemical fertilizers. Biofertilizers from beneficial microorganisms such as bacteria, fungi, and cyanobacteria can increase soil fertility, plant tolerance, and plant productivity while reducing dependence on chemical inputs. One of the main benefits of biofertilizers is their ability to improve soil health by increasing the uptake and availability of nutrients for plants. This is achieved through various mechanisms such as mineral dissolution, production of plant growth hormones, and suppression of plant pathogens. Additionally, biofertilizers can increase crop tolerance to environmental stresses such as drought, salinity, and extreme temperatures, which is critical for agricultural sustainability in climate change (Bhardwaj *et al*., 2014).

Biofertilizers offer a more sustainable approach to farming by reducing the environmental impact of chemical fertilizers. Chemical fertilizers can pollute waterways, contribute to greenhouse gas emissions, and harm beneficial microorganisms in soil ecosystems. In contrast, biofertilizers are generally biodegradable and non-toxic, minimizing environmental impacts. In addition, biofertilizers can contribute to developing more resilient and diverse agricultural ecosystems. By promoting beneficial microorganisms in the soil, biofertilizers can improve biodiversity and soil structure, which is important for maintaining ecosystem services and supporting long-term agricultural productivity (Chittora *et al*., 2020).

Areas for future research

The challenges and prospects of biofertilizers are multifaceted and involve various aspects of their development, production, and application. Biofertilizers face challenges such as temperature sensitivity, regulatory frameworks, social acceptance, production costs, matching crops and nutrient concentration, research and development, public education and awareness, and market development. Despite these challenges, biofertilizers are expected to play a significant role in sustainable agriculture, particularly in climate change and the need to reduce chemical fertilizer use. The development of biofertilizers that are more efficient, scalable, and cost-effective will be crucial to their widespread adoption, and their integration into precision agriculture and digital farming practices can enhance their effectiveness and efficiency (Chakraborty and Akhtar 2021; Aloo *et al*., 2022).

CONCLUSION

The bibliometric and systematic literature review analysis provides a comprehensive overview of the current state of research on biofertilizers for sustainable agriculture globally and in Indonesia. The analysis highlights the multifaceted applications of biofertilizers, including the use of rhizobacteria, experiments, and the development of biofertilizers for climate change tolerance and their microbial community in soil. The article emphasizes the significant potential of biofertilizers in promoting eco-friendly sustainable agriculture in Indonesia, despite the challenges faced in their adoption, such as inconsistent field results, limited farmer awareness, and inadequate infrastructure for production and distribution. To overcome these hurdles, the article proposes strategies like farmer education, developing region-specific strains, and supportive government policies. Additionally, it underscores the need for robust research and development efforts and improved distribution networks to ensure the quality and accessibility of biofertilizers. The conclusion emphasizes the importance of this transition for achieving long-term agricultural sustainability and food security in Indonesia.

AUTHOR CONTRIBUTION

All authors contributed equally.

COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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