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RESEARCH ARTICLE

Augmenting Sustainable Agricultural Land with Bio-fertilizers to Boost Food Production in Kalimantan, Indonesia

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ABSTRACT

Indonesia strongly emphasizes ensuring food security through initiatives like the Sustainable Food and Food Estate programs. A significant component of these efforts involves the utilization of bio-fertilizers, which employ microbiological techniques to enhance soil fertility and crop nutrition in an environmentally friendly manner. This adoption of bio-fertilizers aims to reduce reliance on chemical alternatives, especially for vital crops like rice and wheat. This research, conducted across various regions in Kalimantan, meticulously isolated Rhizobium spp. and Phospho-bacteria to develop bio-fertilizers that met stringent criteria. These criteria included containing 10^8 viable cells per gram, a 12-month shelf life, freedom from contaminants, and a pH range of 6.0-7.5. An economical medium was formulated using fish extract, algal water, aloe vera, and tap water, followed by incubation at 27°C with agitation. The study highlights different bio-fertilizers and their specific applications for targeted crops, demonstrating their potential to reduce the need for chemical fertilizers. Results of this study include Azolla pinnata, which can reduce Nitrogen fertilizer demand in rice cultivation by 20–30 kg, and Bacillus circulans, which has the potential to decrease Phosphorus fertilizer requirements in cowpea cultivation by 10–30 kg. Moreover, organic fertilizers showed varying yield increases, with rice at 3% and cauliflower at 30%. This research provides valuable insights for farmers, enabling them to make informed decisions about adopting bio-fertilizers. It aligns with sustainable agricultural practices by promoting soil health, increasing crop productivity, and minimizing environmental impacts. The innovative approach of promoting and implementing bio-fertilizers within the Indonesian agricultural context, particularly in Kalimantan, distinguishes this research from conventional agricultural practices.

INTRODUCTION

In the relentless pursuit of the "Zero Hunger" objective, a core United Nations Sustainable Development Goal established in 2015, the global community has turned its gaze to the intricate interplay between agriculture, sustainability, and food security (Sneddon et al., 2006; Wulandari and Rahman, 2017). This symphony of interconnected themes has resonated across borders, echoing Indonesia's commitment to ensure food security through the Sustainable Food Agricultural Land Protection Policy (LP2B), strategically allocating specific agricultural zones to secure the production of essential food staples for national self-sufficiency (Martianto, 2010; Barlian et al., 2020). However, amidst this harmonious endeavour, the discordant note of land encroachment threatens the availability of arable land, a challenge not unique to Indonesia but part of a global crescendo (Akhmaddhian et al., 2017; Leonard et al., 2020).

Indonesia's agricultural landscape, spanning five distinct agroecological zones, resembles the intricate melodies of a well-orchestrated composition. To counter food crises, the nation initiated the Food Estate (FE) program in Central Kalimantan to cultivate 165,000 hectares for rice production and elevate smallholder farmers through cooperative harmony (Bappenas, 2020; Kementan, 2020). Yet, this agricultural concerto in the ex-PLG region of Kalimantan presents opportunities contingent on refining water management and enhancing infrastructure to strike a harmonious chord (Suriadikarta & Sutriadi, 2007).

Sustainable agricultural land management, a complex and nuanced sonata, revolves around legislative frameworks, policy formulation, and the precise execution of these policies. However, when the composition aims to crescendo in food production to combat pressing food security issues, a scientific approach emerges as a pivotal movement. This movement, an innovative, sustainable, and economically viable composition, conducts a symphony through the contemporary agricultural landscape. The application of modern bio-fertilizers emerges as a prominent cadence, orchestrating significant enhancements in food productivity.

Modern bio-fertilizers, rooted in advanced microbiological and biotechnological techniques, represent a revolutionary departure from conventional fertilization methods (Tan et al., 2022). They harmonize with beneficial microorganisms, such as Nitrogen-fixing (Figure 1) bacteria and Mycorrhizal fungi, to elevate soil fertility and crop nutrient availability. This symbiotic relationship between crops and bio-fertilizers mitigates the environmental discord created by chemical fertilizers and contributes to the sustainable cultivation of food crops (Kumar et al., 2019).

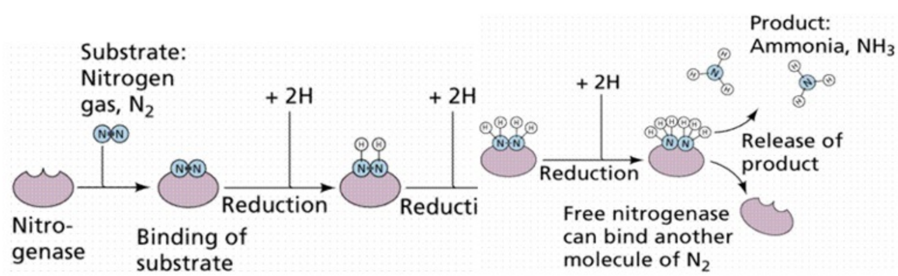

Figure 1: Biochemistry of Nitrogen fixation

Current research movements are placing a sonorous emphasis on developing and implementing bio-fertilizers across diverse agroecosystems. The versatility and adaptability of these scientifically composed solutions render them suitable for a wide array of agricultural circumstances (Sharma et al., 2023). By fostering harmonious microbial biodiversity within the soil and promoting nutrient cycling, modern bio-fertilizers can compose melodies that crescendo in crop yields while minimizing the discordant notes of adverse environmental effects. This scientific composition promises to address global food-related challenges and establish a resilient foundation for agricultural sustainability. As the scientific community continues to explore the intricate harmonies between soil microbiota and plant health, the potential for further innovations in bio-fertilizer technology remains vast, opening new horizons in pursuing food security and sustainable agriculture (Brewis, 2020; Lal et al., 2021).

Recognizing the vital role of sustainability and nutrient availability in agriculture, Indonesia has turned to bio-fertilizers to compose a harmonious soil orchestra. Bio-fertilizers, primarily orchestrated by Nitrogen-fixing bacteria, have been employed to reduce reliance on the discordant accompaniment of chemical fertilizers (Subba Rao, 1988; Boraste et al., 2009; Gupta and Rog, 2004; Ellafi et al., 2011; Mandal et al., 2011).

In the symphony of attaining food self-sufficiency in Indonesia, focusing on elevating the production of essential staples like rice, corn, and soybeans, the integration of bio-fertilizers emerges as an indispensable note in the agricultural score. These bio-fertilizers enhance plant growth and productivity and improve soil fertility by working in harmony. They have the potential to significantly lessen the negative effects brought on by synthetic fertilizers. This includes addressing various ecological challenges, such as soil degradation, water pollution, loss of biodiversity, greenhouse gas emissions, and disturbances to beneficial organisms associated with using chemical fertilizers in agriculture (Hathaway, 2016).

The trajectory of bio-fertilizers in Indonesia has seen a meteoric rise since the turn of the millennium. In the nascent year of 2003, a mere 35 bio-fertilizer brands graced the market. However, fast-forward to 2013, and over 200 diverse bio-fertilizer brands flourished in various forms—liquid, powder, tablets, and beads—each meticulously tuned to specific microbial strains, botanical varieties, and the prevailing environmental melody (Pratiwi et al., 2016).

Most bio-fertilizers used in Indonesia are consortia bio-fertilizers, which are complex mixtures made up of a group of microbial isolates. These isolates typically resonate with Nitrogen-fixing microorganisms, phosphate-solubilizing microbes, and phytohormone-producing agents. Bio-fertilizers find resonance across a diverse spectrum of crops, spanning from staple field crops to the lush greens of horticultural paradigms and sprawling estates (Nosheen et al., 2021).

The microbes that live in bio-fertilizers are diverse and include well-known types like Aspergillus, Bacillus, Pseudomonas, Lactobacillus, Streptomyces, Cytophaga, Pantoea, Alcaligenes, Pantoea, and Aspergillus. The Ministry of Agriculture of Indonesia put out Minister of Agriculture Regulation No. 70/2011, which lays out the standards for organic fertilizers, bio-fertilizers, and ameliorants (Regulation, 2011). This was done to ensure that these biological compositions' quality was strictly controlled and to prove that they worked. A harmonious blend of quality assessments and effectiveness appraisals for these consortia bio-fertilizers is indispensable to ascertaining their prowess in producing harmonious soil health and elevating crop productivity.

Pioneering the charge, the Indonesian Agricultural Research and Development Agency (IAARD) has been orchestrating agricultural melodies since 1995, tirelessly composing and refining more than 20 multifaceted bio-fertilizers. Simultaneously, a harmonious composition of bio-fertilizer candidates is undergoing rigorous testing and fine-tuning processes, poised to enrich the nation's agricultural symphony soon (https://iaard.academia.edu/).

In this grand symphony of agricultural innovation, bio-fertilizers ascendancy is not merely a paradigm shift but a potent herald of sustainable, eco-friendly agricultural practices, promising greater food security and ecological equilibrium in Indonesia (Simarmata et al. 2018).

Our research endeavors to strike harmonious chords within this intricate orchestration of agriculture, sustainability, and food security. Firstly, it seeks to comprehensively analyze the latent potentialities and entrenched impediments within the food estate program, exploring how it can best harmonize food security and sustainability. Secondly, our research aims to understand the dynamics of agriculture in Kalimantan, unravelling strategies to promote harmonious farming and food production. Through this empirical symphony, we aspire to offer erudite insights and cogent recommendations, e.g., the use of bio-fertilizer, serving as a catalyst for advancing land-based farming in Kalimantan, and addressing the urgent challenges of sustainability and food security with a harmonious composition.

LITERATURE REVIEW

Sustainable agriculture is a critical component of global efforts to ensure food security while minimizing environmental impact (Balasundram et al., 2023, 20011). Fundamental sustainable agriculture principles include crop rotation, reduced chemical inputs, soil conservation, and biodiversity promotion (Altieri, 2018). Historically, agricultural practices have relied on organic amendments like compost and manure to enhance soil fertility and microbial activity (Drinkwater et al., 1998).

In recent years, scientific advancements have introduced innovative solutions to boost soil health and crop productivity while aligning with sustainable agriculture principles. Bio-fertilizers, rooted in microbial interactions, have emerged as a promising approach to improving soil fertility, reducing environmental degradation, and promoting sustainable food production (Itelima et al., 2018; Alori et al., 2017). This literature explores both classical agricultural practices and modern scientific developments, highlighting the pivotal role of bio-fertilizers.

Role of soil microorganisms

Soil microorganisms are essential to terrestrial ecosystems and are pivotal in sustaining agriculture. Classical agricultural wisdom has long recognized the fundamental contribution of these microorganisms to nutrient cycling, soil structure improvement, and plant health promotion (Nannipieri et al., 2003). The literature delves into historical understanding and contemporary scientific insights regarding the role of soil microorganisms, with a particular emphasis on the benefits conferred by beneficial microorganisms, including Nitrogen-fixing bacteria, in enhancing soil fertility. Microbes break down organic matter, releasing essential nutrients like Nitrogen, Phosphorus, and Potassium for plant uptake. This natural recycling process has been a cornerstone of sustainable agriculture for centuries (Beatrice, 2023; Van, 2021). Soil microorganisms, through their metabolic activities and organic matter production, contribute to improved soil structure. Enhanced soil structure facilitates root penetration, water infiltration, and aeration, which are vital for plant growth (Tisdall and Oades, 1982). One of the most well-documented functions of beneficial soil microorganisms is Nitrogen fixation. Certain bacteria, such as species of Rhizobium, Azotobacter, and Frankia, form symbiotic relationships with leguminous plants, converting atmospheric Nitrogen (N_2) into Ammonia (NH_3), which can be used by plants (Bohlool et al., 1992; Herridge et al., 2008). This process significantly enhances soil fertility. Soil microorganisms also contribute to plant health. Mycorrhizal fungi, for example, form mutualistic associations with plant roots, aiding in nutrient uptake and disease resistance (Smith and Read, 2010). They can enhance the availability of phosphorus and other nutrients for plants. In recent years, the scientific community has harnessed the potential of beneficial microorganisms for sustainable agriculture through bio-fertilizers. These formulations contain specific strains of microorganisms, such as Nitrogen-fixing bacteria and Mycorrhizal fungi, designed to enhance soil fertility and improve nutrient availability (Abdel-Gawad and Youssef, 2019). Soil microorganisms have found applications beyond nutrient cycling. They are also used in bioremediation to clean up contaminated soils by breaking down pollutants and restoring soil health (Das, 2014). Soil microorganisms have been instrumental in agriculture throughout history, aiding nutrient cycling, soil structure improvement, and plant health promotion. The symbiotic relationships formed between beneficial microorganisms, such as Nitrogen-fixing bacteria and mycorrhizal fungi, and plants play a pivotal role in enhancing soil fertility and plant growth. In modern agriculture, these insights have led to the development of bio-fertilizers and bioremediation techniques that harness the potential of soil microorganisms for sustainable farming and environmental restoration.

Crop rotation in sustainable agriculture

Sustainable agriculture is vital to global efforts to balance food production with environmental conservation (Pretty et al., 2006). One classical and sustainable farming practice that has stood the test of time is crop rotation. In particular, crop rotation often involves the inclusion of legumes in the rotation cycle due to their unique ability to form symbiotic relationships with Nitrogen-fixing bacteria. The scientific literature describes this practice's historical and scientific perspectives, emphasizing its contribution to reducing the dependency on synthetic Nitrogen fertilizers and enhancing soil Nitrogen availability.

Crop rotation is a time-honoured practice used for centuries to maintain soil fertility and reduce the risk of pests and diseases (Magdoff and Van, 2000). This practice involves alternating the crops grown in a specific field over several seasons, preventing the depletion of soil nutrients associated with monoculture. Legumes, such as Peas, Beans, and Clover, have been a staple in crop rotation systems. Their unique ability to host Nitrogen-fixing bacteria in their root nodules makes them valuable additions to crop rotations. This symbiosis enhances soil fertility by converting atmospheric Nitrogen into a form that plants can readily use (Drinkwater et al., 1998). Scientific research has elucidated the process of Nitrogen fixation in legumes. Within the root nodules, legumes form a symbiotic relationship with Nitrogen-fixing bacteria, primarily species of Rhizobium. These bacteria convert atmospheric Nitrogen (N_2) into Ammonia (NH3), which plants can take up (Oldroyd and Dixon, 2014). Crop rotation that includes legumes offers several benefits, most notably a reduction in the need for synthetic Nitrogen fertilizers. Legumes contribute to soil Nitrogen pools, making them available for subsequent non-legume crops in the rotation (Bezabeh, 2021). Legumes also improve soil health by increasing organic matter content and microbial activity. Leguminous plants' decaying roots and residues enrich the soil with carbon and nutrients, further enhancing its fertility (Drinkwater et al., 1998). Studies have demonstrated that incorporating legumes into crop rotations can lead to increased yields of subsequent crops due to improved soil fertility and reduced Nitrogen limitations (Sainju et al., 2008). Crop rotation, particularly when integrating legumes into the rotation cycle, represents a classical and scientifically validated practice in sustainable agriculture. It has been employed historically to maintain soil fertility and reduce the need for synthetic Nitrogen fertilizers. The symbiotic relationship between legumes and Nitrogen-fixing bacteria is at the heart of this practice, providing a natural and environmentally friendly means of enriching soil Nitrogen availability. As sustainable agriculture continues to gain importance in the modern world, the time-tested wisdom of crop rotation with legumes remains a valuable strategy for ensuring food security while preserving our environment.

Modern Bio-fertilizer formulations

Modern agriculture has witnessed significant advancements in developing bio-fertilizer formulations in recent years. These formulations, rooted in scientific research, are tailored to specific crops and soil conditions and have revolutionized nutrient management practices. This literature looks at the most important changes in modern bio-fertilizer formulations and how they can improve the interactions between microorganisms and plants so that plants can take in more nutrients. Historically, agriculture has relied on synthetic fertilizers to meet nutrient requirements for crop growth. While effective, these fertilizers have drawbacks, including nutrient leaching, soil degradation, and environmental pollution (Azeez et al., 2010; Dehaghi, 2021; Hernández et al., 2002). Recognizing the limitations of synthetic fertilizers, the scientific community has increasingly focused on bio-fertilizers. These formulations contain beneficial microorganisms that improve nutrient availability and soil health while minimizing adverse environmental impacts (Abdel-Gawad and Youssef, 2019).

Recent research has emphasized the importance of tailoring biofertilizer formulations to specific crops and their nutrient requirements. For example, formulations designed for leguminous crops may contain Nitrogen-fixing bacteria, while those for Phosphorus-demanding crops contain Phosphate-solubilizing microorganisms (Bashan et al., 2014). Modern bio-fertilizer formulations often include a consortium of microbial strains. This diverse community of microorganisms enhances nutrient cycling, disease suppression, and overall soil health (Dobbelaere et al., 2001). Mycorrhizal fungi have gained prominence in modern bio-fertilizer formulations due to their symbiotic associations with plant roots. These fungi significantly improve nutrient uptake, especially Phosphorus, and enhance plant tolerance to various stresses (Smith and Read, 2010). Advances in encapsulation technology have enabled the development of coated or encapsulated bio-fertilizers. These formulations protect microorganisms from environmental stresses and enhance their survival and efficacy in the field (Gulshan et al., 2022; Saberi-Riseh et al., 2021). Modern bio-fertilizer formulations have demonstrated their ability to improve nutrient uptake by plants. Microbial interactions with plant roots, such as Nitrogen fixation and nutrient solubilization, increase nutrient availability (Bhattacharyya and Jha, 2012). Bio-fertilizers enhance soil health by increasing microbial diversity, organic matter content, and soil fertility (Abdel-Gawad and Youssef, 2019). By reducing the reliance on synthetic fertilizers, modern bio-fertilizers mitigate environmental issues such as nutrient runoff and soil pollution (Bashan et al., 2014; Sahito et al., 2021). Advancements in modern bio-fertilizer formulations represent a significant departure from traditional fertilization practices. These formulations are tailored to specific crops and soil conditions, optimizing synergistic interactions between microorganisms and plants for enhanced nutrient uptake. Their potential to improve nutrient management, enhance soil health, and reduce environmental impacts positions them as valuable tools in sustainable agriculture.

Recent scientific research has led to the developing of advanced bio-fertilizer formulations tailored to specific crops and soil conditions (Abdel-Gawad and Youssef, 2019). These formulations optimize synergistic interactions between microorganisms and plants, enhancing nutrient uptake. Scientific studies emphasize the environmental advantages of bio-fertilizers over synthetic fertilizers. Bio-fertilizers mitigate environmental issues such as nitrate leaching and greenhouse gas emissions, aligning with sustainable agriculture goals (Jangid et al., 2011; Sul et al., 2013). Researchers are increasingly tailoring bio-fertilizer applications to specific crops. For example, bio-fertilizers containing Phosphate-solubilizing microbes are designed to improve Phosphorus availability in low-phosphorus soils, benefiting crops like maize (Bashan et al., 2014). Recognizing the importance of quality control and product efficacy, regulatory standards for bio-fertilizers have been established in several countries, including Indonesia (Mahanty et al., 2017). These frameworks ensure that bio-fertilizers meet the necessary standards for responsible agricultural use.

Ongoing scientific research in bio-fertilizers holds promise for further innovations. Future developments may include genetic engineering to create bio-fertilizers with enhanced capabilities and the exploration of novel microorganisms for specific agricultural applications (Meena et al., 2021).

Conclusively, sustainable agriculture is a dynamic interplay of classical wisdom and modern scientific innovations. This synthesis exemplifies the role of beneficial soil microorganisms, the historical use of organic amendments, and the emergence of bio-fertilizers. As sustainable agriculture gains momentum globally, integrating classical principles and modern bio-fertilizer technologies promises to usher in a more sustainable and productive era of food production in harmony with nature.

METHODS

Study area

Within the province of Kalimantan, this research covered various geographical areas with distinctive ecological settings.

Isolation technique for Rhizobium spp.

To isolate Rhizobium spp., intact root nodules from a healthy Sysbania exaltata plant were meticulously chosen. A pink juvenile root nodule was meticulously selected and introduced into a droplet of sterile water in a Petri dish. Following that, the nodule was broken up mechanically between two glass slides. This lets Nitrogen-fixing Rhizobium bacteria into the clean water environment. A carefully applied smear from the broken root nodule was then carefully streaked onto a YEMA plate with 1% Congo red dye added. Following these procedures, the culture was incubated under controlled conditions at a temperature range of 20 to 25°C for three days, by the protocol initially established by Boraste in 2009.

Isolation of Phosphobacteria from Rhizoids

Soil sample collection: Soil specimens were collected from various agricultural sites, each characterized by distinct soil compositions and agronomic practices (Vatsyayan et al., 2013).

Serial dilution method: 10 grams of soil sample was solubilized within 100 ml of distilled water, ensuring thorough homogenization. Subsequently, the soil sample was subjected to a systematic serial dilution process, resulting in a gradient of dilutions spanning from 10^1 to 10^7. The 10^5, 10^6, and 10^7 dilutions were then judiciously selected for utilization within the spread plate technique (Reynolds 2005).

Spread plate technique: Nutrient agar medium was poured into designated petri dishes. When the culture medium was fully set, 0.1 ml portions from the 10^5, 10^6, and 10^7 dilutions were carefully spread out on the nutrient agar medium plates. These plates were subsequently subjected to an incubation regimen sustained at 37°C over 24 hours.

Standardization criteria

In conformity with established industry standards, bio-fertilizers must adhere to stringent criteria. 15 days after they were made, the inoculants should show a carrier-based formulation with at least 10^8 viable cells per gram of carrier material, calculated on a dry mass basis. Moreover, the shelf life of the inoculums should be at most 12 months from the production date. Contaminants represent a paramount concern within the bio-fertilizer industry and should be conspicuously absent from the inoculants. Maintaining the pH of the inoculant within the range of 6.0 to 7.5 is imperative. Each bio-fertilizer packet should bear essential labelling information, including product nomenclature, target leguminous crop, manufacturer's identity, production batch number, and expiration date. In addition, packets should prominently display the ISI quality certification mark. To ensure product integrity, it is essential to store bio-fertilizers in a cool environment, well protected from direct heat.

Economic growth medium preparation for PSB

A cost-effective substitute for King's B broth, tailored for Pseudomonas spp., was devised, comprising the following components:

- Fish extract: 10 ml
- Algal water: 25 ml
- Aloe vera extract: 5 ml
- Tap water: 100 ml
- pH adjusted to 7.2

The resultant broth was meticulously prepared, subsequently inoculated with Pseudomonas fluorescens, and then subjected to incubation at a controlled temperature of 27°C for 24 hours, utilizing a rotary shaker for optimized culture agitation (Shankar et al., 2013).

RESULTS AND DISCUSSION

The focus of the current study area for sustainable agriculture land is Kalimantan Province, Indonesia. It is the Indonesian part of Borneo and boasts a multifaceted agricultural landscape pivotal to Indonesia's economy. This province is distinguished by extensive palm oil and rubber plantations, benefiting from the region's fertile soil and tropical climate. Rice paddies are widespread, serving as a staple food source locally and for exports. Fruit orchards feature Durian, Banana, Pineapple, and Citrus groves, capitalizing on the tropical climate. Sustainable forest agriculture yields Rattan, Spices, and Timber. Aquaculture is also significant, with fish farms and Shrimp ponds. Traditional subsistence farming is found in remote areas, while sustainability practices address deforestation and land-use conflicts. Kalimantan's agriculture is a dynamic blend of economic opportunity and environmental responsibility (Figure 1).

Figure 2: Kalimantan province of Indonesia (https://shorturl.at/cewx0)

Table 1 provides a comprehensive analysis of the comparative effects of organic fertilizers vis-à-vis chemical fertilizers on crop yields, encompassing a rich array of crop varieties, spanning both cereals like Wheat, Rice, Maize, Sorghum, and Sugarcane, and horticultural specimens such as Potato, Carrot, Cauliflower, Tomato, and Cotton. Significantly, the data underscores the magnitude of yield enhancement attributable to organic fertilization, revealing a spectrum of responses. For instance, Rice exhibits a modest 3% incremental gain, while Cauliflower displays an impressive 30% surge in yield. Notably, the dataset also highlights significant intra-crop variability, typified by Maize and Sugarcane, underscoring the multifaceted influence of edaphic factors and climatic conditions. This implies the necessity of a nuanced approach to fertilizer selection, contingent upon the precise geo-agricultural context. Furthermore, the table obliquely advocates for ecologically sound agricultural paradigms, elucidating the potential ecological merits of organic fertilizers, including ameliorated soil Microbiome, enhanced nutrient retention, and mitigation of chemical leaching. In summation, the table, steeped in scientific rigour, serves as an invaluable reference for agronomists and researchers, enticing judicious choices to optimize crop productivity while preserving agroecological equilibrium.

A study published in "Communications in Soil Science and Plant Analysis" in 2020, conducted by Hammad et al., delved into the comparative effects of organic and chemical fertilizers on various crops. The study examined several crop types, including Wheat, Rice, Maize, Sorghum, and Sugarcane, as well as horticultural varieties such as Potato, Carrot, Cauliflower, Tomato, and Cotton. Adediran et al. (2005) reported a range of findings regarding the percentage increase in crop yields associated with using organic fertilizers compared to chemical fertilizers. Notably, they found that the response to organic fertilization varied significantly among different crops. For example, Rice exhibited a relatively modest 3% increase in yields, while Cauliflower demonstrated a remarkable 30% boost in production. The study also highlighted significant intra-crop variability, particularly in the cases of Maize and Sugarcane, underscoring the multifaceted influence of environmental factors such as soil quality and climate on yield responses.

The research by Bless et al. (2023) resonates with the broader literature on sustainable agriculture and aligns with the principles of organic farming. Organic fertilizers are recognized for their potential environmental benefits, including enhanced soil microbiome, improved nutrient retention, and reduced chemical leaching (Siedt et al., 2021). Comparative analysis of the environmental impacts of agricultural production systems, agricultural input efficiency, and food choice (Clark and Tilman, 2017). This study adds to the body of knowledge supporting the advantages of organic fertilizers in sustainable agriculture, as Smith et al.'s (2010) work serves as an example. The variability in crop responses emphasizes the importance of tailored fertilizer selection based on specific local conditions. Furthermore, it underscores the significance of adopting ecologically sound agricultural practices to optimize crop productivity while preserving environmental equilibrium.

Table 1: Influence of Azotobacter on crop yield

S.No	Name of Crop	Percentage Rise in Yields Compared to Those Achieved with Chemical Fertilizers	S.No	Name of Crop	Percentage Rise in Yields Compared to those Achieved with Chemical Fertilizers
1.	Wheat	5-7	1.	Potato	11
2.	Rice	3	2.	Carrot	13
3.	Maize	7-9	3.	Cauliflower	30
4.	Sorghum	8-15	4.	Tomato	2-10
5.	Sugarcane	4-20	5.	Cotton	5-15

For example, the table shows different types of bio-fertilizers and how they are supposed to be used in crop cultivation. This shows how chemical fertilizer needs might go down. It commences with a serial number (S.No.) column as a unique identifier for each entry. The "Bio-fertilizer" column enumerates several bio-fertilizers, encompassing Azolla Pinnata in both its fresh and desiccated forms, Azotobacter Chroococcum, Azospirillum Lipoferum, Acetobacter Diazotrophicus, Rhizobium spp., and Bacillus Circulans. These bio-fertilizers have been strategically chosen to cater to various crops, including but not limited to Rice, Potato, Wheat, Sorghum, Sugarcane, Maize, Cotton, and Cowpea.

In particular, the "Conservation of Chemical Fertilizers" column is important because it shows how much less chemical fertilizer could be used if these bio-fertilizers were used. It illuminates that Azolla Pinnata (fresh) used in Rice cultivation can mitigate the demand for Nitrogen (N) chemical fertilizers by an estimated 20–30 kilograms. Similarly, adopting Bacillus Circulans in Cowpea cultivation can potentially curtail the necessity for phosphorus (P205) chemical fertilizers by a range of 10–30 kilograms.

This tabular representation is a scientifically grounded reference for agricultural practitioners, facilitating judicious decision-making regarding bio-fertilizer deployment. By leveraging these bio-fertilizers, farmers can optimize nutrient management strategies in crop production, reducing their reliance on synthetic chemical fertilizers. This approach aligns with sustainable agricultural practices by mitigating the environmental impact of excessive chemical fertilizer use while enhancing soil health and crop productivity through the biological Nitrogen fixation and Phosphorus solubilization mechanisms offered by these bio-fertilizers.

The table offers a valuable glimpse into bio-fertilizers potential to optimize nutrient management in agriculture while reducing reliance on chemical fertilizers. This aligns with broader scientific research in sustainable agriculture and soil science. For instance, studies such as "Symbiotic Nitrogen Fixation in Legumes by Bruning, B., and Rozema (2013) emphasize the role of Nitrogen-fixing bacteria like Rhizobium spp. in enhancing Nitrogen availability to plants, reducing the need for synthetic Nitrogen fertilizers.

The use of Azolla pinnata, both in its fresh and dry forms, to benefit Rice and Potato/wheat crops aligns with research on the Nitrogen-fixing potential of Azolla. Pabby et al. (2003) discuss the symbiotic relationship between Azolla and Nitrogen-fixing Cyanobacteria, which can significantly contribute to Nitrogen availability in paddy fields.

Moreover, the application of Acetobacter Diazotrophicus for Sugarcane aligns with studies such as " Diversity of culturable plant growth-promoting bacterial endophytes associated with Sugarcane roots and their effect on growth by co-inoculation of Diazotrophs and Actinomycetes " by Kruasuwan and Thamchaipenet (2016) which explores the beneficial effects of Diazotrophic bacteria on sugarcane growth and Nitrogen uptake.

As presented in the table, the conservation of chemical fertilizers is a critical aspect of sustainable agriculture. The potential reduction in Nitrogen and Phosphorus fertilizers is corroborated by numerous studies emphasizing the environmental and economic benefits of reducing chemical fertilizer usage, including "Fertilizer and pesticide reduction in Cherry Tomato production to achieve multiple environmental benefits in Guangx" by Guo et al. (2021) and "Phosphorus Runoff from Agricultural Soils" by Hart et al. (2004), Journal of Environmental Quality.

Table 2: Bio-fertilizers employed for crop cultivation

S.No.	Bio-Fertilizer	Crop	Conservation of Chemical Fertilizers
1.	Azolla pinnata (fresh)	Rice	20-30 kg N
2.	Azolla pinnata (dry)	Potato and Wheat	20-40 kg N
3.	Azotobacter chroococcum	Sorghum, Sugarcane, Maize,Potato, Cotton	10-30 kg N
4.	Azospirillum lipoferum	Maize and Sorghum,	10-30 kg N
5.	Acetobacter diazotrophicus	Sugarcane	60 kg N
6.	Rhizobium spp	Sorghum	20-40 kg N
7.	Bacillus circulans	Cow pea	10-30 kg P205

The table lists various agricultural inoculant products, details about the associated organizations, the specific microorganisms they contain, and the crops they are designed for. These products play a crucial role in agriculture by enhancing crop growth and yields by introducing beneficial microorganisms into the soil. One of the products, "Nitragin TM," is offered by Nitragin Sales Corporation in Wisconsin and contains Rhizobium. This particular inoculant is tailored for soybean cultivation, where Rhizobium forms a symbiotic relationship with Soybean plants, aiding in Nitrogen fixation from the atmosphere. "Rhizocote," distributed by Coated Seed Ltd. in New Zealand, also contains Rhizobium and is designed for legume crops. Similarly, "Nodosit" from Uniob Chemiques S.A. in Belgium is intended for legume cultivation and employs Rhizobium as its active microorganism.

Another product, "Nitrazina" from Wytwornia Walcz in Poland, contains Azotobacter and is specifically formulated for cereals and vegetable crops. Azotobacter helps in Nitrogen cycling and improves nutrient availability for these crops. The "N-germ" product from Laboratoire de Microbiologie in France utilizes BGA (Blue-Green Algae) and is beneficial for Rice cultivation. Blue-green algae plays a role in Nitrogen fixation and is valuable for rice production. "Tropical inoculants," focusing on Azotobacter, are suitable for rice and wheat crops. These inoculants are adaptable to tropical climates, where Nitrogen-fixing bacteria like Azotobacter can enhance soil fertility. "Nodulaid," produced in Brisbane by the Queensland Agricultural Lab, employs Rhizobium and is tailored for legume crops, similar to other Rhizobium-based products.

Lastly, "Azotobacterin" from Tashkent Laboratories in Moscow contains Azotobacter and is beneficial for vegetable and cereal crops. Azotobacterin helps improve nutrient availability and soil health in these agricultural systems.

These agricultural inoculant products and their associated microorganisms are vital for sustainable farming practices, enhancing crop productivity, and contributing to more efficient nutrient cycling in various crop types and geographical regions.

Table 3: Bio-fertilizers readily available on the market, the types of crops they support, and the microorganisms associated with their agricultural use

Product Name	Organization Details	Microorganisms	Crops Name
Nitragin TM	Nitragin Sales Corpn.Wisconsin, 53209	Rhizobium	Soyabean
Rhizocote	Coated Seed Ltd, Nelson, New Zealand	Rhizobium	Legumes
Nodosit	Uniob Chemiques S.A. Belgium	Rhizobium	Legumes
Rhizonit	Phlylaxia Allami Budapest, Hungary	Rhizobium	Legumes
Nitrazina	Wytwornia Walcz Poland	Azotobacter	Cereals and vegetables
N-germ	Laboratoire de Microbiologie, France	BGA	Rice
Tropical inoculants	Tropical inoculants	Azotobacter	Rice and Wheat
Nodulaid	Brisbane, Queensland Agricultural Lab.	Rhizobium	Legume
Azotobacterin	Tashkent laboratories Moscow	Azotobacter	Vegetable and cereals.

Theoretical implications of the study

The comprehensive study on sustainable agriculture and the role of bio-fertilizers has profound theoretical implications that span a wide range of key areas within the agricultural field. Firstly, it advances agricultural theory by amalgamating traditional wisdom with contemporary scientific insights, bridging the gap between age-old practices and modern innovations. This integration contributes to a more comprehensive understanding of sustainable agriculture, encompassing time-tested knowledge and innovative methodologies. Additionally, the study underscores the importance of adopting a holistic sustainability framework in agriculture, emphasizing crop productivity, soil health, environmental impact, and long-term food security. This integrated approach provides a robust theoretical foundation for sustainable agricultural practices.

Furthermore, the study reaffirms the pivotal role of soil microorganisms in sustainable agriculture and highlights the theoretical potential of bio-fertilizers as sustainable solutions for nutrient management and soil enhancement. It also brings environmental considerations to the forefront, advocating for practices that reduce synthetic fertilizer use and mitigate ecological issues. These theoretical insights encourage the development of agricultural theories that prioritize sustainability and address the global challenges of food security and environmental preservation. The study's interdisciplinary approach further underscores the need for diverse perspectives in agriculture, recognizing it as a multidisciplinary field that benefits from integrating Microbiology, Ecology, Agronomy, and Environmental science. The study's theoretical implications provide a solid foundation for the evolution of agricultural theories aligned with the imperatives of sustainable food production and ecosystem conservation.

Practical implications of this study

The comprehensive examination of sustainable agriculture and bio-fertilizers role offers valuable insights with far-reaching implications for agricultural practices, policymaking, and research endeavors. Firstly, it encourages the adoption of enhanced soil management practices. Farmers and agricultural practitioners can utilize these insights to prioritize soil health, utilizing bio-fertilizers and organic amendments to boost nutrient availability and crop productivity. The study's results can also be used to make useful guidelines for applying bio-fertilizer, such as how to mix and use it. These guidelines will help farmers get the most out of bio-fertilizer use to get better crops and use less synthetic fertilizers.

Additionally, the study encourages effective crop rotation strategies, especially those that include leguminous crops, to take advantage of the soil's Nitrogen-fixing abilities, improve its fertility, and lower its need for Nitrogen fertilizer. It underscores the importance of environmental sustainability, prompting farmers and policymakers to minimize nutrient runoff, soil degradation, and greenhouse gas emissions through sustainable agricultural practices. The study's focus on customized nutrient management plans, quality control and certification, research priorities, educational programs, policy formulation, international cooperation, economic viability assessment, and even soil microorganisms for environmental remediation gives useful information to many groups, encouraging them to work together for long-term farming, better food security, and environmental protection.

Limitations

This study on sustainable agriculture and the pivotal role of bio-fertilizers offers valuable insights while acknowledging certain limitations. It primarily focuses on aspects of sustainable agriculture, including bio-fertilizer benefits, such as enhanced soil fertility and reduced environmental impact. However, its limitations include a narrow scope, temporal constraints, and potential geographic bias. It also relies on research from specific regions, possibly overlooking regional variations. The review's qualitative approach limits its quantitative data analysis, which could have provided more robust statistical insights. While it acknowledges bio-fertilizers benefits, it only partially assesses their environmental impact. A more in-depth economic analysis and a forward-looking perspective on future trends and innovations could have added depth to the study. Despite these limitations, the study serves as a valuable starting point for understanding sustainable agriculture and bio-fertilizers, offering practical insights for stakeholders in the agricultural sector.

Future research directions

Future research in the realm of sustainable agriculture and bio-fertilizers holds immense promise, with several key directions deserving attention. One vital avenue involves unravelling the intricate biological mechanisms underlying bio-fertilizer interactions with plants and soil Microbiota, delving into molecular and genetic levels for deeper insights. Tailoring bio-fertilizer formulations to specific crops, soil types, and Agro ecological contexts is another imperative, maximizing their synergistic effects. Long-term field trials can shed light on the sustained impacts of bio-fertilizers, which is crucial for gauging their durability in real-world scenarios. In parallel, comprehensive economic analyses must assess the financial implications of bio-fertilizer adoption, aiding decision-making for farmers and policymakers alike.

Furthermore, an extensive examination of the environmental impact, encompassing soil health, water quality, and greenhouse gas emissions, is essential. Integrating bio-fertilizers into holistic soil health management strategies, research into climate-resilient agriculture, and efforts to enhance global collaboration in sustainable agricultural practices all form integral facets of future research. Additionally, the research agenda is essential to the scaling-up of bio-fertilizer production methods, understanding farmers' perspectives and knowledge gaps, policy analysis, and education and outreach initiatives. Finally, exploring emerging technologies like precision agriculture to optimize bio-fertilizer applications can further enhance nutrient management practices. Collaboration among diverse stakeholders will be pivotal in addressing the multifaceted challenges of sustainable agriculture in the years ahead.

CONCLUSION

In conclusion, Indonesia's quest for food security, particularly in Kalimantan, faces land encroachment challenges. To address this, the Food Estate (FE) program is key, relying on improved land management and infrastructure. Bio-fertilizers, rooted in advanced microbiology, offer a sustainable solution by enhancing soil fertility and reducing ecological harm compared to chemical fertilizers. Indonesia is increasingly adopting these bio-fertilizers to bolster crop yields and soil health. Their potential for eco-friendly agriculture aligns with global sustainability goals, making them a promising tool for Indonesia's agricultural future.

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