Research Article

Samijan, Sri Minarsih, Sodiq Jauhari, Seno Basuki, Arif Susila, Endah Nurwahyuni, Yulis Hindarwati, Agus Supriyo, Vina Eka Aristya*

Revitalizing sub-optimal drylands: Exploring the role of biofertilizers

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Abstract: Indonesia has a dry land area of 79.69%, with low soil productivity (physical, chemical, and biological), as well as uneven and unpredictable rainfall. The dryland potential is optimally utilized using biofertilizers that can produce microbes to increase soil fertility. This research aims to determine the effects of biofertilizers on dryland improvement and crop production. The study was conducted from February to May 2021 in Central Java, Indonesia. Using a randomized block design in peanut cultivation. Six biofertilizers (Controlled, Agrimeth, BioNutrient, Gliocompost, Agrimeth + BioNutrient, Agrimeth + BioNutrient + Gliocompost) were applied with four replications. The performance of each biofertilizer was assessed based on chemical soil parameters, soil microbe population, plant growth, and yields. The soil in the study area belonged to the Inceptisols group and exhibited moderately acidic pH, low organic carbon content, and low nitrogen levels. However, it had high potential and available phosphorus, as well as moderate potential and high available potassium. BioNutrient and Gliocompost increased available phosphate by 12 and 19%, respectively, due to the presence of *Pseudomonas fluorescens* and *Aspergillus* sp. Agrimeth influenced the population of *Azospirillum* (45–63%) and enhanced phosphate-solubilizing bacteria. Agrimeth + BioNutrient + Gliocompost promoted the growth of the *Azospirillum* and *Trichoderma* populations (17–18%), resulting in a 45.04% increase in profits. Biofertilizer inoculation positively affected peanut development, root nodule formation, and yield. This novelty showed the potential of biofertilizers in improving dryland conditions, increasing crop productivity, and contributing to sustainable agriculture in the long term.

Keywords: crop production, dryland improvement, biofertilizer, soil fertility, sustainable agriculture

*** Corresponding author: Vina Eka Aristya,** Research Organization for Agriculture and Food, National Research and Innovation Agency (BRIN), Cibinong Science Center, Jl. Raya Jakarta-Bogor Km. 46, Cibinong, Bogor, 16911, Indonesia, e-mail: vina002@brin.go.id
Samijan, Sri Minarsih, Sodiq Jauhari, Arif Susila, Endah Nurwahyuni, Yulis Hindarwati, Agus Supriyo: Research Organization for Agriculture and Food, National Research and Innovation Agency (BRIN), Cibinong Science Center, Jl. Raya Jakarta-Bogor Km. 46, Cibinong, Bogor, 16911, Indonesia
Seno Basuki: Research Center for Social Welfare, Villages and Connectivity, National Research and Innovation Agency, Jl. Gatot Subroto 10, Jakarta Selatan, Jakarta, 12710, Indonesia

1 Introduction

The program to increase food production still relies heavily on the potential of lowland fields, while the opportunities and potential of dryland are yet to be optimally utilized. In general, dryland has lower productivity. Most of the dryland in Indonesia is in less than optimal (sub-optimal) conditions. Sub-optimal land is defined as land that naturally has low productivity due to internal (physical, chemical, and biological soil conditions) and external (such as rainfall and temperature) limiting factors [1].

Sub-optimal land use will be the foundation of hope for the future, but it requires technological innovation to overcome the obstacles according to the characteristics and typology of the land. Due to the limited reserves of fields, it must immediately change the orientation by preparing alternatives to increase production on dryland to meet national food needs.

Dryland in Indonesia was about 79.69% of the existing land area, while lowland fields are only 20.31% [2]. Central Java province has 712,111 ha of dryland and 18,546 ha of lowland fields [3]. The sub-optimal land was identified as an acidic sub-optimal dryland of 34.3% and a dry sub-optimal climate of around 19.8% in Central Java [1]. Sub-optimal dryland in Central Java is generally dominated by food crop development such as upland rice, corn, peanuts, soybeans, and cassava with varying cropping patterns, monoculture, and intercropping [4].

As one of the sub-optimal lands, dryland productivity can be increased through adaptive technological innovations supported by appropriate land management technology [5].

The main constraints on dryland revolve around the problems of moderate to high acidity levels, low availability of macronutrients, organic C content, cation exchange capacity, and base saturation [6]. In addition, the elements of Al and Fe are also usually high. These element factors inhibited nutrient availability and can be concentrated in the root, so it has the potential to inhibit the availability of essential elements to poison plants [7–9]. These conditions encourage the need for research on adaptive agricultural technology to increase sub-optimal dryland productivity.

Land enhancement technology should be prioritized to reduce the effect of low soil fertility using ameliorant materials such as dolomite, organic matter, biochar, and biofertilizers [10,11]. Biofertilizers are non-pathogenic microbial-based fertilizers that increase soil fertility and health through several activities produced by these microbes, including fixing nitrogen, dissolving phosphates, and producing phytohormones [12].

Soil fertility determines plant growth and productivity. Land improvement with biological fertilizers is a technological innovation for increasing dryland productivity. Biological fertilizers such as Agrimeth and BioNutrient and Gliocompost have been reported to contain several microbes, including *Methylobacterium* sp., *Azotobacter* sp., *Bacillus* sp., *Rizhobium* sp., and *Bradyrhizobium japonicum* [13,14].

Agrimeth contains nitrogen-fixing and phosphate-solvent microbes. BioNutrient contains *Alcaligenes*, *Azospirillum* sp., and *Bacillus* sp. microbes. Furthermore, Gliocompost contains *Azotobacter* sp., *Azospirillum* sp., *Bacillus* sp., and *Pseudomonas fluorescens* [7].

The microbes have enzymatic activity as well as phytohormones. They have a positive effect on macro and micronutrient uptake in the soil, promoting growth, flowering, seed ripening, breaking dormancy, increasing seed vigor and viability, efficient absorption of inorganic compound fertilizers, and crop productivity.

Methylobacterium inoculation can induce plant resistance to diseases caused by pathogens [15,16]. Biofertilizers containing *Azospirillum* sp. and *Azotobacter* sp. [17] significantly increased rice growth variables and compound fertilizer uptake. Arbuscular mycorrhizae and rhizobium interaction with their host plants increased nitrogen and phosphorus uptake, resulting in the highest dry weight and seed yield [18].

Biofertilizers are expected to be an alternative technology that can help improve nutrient balance in the soil. It can sustainably increase land and plant productivity [10,19]. This research aims to determine the effect of biofertilizers on land improvement and crop production.

2 Materials and methods

The study employed a randomized block design in peanut cultivation, with the experimental plots set up in sub-optimal dryland in Watangrejo, Pracimantoro, Wonogiri, Central Java, Indonesia (−8.097180 S, 110.800758 E). The study period lasted from February to May 2021.

The design involved six treatments and four replications, resulting in a total of 24 experimental plots. The treatments included a control group (P1) and five different biofertilizer treatments: Agrimeth (P2), BioNutrient (P3), Gliocompost (P4), Agrimeth + BioNutrient combination (P5), and Agrimeth + BioNutrient + Gliocompost combination (P6). Biofertilizers were applied through seed treatment, with any remaining solution sprinkled onto the land according to each treatment.

The study involved multiple observations and analyses. Chemical soil parameters, such as pH, organic carbon, total nitrogen (N), potential phosphorus (P), potential potassium (K), available P, and available K, were assessed. The population of soil microbes, including *Azotobacter* sp., *Rhizobium* sp., *Azospirillum* sp., *Trichoderma* sp., and phosphate-solubilizing bacteria, was measured at the beginning and end of the study.

Soil samples and microbes were collected and analyzed in Chemistry Laboratory at the Assessment Institute for Agricultural Technology of Central Java. Agrometeorological data, necessary for assessing the study's supporting data on the climatic conditions, were obtained from the Prediction of Worldwide Energy Resource (POWER) Data Access Viewer [20].

Plant growth parameters, such as plant height, canopy diameter, number of branches, and number of root nodules, were recorded. Plant yields, including stover, unpeeled peanut, seed weight, and overall yield, were also determined.

The data on plant growth and yields were analyzed both descriptively and statistically. Descriptive analysis involved summarizing and presenting the data using appropriate statistical measures. The Duncan Multiple Range Test was applied to compare the means among different treatments. This test helps identify significant differences between treatment groups [39].

In terms of economic feasibility, the analysis uses a simple benefits analysis and Marginal Benefit Cost Ratio (MBCR) approach. Benefits analysis was focused on considering only the differences in main inputs and yields [21], while MBCR determined the feasibility of new technology (NT). This analysis aims to assess the economic feasibility of changing treatment compared to farmers' practices. MBCR was calculated as added returns by shifting to NT from farmer technology/additional costs incurred by shifting to NT. The use of NT was considered feasible if the increase in the value of profits was MBCR >2 [22].

3 Results

3.1 Soil characteristics

The site land has chemical characteristics that were relatively less optimal for plant growth, such as moderately acidic soil pH and low content of soil organic C and N. The potential P and available P elements were in high status, whereas the content of potential K was moderate and available K was high. This condition indicates an imbalance of nutrients in the soil, causing land productivity to be less than optimal. The potassium content in the soil was seen to decrease descriptively but did not change the status of the category, which was very high. The decline that occurred descriptively in all treatments was thought to be due to environmental factors, and very high rainfall throughout the study, because of which there was leaching of potassium elements. The average potassium after biofertilizer treatment was still higher than the control (Table 1).

3.2 Climate condition

In addition to limiting issues induced by soil characteristics, sub-optimal drylands are also confronted with environmental limits, particularly unpredictable rainfall, and temperature. The research location was dryland with a humid climate with an uneven distribution pattern of rainfall throughout the year. The average rainfall under normal conditions was around 1,400 mm/year, with a dry month range (<60 mm/month) of 6 months [23]. The climatic conditions during the research period (February–May 2021) are shown in Figure 1.

The rainfall data during the research period (from day 59 to 151 in 2021) were far beyond normal conditions, reaching about 520 mm/3 months or about 170 mm/month, with an average air temperature of around 26°C at the soil surface. The soil moisture in the root zone was at a level of 0.9. Soil moisture at level 0.9 indicates that the soil was almost always saturated with water, almost 90% of the entire soil pore space (Figure 1).

3.3 Soil microbiology

Land improvement using biological fertilizers affects the soil's microbial population before and after the study. The *Azospirillum* population increased significantly in the range of 45–63% compared to that before the study and increased by 0.6–13% from the control without biological fertilizers. The combination of Gliocompost + BioNutrient + Agrimeth increases the *Azospirillum* population. Meanwhile, the combined application of Agrimeth + BioNutrient increased the *Azospirillum* population, which was lower than the single application but still higher than the control. The Trichoderma population increased by 17–18% from before the study but was not significantly different from the control, with an average increase of 0.36–1.48%. The combination Gliocompost + BioNutrient + Agrimeth also intensifies the Trichoderma population (Figures 2–4, Table 2).

3.4 Plant growth

Research on the effect of biofertilizers on the growth and production of peanuts was carried out during one growing

Table 1: Soil chemical properties before and after the study

Detail	pH_H_2O	pH_KCl	C Org	Total N (Kjeldahl)	P_2O_5_HCl	K_2O_HCl	P_2O_5 (Olsen)	Available K (Morgan)
Before	5.89	5.00	1.24	0.19	56.79	19.64	20.71	232.84
	Moderately acid	Acid	Low	Low	High	Moderate	Very high	Very high
P1	5.70	4.79	1.14	0.18	30.33	27.24	19.34	146.73
P2	5.78	4.81	1.23	0.18	31.14	27.31	18.36	154.68
P3	5.82	4.80	1.11	0.18	32.86	28.10	23.25	156.31
P4	5.77	4.75	1.18	0.18	34.38	19.10	24.68	223.58
P5	5.79	4.80	1.08	0.17	34.96	21.31	21.24	199.87
P6	5.74	4.78	1.14	0.18	38.16	24.46	22.57	211.76
	Moderately acid	Acid	Low	Low	Very high	Very high	Very high	Very high

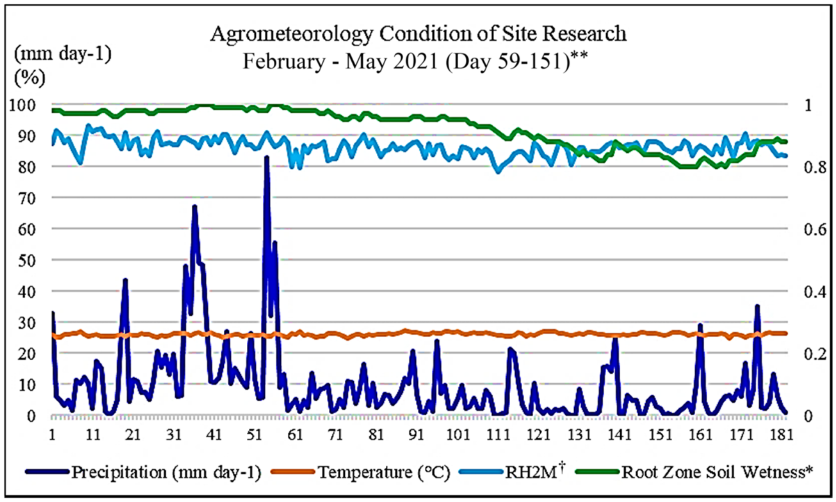

Figure 1: Climate condition. *The root zone wettability percentage value of 0 indicates that the soil was completely free of water and a value of 1 indicates the soil was completely saturated, where the root zone was the layer from the surface 0 to 100 cm below the soil. †RH2M is the relative humidity (%) at 2 m. **Source of data: NASA POWER Data Access Viewer-Prediction of worldwide energy resource-agro climatology location of latitude −8.0972, longitude 110.8008, 2021. https://power.larc.nasa.gov/data-access-viewer/.

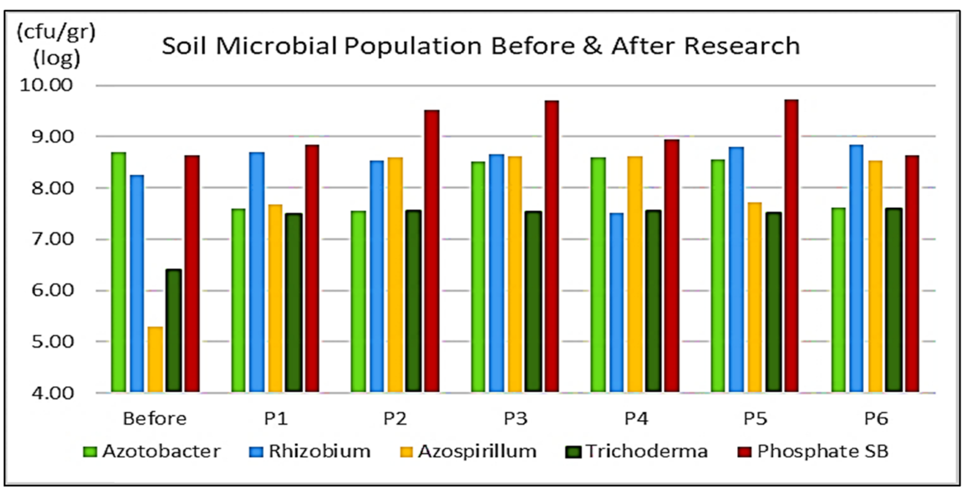

Figure 2: Soil microbial populations before and after biofertilizer application.

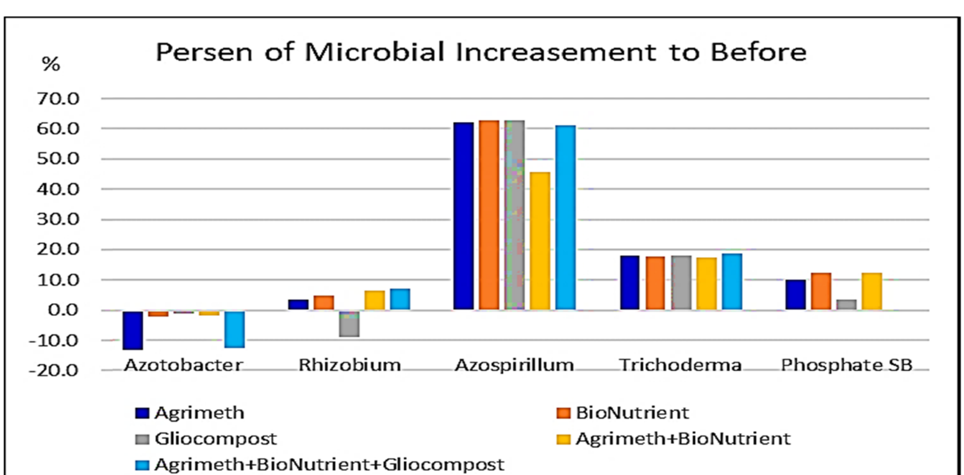

Figure 3: Percentage increase in microbial in biofertilizer application from before treatment.

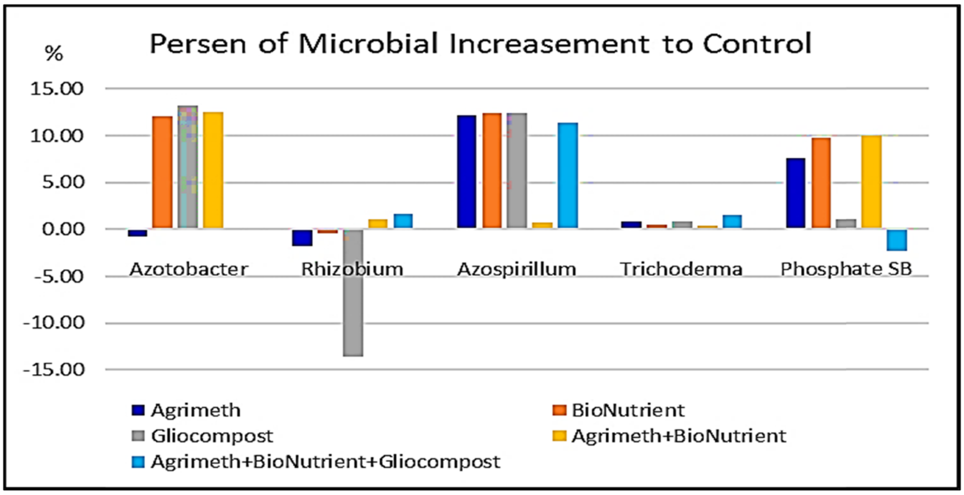

Figure 4: Percentage increase in microbial in biofertilizer application compared to control.

Table 2: Soil microbial characteristics before and after the study

Treatment		Microbial population (cfu/g)				
		Azotobacter sp.	*Rhizobium* sp.	*Azospirillum* sp.	*Trichoderma* sp.	Phosphate-solubilizing bacteria
Before	P01	3.4×10^8	4.0×10^7	3.2×10^4	1.9×10^6	3.8×10^8
	P02	6.8×10^8	3.2×10^8	3.7×10^5	3.2×10^6	5.0×10^8
After	P1	4.0×10^7	5.0×10^8	4.7×10^7	3.1×10^7	7.0×10^8
	P2	3.5×10^7	3.5×10^8	4.0×10^8	3.6×10^7	3.3×10^9
	P3	3.3×10^8	4.6×10^8	4.2×10^8	3.4×10^7	5.1×10^9
	P4	4.0×10^8	3.3×10^7	4.2×10^8	3.6×10^7	8.7×10^8
	P5	3.6×10^8	6.2×10^8	5.3×10^7	3.3×10^7	5.3×10^9
	P6	4.1×10^7	7.0×10^8	3.5×10^8	4.0×10^7	4.3×10^8

season. The average value of the peanut plant growth variable in biological fertilizer treatments is presented in Table 3.

The application of biological fertilizers did not significantly affect the peanut's growth component, due to very high rainfall during the study, which was 170 mm/month. Meanwhile, peanut plants require ideal growing conditions such as 800–1,300 mm/year rainfall or equivalent to 100–200 mm/month wet or about 3–7 mm/day; 28–30°C air temperature; humidity 65–75%; and slightly moist soil with good drainage (Table 3).

Table 3: Peanuts growth variables

Treatment	Plant high 38 DAP** (cm)	Plant high 92 DAP** (cm)	Plant canopy diameter 38 (cm)	Plant canopy diameter 66 (cm)	Branch number 38 DAP	Branch number 66 DAP**	Root nodule number
P1	24.9a*	50.5a*	26.0a*	44.2a*	6a*	6a*	45a*
P2	24.6a	51.2a	25.3a	46.0a	6a	7a	65ab
P3	23.7a	52.9a	26.2a	47.3a	6a	7a	74abc
P4	24.2a	46.4a	26.9a	48.0a	7a	7a	76bcd
P5	23.2a	52.1a	27.7a	46.4a	6a	7a	105d
P6	24.6a	52.9a	26.7a	44.5a	6a	7a	97cd

*The same letter in the same column was not significantly different based on DMRT 5%. **DAP – days after planting.

Table 4: Peanut yield components

Treatment	Fresh stover (g)	Dry stover (g)	Fresh unpeeled peanut (g)	Dry unpeeled peanut (DUP) (g)	Unpeeled pithy	Unpeeled empty	Dry seed weight (g)	Yield (t/ha) DUP**
P1	61.13a*	18.32a*	24.13a*	16.32a*	20a*	4a*	12.98a*	2.85a*
P2	65.89a	19.72a	30.21abc	21.50ab	22a	5a	16.23ab	2.98a
P3	76.51ab	23.01ab	25.58ab	17.38a	21a	6a	13.22a	2.91a
P4	77.65ab	22.95ab	34.81abc	21.62ab	23a	4a	16.72ab	3.48a
P5	114.23c	33.99c	37.78c	25.96b	26a	5a	19.08b	3.67a
P6	102.44bc	30.81bc	36.70bc	25.41b	26a	5a	20.25b	4.03a

*The same letter in the same column was not significantly different based on DMRT 5%. **DUP – Dry Unpeeled Peanut.

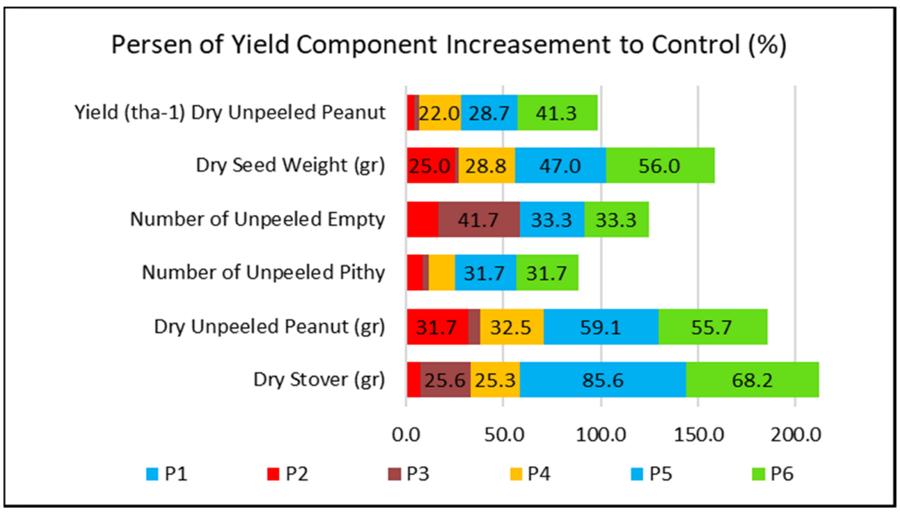

Figure 5: Peanut yield components on biofertilizers application.

3.5 Yield

The study on land improvement using biological fertilizers was also carried out to see its effect on peanut crop yields. The use of biological fertilizers for land improvement is yet to show a significant effect on peanut yields. The resultant yields show a positive tendency to increase in one growing season, with relatively abnormal weather conditions. Data on the components and yield of peanuts in several biofertilizer treatments are presented in Table 4 and Figure 5.

3.6 Benefit analysis

The MBCR calculation was derived from total production costs (seeds, fertilizer, labor) that change due to the new implementations of soil amelioration using a biofertilizer and revenue from the sales of peanuts. MBCR can be determined by the difference between profits and costs that can be achieved by implementing introduced innovations. The highest increase in benefit was achieved by applying a combination of three types of biofertilizers (Agrimeth + BioNutrient + Gliocompost), with an increase in the yield of 45.04% (Table 5).

4 Discussion

4.1 Soil characteristics

The research was conducted in a dryland area with Inceptisols (Typic Dystrudepts) soil, which has a loamy clay texture. The limitations of this soil type resulted in conditions that were less than optimal. To determine the effect of using biofertilizers on land improvement, the chemical and biological properties of the soil before and after the treatment were studied. Some of the soil chemical characteristics included pH, organic C content, total and available N, total and available P, and total and available K. The

Table 5: Benefit analysis in the assessment of soil amelioration

Treatment	Total Cost (IDR/ha)	Yield (t/ha)	Revenue (IDR/ha)	Benefit (IDR/ha)	Increase				MBCR
					Cost		Revenue		
					IDR/ha	%	IDR/ha	%	
P1	3,590,000	2.85	22,804,480	19,214,480	–	–	–	–	–
P2	4,024,000	2.98	23,827,200	19,803,200	434,000	1.21	588,720	3.06	1.36
P3	3,850,000	2.91	23,283,200	19,433,200	260,000	0.07	218,720	1.14	0.84
P4	3,674,000	3.48	27,831,040	24,157,040	84,000	0.02	4,942,560	25.72	58.84
P5	4,284,000	3.67	29,354,240	25,070,240	694,000	0.19	5,855,760	30.48	8.44
P6	4,368,000	4.03	32,237,440	27,869,440	778,000	0.22	8,654,960	45.04	11.12

biological characteristics of the soil observed included the populations of *Azotobacter* sp., *Rhizobium* sp., *Azospirillum* sp., *Trichoderma* sp., and solubilizing phosphate bacteria.

Biofertilizer is expected to be an alternative technology that can help improve soil nutrient balance, increase land productivity, and increase plant growth in the long run [10,19,21]. Land improvement using biofertilizers did not show changes in soil chemical properties from before the study. The available nitrogen content (NH_4^+ and NO_3^-) increased significantly while the total nitrogen content was low.

The influence of the activities of symbiotic and non-symbiotic bacteria contained in biofertilizers, such as *Azotobacter, Azospirillum, Bacillus* sp., *Rhizobium* sp., *Pseudomonas* fluorescent, and *Bradyrhizobium*, the available P_2O_5 content remained very high before and after the assessment, there was a tendency that rose descriptively in some biofertilizer treatments.

In the treatment of BioNutrient (P3) and Gliocompost (P4), there was an increase in the content of available P by 12 and 19% compared to before research, and 20 and 27% higher than the control. The increased availability of phosphate elements were thought to be one of the effects of using biological fertilizers containing *Pseudomonas fluorescens* and *Aspergillus* sp.

This increase in the availability of elemental content was the results of previous studies, that the application of biofertilizers containing N-fixing bacteria and phosphate solubilizing microbes + 50% N, P, and K increase soil phosphorus availability [9]. Applying organic and inorganic fertilizers, and biofertilizer packages significantly affect the parameters of organic C and soil available P [24].

4.2 Climate condition

Soil quality and climate conditions were indicators for evaluating increased crop production. Climate change mitigation was needed in managing agriculture based on nutrient-rich soil research. The pattern of suboptimal land management also needs to be driven by policy support [40].

Rainfall that exceeded normal during the study impacted the optimization of land improvement processes and plant productivity by applying biofertilizers. The effectiveness of commercial biofertilizers was incredibly reliant on seasonal and site-specific environmental factors [25]. Flowers would be challenging to pollinate and fall out due to excessive rains. It affects rising soil water content and air moisture, causing poor plant growth and the rotting of some roots and pods [26].

Uncertainty of rainfall intensity and distribution was a major constraint and limiting agriculture factor in dryland. Therefore, in the long run, it was necessary to identify and delineate dryland areas with several main weather factors that often occur to obtain accurate information regarding land potential and alternative technological innovations to be implemented.

An integrated approach of two methodologies, Moderate Resolution Imaging Spectroradiometer and Normalized Difference Vegetation Index data, has been used to estimate the long-term changes in agricultural development areas. Three independent variables (rainfall, temperature, and agricultural area) were used in the multiple regression analysis to understand the impact of the main drivers affecting the crop production indicating an increasing trend in crop production. Correlation analysis indicated that crop production was significantly related to annual rainfall but less sensitive to temperature [27].

4.3 Soil microbiology

The application of biofertilizers seems to increase the population of phosphate-solubilizing bacteria, especially the Agrimeth + BioNutrient combination, by 10–12% before the study. The combination of Agrimeth + BioNutrient also significantly increases the population of phosphate-solubilizing bacteria compared to the control (7–9%).

The use of Gliocompost only caused a slight increase in the population. Even when Gliocompost was combined with Agrimeth and BioNutrient, the phosphate-solubilizing bacteria population decreased slightly. This fact indicates the need for further research on mixing biofertilizers with phosphate-solubilizing bacteria populations. Adding biofertilizer changed the organization of the soil microbial population, backing up this theory. They found that adding biofertilizers had a more significant impact, notably in soil treated with bio sludge and bio sludge + *Azotobacter* [28].

The descriptive explanation confirms the prior knowledge that each biofertilizer tends to change specific microbial populations in suboptimal land. Agrimeth tends to increase the population of *Azospirillum* and phosphate-solubilizing bacteria positively. BioNutrient affects an increase in the populations of *Azotobacter, Azospirillum*, and phosphate-solubilizing bacteria. Meanwhile, Gliocompost tends to increase the population of *Azotobacter* and *Azospirillum*.

The combination of Agrimeth affected the population of A*zotobacter* and phosphate-solubilizing bacteria. Meanwhile, combining the three biofertilizers only increased the *Azospirillum* population. Continuous application of biofertilizers allows the microbial population to persist and grow in the soils, assisting in soil fertility maintenance and contributing to sustainable agriculture [29].

4.4 Plant growth

Applied biofertilizers tend to increase peanut growth by increasing plant height, plant crown diameter, and several branches. This performance was consistent with the findings of the present study, inoculation of *Bacillus subtilis* QST713 resulted in enhanced plant growth and total phosphorus content in cucumber plants and P total. [19,30]. Meanwhile, based on the development of peanuts, Gliocompost biofertilizer significantly influenced the rise in root nodules but was not significantly different from the biofertilizers Agrimeth + BioNutrient.

The use of Agrimeth + BioNutrient has proven to increase the number of nodules, but not statistically significantly different from the control. The combination of Agrimeth + BioNutrient produced the highest increase in root nodules. The number of nodules increased in the Agrimeth + BioNutrient + Gliocompost combinations. This increase supports the findings of other studies [31,32], which concur that the presence of *Bradyrhizobium* in the soil promotes the formation of root nodules in peanuts and nitrogen fixation.

The application of biofertilizers significantly increases the growth of shoots and roots in green beans, cowpeas, and soybeans compared to controls. Biofertilizers were very effective on plant growth, nodulation, nitrogen fixation, nitrogen uptake, phosphorus, potassium, and yield of green bean and soybean seeds from N application [33].

Furthermore, biofertilizers *Bradyrhizobium japonicum*, *Bradyrhizobium elkanii*, and *Streptomyces griseoflavus* significantly increased plant growth, nodulation, nitrogen fixation, nutrient uptake, and soybean yields. Overall, the effectiveness of biofertilizers and the efficiency of soybean varieties have an important role in plant growth, nodule formation, nitrogen fixation, and higher yields [34].

4.5 Yield

The combination of biofertilizer Agrimeth + BioNutrient produced the highest dry weight compared to other treatments, with an increase of 85% than the control. Furthermore, the Agrimeth + BioNutrient + Gliocompost increased dry weight by 68%. The combinations of Agrimeth + BioNutrient (P5) and Agrimeth + BioNutrient + Gliocompost (P6) also significantly affect the quantitative parameters of dry unpeeled peanuts. Both treatments increased by 59 and 56% compared to the control, respectively.

The treatment of Agrimeth + BioNutrient + Gliocompost resulted in the highest dry seed weight but produced a dry seed weight 56% heavier than the control. Furthermore, the high dry seed weight was obtained in the combination of Agrimeth + BioNutrient, with an increase of approximately 47% over the control.

Demonstrated that biofertilizer inoculation increased peanut development and yield components [32]. The use of biofertilizer 500 g Agrimeth/ha plus fertilizers (50 kg Urea + 150 kg Phonska)/ha also increases plant growth and yield by 0.25–0.70 t/ha or 15.15–33.33% compared to planting without biofertilizer [41].

The biofertilizer application has not significantly affected peanuts' growth and yield components. The same was also seen in the average achievement of peanut yields, as presented in Table 4. The biofertilizers, independently or in combination, did not show statistically significant differences between controls and treatments. However, the yield of peanuts achieved by all treatments using biological fertilizers was relatively higher than when not using them. The 41.3% increase in yield was achieved in the combination treatment of Agrimeth + BioNutrient + Gliocompost (P6).

Then, successive increases were shown in the treatment of P5 (28.7%), P4 (22.0%), P2 (4.5%), and P3 (2.2%).

Gliocompost biofertilizer contains a *Pseudomonas* microbe, which positively increases peanut yield. *Pseudomonas*-based biofertilizers could be an appropriate alternative to increase sweet potato yields, saving 50% of the currently recommended mineral fertilizers, and making them more environmentally friendly to support efficient and productive sustainable agriculture [35]. Furthermore, the application of biofertilizers such as Gliocompost, Probio, and Starmix were combined with 50% NPK recommended giving the increased yield, which means biofertilizers can make fertilizers efficient [42].

This phenomenon indicated that biofertilizers in a synergistic and integrated conditions have a better yield than the independent and partial applications. This study also gives hope that, in the long term, biofertilizers have positive prospects for field improvement and increased crop productivity.

The results indicated the application of biofertilizers proved to be able to increase the available P content, population of soil microbes *(Azospirillum*, *Trichoderma*, Phosphate-solubilizing bacteria), and peanut yield, although still at small level. This points that land improvement and crop productivity using biofertilizers needs to be carried out continuously but still must prioritize the ease and cheapness of the application. Therefore, the application of this innovation needs to be combined with more efficient technology.

Automation systems through the Internet of Things and cloud computing was one of the alternatives offered by two technologies that contribute to the development of smart technology by replacing traditional agricultural practices [36]. These smart devices monitor the needs of the plant health through sensors that can monitor temperature, soil moisture, sunlight intensity, soil air quality values, vibration, and humidity in the environment surrounding the plants. The network of sensors ensures that the plants will continue to be healthy and function in the right way. Follow-up research on dryland crop yields can be conducted to determine carbohydrates, protein, moisture, ash, fat, and fiber contents [43].

4.6 Benefit analysis

Benefit and MBCR analysis were presented in the use of innovative soil improvement technologies using a combination of three types of biofertilizers (Agrimeth-BioNutrient-Gliocompost) proved effective in increasing the yields and profits compared to the existing ones. The highest increase in profit was achieved by applying a combination of three types of biofertilizers together, with an increase in yield of 45.04%.

The second increase in profit occurred in Agrimeth and BioNutrient biofertilizers simultaneously. Meanwhile, Gliocompost biofertilizer proved to be the most effective in increasing yields and profits in biofertilizers independently, with a profit increase of 25.72% compared to the existing ones.

Application of technology using single or combinations of biological fertilizers in treatments P4, P5, and P6 was economically feasible and can be recommended to farmers [22]. Increasing benefits and reducing costs occurring in the application of this technology not only plays an important role in sustainably improving land but is also a solution for small farmers on marginal lands who want cheap inputs [37,38].

5 Conclusion

Biofertilizers application could improve agricultural sub-optimum and increase crop productivity. This study demonstrates the potential of biofertilizers to contribute to long-term sustainable agriculture. Biofertilizers (BioNutrient, Gliocompost, and Agrimeth) were shown to increase the beneficial microbe population (*Azospirillum* and *Trichoderma*), which play an essential role in nutrient availability and plant growth. The result indicated that biofertilizers effectively improve nutrient balance in the soil and available phosphorus, through the activities of microorganisms such as *Pseudomonas fluorescens* and *Aspergillus* sp. This study contributes to new knowledge by highlighting the importance of biofertilizers in improving sub-optimal drylands and increasing crop productivity. The findings emphasize the importance of adopting innovative approaches, such as biofertilizers, to harness the potential of drylands, assist in soil fertility maintenance, and achieve sustainable agriculture. The limitations of this study were abnormal weather conditions, so it was highly recommended that future research addresses these limitations and consider long-term studies to validate the findings. In addition, further research could explore the effects of different combinations and doses of biofertilizers on various crops in other dryland regions. The science community was encouraged to engage by exploring the possibility of biofertilizers in addressing sub-optimal dryland challenges and developing adaptive agricultural technologies. By doing so, we can promote sustainable agricultural development and meet the growing demand for food.

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References

[1] Rahmasary AN, Fawzi NI, Qurani IZ. Suboptimal land series: an introduction to sustainable agriculture practice on suboptimal land. TJF Brief; 2020. https://tayjuhanafoundation.org/resources/.

[2] Aristya VE, Samijan. Rice breeding breakthrough for rainfed fields. Rainfed Rice Field Management, Technology, and Institutional. Surakarta: UNS Press; 2021. p. 245–65.

[3] BPS Provinsi Jawa Tengah. Jawa Tengah Dalam Angka; 2015.

[4] Minardi. Optimalisasi pengelolaan lahan kering untuk pengembangan pertanian tanaman pangan. Naskah pidato pengukuhan Guru Besar Bidang Ilmu Tanah (Pengelolaan Tanah) Fakultas Pertanian, Universitas Sebelas Maret; 2016.

[5] Rejekiningrum P, Apriyana Y, Estiningtyas W, Sosiawan H, Susilawati HL, Hervani A, et al. Optimizing water management in drylands to increase crop productivity and anticipate climate change in Indonesia. Sustainability. 2022;14(11672):1–24. doi: 10.3390/su141811672.

[6] Lone BA, Nazir A, Fayaz A, Hassan B, Abidi I. Constrain and remedial measures in dryland agriculture. Frontiers in Crop Improv. 2022;9:2054–60.

[7] Nurlaily R, Samijan, Aristya VE, Lestari F. Effect of biofertilizer application on the population of nitrogen-fixing bacteria and yields of chili pepper at Temanggung, Central Java. Proceeding of the International Workshop and Seminar Innovation of Environmental-Friendly Agricultural Technology Supporting Sustainable Food Self-Sufficiency; 2019. p. 346–54. doi: 10.5281/zenodo.3345272.

[8] Vejan P, Abdullah R, Khadiran T, Ismail S, Boyce AS. Role of plant growth promoting rhizobacteria in agricultural sustainability—a review. Molecules. 2016;21(573):1–17. doi: 10.3390/molecules21050573.

[9] Fitriatin BN, Dewi VF, Yuniarti A. The impact of biofertilizers and NPK fertilizers on soil phosphorus availability and upland rice yield in a tropic dry land. E3S Web of Conf. 2021;232. doi: 10.1051/e3sconf/202123203012.

[10] Herawati A, Syamsiyah J, Mujiyo, Rochmadtulloh M, Susila AA, Romadhon MR. Mycorrhizae and a soil ameliorant on improving the characteristics of sandy soil. Sains Tanah. 2021;12(2):73–80. doi: 10.20961/STJSSA.V18I1.43697.

[11] Haryati U. Application of mulch and soil ameliorant for increasing soil productivity and its financial analysis on shallots farming in the upland. IOP Conf. Series: Earth and Envi. Sci. Vol. 648. Issue 1; 2021. doi: 10.1088/1755-1315/648/1/012155.

[12] Zuo Y, Zhang F. Soil and crop management strategies to prevent iron deficiency in crops. Plant Soil. 2011;339(1–2):83–95. doi: 10.1007/s11104-010-0566-0.

[13] Balittanah. Produk pupuk hayati, pupuk organik dan pupuk hayati. Balai Penelitian Tanah, Balai Besar Litbang Sumberdaya Lahan Pertanian; 2017.

[14] Mng'ong'o M, Munishi KL, Blake W, Comber S, Hutchinson TH, Ndakidemi PA. Soil fertility and land sustainability in Usangu Basin-Tanzania. Heliyon. 2021;7(8):e07745. doi: 10.1016/j.heliyon.2021.e07745.

[15] Madhaiyan M. Growth promotion and induction of systemic resistance in rice cultivar Co-47 (*Oryza sativa* L.) by *Methylobacterium spp*. Bot Bull Acad Sin. 2004;45(4):315–24. doi: 10.7016/BBAS.200410.0315.

[16] Ardonav P, Sessitsch A, Haggman H, Kozyrovska N, Pirttila AM. Methylobacterium-induced endophyte community changes correspond with the protection of plants against pathogen attack. PLoS ONE. 2012;7(10):e46802. doi: 10.1371/journal.pone.0046802.

[17] Marlina N, Gofar N, Subakti AHPK, Rahim AM. Improvement of rice growth and productivity through balance application of inorganic fertilizer and biofertilizer in inceptisol soil of lowland swamp area. Agrivita. 2014;36(1):48–56. doi: 10.17503/agrivita-2014-36-1-p048-056.

[18] Dobo B. Effect of *Arbuscular Mycorrhizal* Fungi (AMF) and *Rhizobium* inoculation on growth and yield of *Glycine max* l. varieties. Int J Agron. 2022;2022:1–10. doi: 10.1155/2022/9520091.

[19] García-López AM, Delgado A. Effect of Bacillus subtilis on phosphorus uptake by cucumber as affected by iron oxides and the solubility of the phosphorus source. Agric Food Sci. 2016;25(3):216–24. doi: 10.23986/afsci.56862.

[20] POWER Data Access Viewer. Prediction of worldwide energy resource-agro climatology location of latitude -8.0972 longitude 110.8008; 2021. https://power.larc.nasa.gov/data-access-viewer/.
[21] IPNI Profit analysis based on fertilizer application. International Plant Nutrition Institute. Singapore: ESEAP Program; 2004.
[22] Gupta PC, O'Toole JC. Upland Rice - A Global Perspective. Los Baños, Laguna, Philippines: International Rice Research Institute; 1986.
[23] Distan Wonogiri. Laporan tahunan Dinas Pertanian dan Kehutanan Kabupaten Wonogiri; 2015.
[24] Vandani Y, Kusmiyarti TB, Susila KD. Pengaruh paket pupuk organik, anorganik dan pupuk hayati terhadap sifat tanah dan hasil tanaman kangkung darat (Ipomea reptana Poir) pada tanah vertisol. Agrotrop J Agric Sci. 2020;10(2):153–64. doi: 10.24843/ajoas.2020.v10.i02.p05.
[25] Rose MT, Phuong TL, Nhan DK, Cong PT, Hien NT, Kennedy IR. Up to 52% N fertilizer replaced by biofertilizer in lowland rice via farmer participatory research. Agron Sustain Dev. 2014;34(4):857–68. doi: 10.1007/s13593-014-0210-0.
[26] Schütz L, Gattinger A, Meier M, Müller A, Boller T, Mäder P, et al. Improving crop yield and nutrient use efficiency via biofertilization-a global meta-analysis. Front Plant Sci. 2018;8:2204. doi: 10.3389/fpls.2017.02204.
[27] Jabal ZK, Khayyun TS, Alwan IA. Impact of climate change on crop productivity using MODIS-NDVI Time Series. Civ Eng J. 2022;8(6):1136–56. doi: 10.28991/CEJ-2022-08-06-04.
[28] Javoreková S, Maková J, Medo J, Kovácsová S, Charousová I, Horák J. Effect of bio-fertilizers application on microbial diversity and physiological profiling of microorganisms in arable soil. Eurasian J Soil Sci. 2015;4(1):54–61. doi: 10.18393/ejss.07093.
[29] Masso C, Ochieng J, Awuor O. Worldwide contrast in the application of bio-fertilizers for sustainable agriculture: lessons for Sub-Saharan. Africa J Biol Agric Healthc. 2015;5(12):34–50. https://core.ac.uk/reader/234661445.
[30] Rahmianna AA, Pratiwi H, Harnowo D. Budidaya Kacang Tanah Monogr Balitkabi no. 13; 2015.
[31] Badawi FSF, Biomy AMM, Desoky AH. Peanut plant growth and yield as influenced by co-inoculation with Bradyrhizobium and some rhizome microorganisms under sandy loam soil conditions. Ann Agric Sci. 2011;56(1):17–25. doi: 10.1016/j.aoas.2011.05.005.
[32] Neelipally RTKR, Anoruo AO, Nelson S. Effect of co-inoculation of Bradyrhizobium and Trichoderma on growth, development, and yield of *Arachis hypogaea* L. (Peanut). Agronomy. 2020;10(9):1–12. doi: 10.3390/agronomy10091415.
[33] Htwe AZ, Moh SM, Soe KM, Moe K, Yamakawa T. Effects of biofertilizer produced from Bradyrhizobium and Streptomyces griseoflavus on plant growth, nodulation, nitrogen fixation, nutrient uptake, and seed yield of mung bean, cowpea, and soybean. Agronomy. 2019;9(2):77. doi: 10.3390/agronomy9020077.
[34] Htwe AZ, Moh SM, Moe K, Yamakawa T. Biofertilizer production for agronomic application and evaluation of its symbiotic effectiveness in soybeans. Agronomy. 2019;9(4):1–16. doi: 10.3390/agronomy9040162.
[35] Santana-Fernández A, Beovides-García Y, Simó-González JE, Pérez-Peñaranda MC, López-Torres J, Rayas-Cabrera A, et al. Effect of a *Pseudomonas fluorescens-based* biofertilizer on sweet potato yield components. Asian J Appl Sci. 2021;9(2):105–13. doi: 10.24203/ajas.v9i2.6607.
[36] Rajak ARA. Emerging technological methods for effective farming by cloud computing and IoT. Emerg Sci J. 2022;6(5):1017–31. doi: 10.28991/ESJ-2022-06-05-07.
[37] Sharma B, Yadav L, Pandey M, Shrestha J. Application of biofertilizers in crop production: A review. Peruvian J Agronomy. 2020;6(1):13–31. doi: 10.21704/pja.v6i1.1864.
[38] Aristya VE, Trisyono YA, Mulyo JH. Participatory varietal selection for promising rice lines. Sustainability. 2021;13:6856. doi: 10.3390/su13126856.
[39] Aristya VE, Taryono, Wulandari RA. Genetic variability, standardized multiple linear regression, and principal component analysis to determine some important sesame yield components. Agrivita. 2017;39(1):83–90. doi: 10.17503/agrivita.v39i1.843.
[40] Līcīte L, Popluga D, Rivža P, Lazdiņš A, Meļņiks R. Nutrient-rich organic soil management patterns in light of climate change policy. Civil Eng J. 2022;8(10):2290–304. doi: 10.28991/CEJ-2022-08-10-017.
[41] Jumakir Endrizal, Abdullah T. The response of biofertilizer on improving soybean productivity in tidal swamps land. J Pangan. 2021;30(1):23–30.
[42] Supriyo A, Minarsih S, Prayudi B. Efectivitas pemberian pupuk hayati terhadap pertumbuhan dan hasil padi gogo di lahan kering. J Agritech. 2014;16(1):1–12.
[43] Usman Pato U, Ayu DF, Riftyan E, Restuhadi F, Pawenang WT, Firdaus R, et al. Cellulose microfiber encapsulated probiotic: viability, acid and bile tolerance during storage at different temperatures. Emerg Sci J. 2022;6(1):106–17. doi: 10.28991/ESJ-2022-06-01-08.