PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 11(1): 388–396
https://doi.org/10.14719/pst.2353

HORIZON
e-Publishing Group
HePG

RESEARCH ARTICLE

Actinomycete inoculant improves the growth and yield of rainfed lowland and upland rice under field conditions

Lanie A. Alejo[1]* & Jayvee A. Cruz[2]

[1]College of Engineering, Isabela State University, Echague 3309, Isabela, Philippines
[2]Philippine Rice Research Institute, Maligaya, Munoz 3119, Nueva Ecija, Philippines

*Email: lhan_1023@yahoo.com

OPEN ACCESS

ARTICLE HISTORY

Received: 23 March 2023
Accepted: 25 October 2023

Available online
Version 1.0 : 27 December 2023
Version 2.0 : 14 January 2024

Check for updates

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

CITE THIS ARTICLE

Alejo L A, Cruz J A. Actinomycete inoculant improves the growth and yield of rainfed lowland and upland rice under field conditions. Plant Science Today. 2024; 11(1): 388–396. https://doi.org/10.14719/pst.2353

Abstract

This study aimed to assess the effectiveness of actinomycete inoculant in enhancing the growth and yield of rainfed lowland and upland rice across wet and dry seasons in real field conditions. This field assessment took place at four sites, comprising two rainfed lowland and two rainfed upland ecosystems, over two cropping seasons (dry and wet seasons). The experiments involved testing both soil-based and carbonized rice hull (CRH) inoculants. Actinomycetes were found to be effectively carried by CRH and soil, and evidence from field studies in rainfed lowland and upland conditions showed that the actinomycete inoculant significantly improved rice production even under stressful environmental conditions. Regarding plant height, root depth, and tiller number, the inoculated treatments outperformed both the control and the full fertilization rates. Rice yield significantly increased with the application of actinomycete inoculum in both lowland and upland experiments. Inoculation alone led to substantial improvements, with yield increases of up to 48% in Lowland Site 1, 50% in Lowland Site 2, 78% in Upland Site 1, and 43% in Upland Site 2. Similarly, growth was enhanced by inoculation alone, reaching up to 50% in Lowland Site 1, 75% in Lowland Site 2, 24% in Upland Site 1, and 26% in Upland Site 2. When added to the full rate of fertilization, the inoculant significantly boosted yield by up to 16% in Lowland Site 1, 82% in Upland Site 1, and 40% in Upland Site 2. Additionally, growth substantially improved with inoculation in conjunction with the full rate of fertilization, reaching as much as 50% in lowland site 1, and 24% in upland site 1. Actinomycete inoculant proves to be a valuable alternative and addition to agricultural fertilizer management, as it was found to significantly increase growth and yield even in adverse weather conditions.

Keywords

field assessment; soil-based inoculant; carbonized rice hull-based inoculant

Introduction

As the population inevitably grows, there is a need to increase upland and rainfed lowland rice production to support the growing demand for staple foods. Due to climate change over the past few decades, some irrigated production areas have become water-scarce. However, there is low production of upland rice and rainfed lowland rice, especially in Asia and other countries (1–3). Weeds, low soil fertility, and moisture stress are some of the factors contributing to the low production (approximately 2 t/ha) of rice in upland areas (4, 5). These challenges have prompted researchers to develop technologies and strategies aimed at increasing upland and rainfed lowland rice production. The importance of plant growth-promoting bacteria (PGPB) in agriculture is now being recognized as a means to reduce the reliance on chemical fertilizer, thereby conserving energy resources. Inoculants have emerged as an alternative to inorganic fertilizers, offering a new approach to addressing diverse agricultural problems while mitigating environmental issues (6). Actinomycetes, among the prokaryotes with the highest commercial and biotechnological value within PGPBs, produce 50% of the bioactive secondary metabolites that have been identified. Over 50 genera of actinomycetes have been utilized in veterinary medicine, human medicine, agriculture, and industry.

Streptomyces is one of the genera within the actinomycete. Typically constituting a significant portion of soil microflora, *Streptomyces* is particularly adept at colonizing plant roots and can withstand adverse growth conditions such as drought by producing spores. The metabolism of several plant-associated bacteria involves the production of chemicals that promote plant growth, influence root structure, and regulate nutrient and water absorption, among other functions (7–9). Studies have demonstrated the effects of streptomycetes on plant growth (10–12). Various parameters, including shoot fresh mass, dry mass, length, and diameter, significantly increased with certain strains at different sampling times. For instance, *S. olivaceoviridis* exhibited a pronounced effect on yield components (spikelet number and length, and fresh and dry mass of the developing grain) in wheat (12). The culture filtrates of three strains (*Streptomyces olivaceoviridis*, *S. rimosus*, and *S. Rochei*) appeared to enhance the growth and crop yield of wheat plants. In field tests with rice, Streptomyces dramatically increased the number of tillers and panicles, stover and grain yields, dry matter, root length, volume, and dry weight (10). In a study by Akbari et al. (2020), various commercial wheat cultivars exhibited varying responses to a PGP Streptomyces in both normal and saline environments. This suggests that certain rhizobacteria, including the actinomycete, may act as plant growth enhancers.

The parameters governing each step of crop development, from seed germination to vegetative growth, maturity, senescence, aging, and postharvest preservation, are influenced by plant growth regulators (13). Since the plant root system and its associated physical and biological environment determine the productivity and quality of crops, manipulating the microorganisms around the roots may provide the opportunity to optimize crop productivity (14). This manipulation can have a positive effect on redox potential (Eh) and ammonium-N (NH4-N) from carbonized rice hulls in the soil during the early rice growth stage (15). A wide variety of rhizosphere microorganisms are known to produce plant growth hormones, including indoleacetic acid (IAA), gibberellins, and cytokinins (16–18), which stimulate root development and contribute to the increased capacity of the root system for soil nutrients and water uptake to support plant growth (19). Similarly, some bacteria can synthesize exopolysaccharide (EPS), which improves water retention and controls the diffusion of organic carbon sources, shielding them from drought stress. Due to the presence of a network of fibrillar material binding the microorganisms to the root surface permanently, EPS enables the bacteria to attach and colonize the roots permanently (20).

Researchers in the Philippines found that actinomycete inoculants improved rice growth based on tests conducted in growth rooms and screen house conditions. They claim that actinomycete inoculants enhanced the root dry weight of upland rice by up to 71% in the growth room (21). Furthermore, findings from a screen house experiment revealed that inoculated upland rice, combined with 50% inorganic fertilizer, was comparable to the full rate of inorganic fertilization (22). However, these studies recommend testing the inoculant in field conditions to determine its efficiency as a plant growth-promoting inoculant. Thus, assuming that actinomycete inoculant will also improve the yield and growth of lowland and upland rice, field experiments were conducted. This study assessed the performance of actinomycete inoculant in enhancing the growth and yield of upland rice in actual rice fields, both in rainfed lowland and upland ecosystems.

Materials and Methods

Experimental locations

This study was conducted in two upland and two lowland rainfed conditions, all of which have a Type III climate characterized by distinct wet and dry seasons. This climate type is unimodal, with the majority of rainfall occurring from May to October. The available rice growing period is short, extending from July to October, necessitating supplemental irrigation for the cultivation of a second, rice or non-rice crop. The topography varies from flat to nearly flat for all four sites, with clay soil with an annual rainfall of approximately 2000mm. One upland site has a sloping topography of 10%. The study involved four sites, two ecosystems, and two cropping seasons (Table 1). The first cropping was established during the wet season, while the second followed during the dry season. NSIC Rc 222 was used as an experimental rice variety in lowland areas, and NSIC Rc 192 was employed in upland sites. Upland rice crops were dry-sown, while rainfed lowland seedlings were transplanted after 21 days. There were six treatments applied to all sites (Table 2), replicated three times. These treatments included: control or zero rates of fertilization (T1: 0% FRR), the full recommended rate of fertilization (T2: FRR) at 120-60-60 NPK, Soil based inoculant only (T3: SBI only), soil-based inoculant + full recommended rate of fertilization (T4: SBI + FRR), carbonized rice hull-based inoculant (T5: CRHI only, and carbonized rice hull-based inoculant + full recommended rate of fertilization (T6: CRHI + FRR). The full-rate fertilizer application was at 120-60-60 kg/ha of N-P-K.

Table 1. Information about the sites

Location	Topography	Season	Soil Type	Planting method	Variety Planted
Lowland Site 1	Flat	WS* and DS**	Clay	Transplanted	NSIC Rc 222
Lowland Site 2	Flat	WS and DS	Clay	Transplanted	NSIC Rc 222
Upland Site 1	10% slope	WS and DS	Clay	Dry seeded	NSIC Rc 192
Upland Site 2	Flat	WS and DS	Clay	Dry seeded	NSIC Rc 192

*Wet Season; **Dry Season

Table 2. Treatments applied at all sites.

No	Treatments	Description	Dosage
T1	0% FRR	Zero rate of fertilization (Control)	0-0-0
T2	FRR	Full rate of fertilization	120-60-60
T3	SBI only	Soil-based inoculant (SBI) only	100g SBI per 2 liters of water
T4	SBI + FRR	Full rate of fertilization applied with soil-based inoculant	120-60-60 NPK and 100g SBI per 2 liters of water
T5	CRHI only	Carbonized rice hull -based inoculant (CRHI)	100g CRHI per 2 liters of water
T6	CRHI + FRR	Full rate of fertilization applied with CRH-based inoculant	120-60-60 NPK and 100g CRHI per 2 liters of water

Application of actinomycetes

Inoculants were applied to the corresponding treatments at planting; 14 DAP, 30DAP, 40DAP, and 60DAP. The actinomycete inoculants were provided by the Philippine Rice Research Institute (PhilRice). For the upland ecosystem, seeds were soaked in water and mixed with inoculants for 30 minutes. Conversely, seeds for the lowland sites were soaked for 24 hours before sowing. The difference in soaking duration between ecosystems was a protocol established by PhilRice and was consistently applied to all inoculant evaluation sites in the Philippines. An automatic weather station (AWS) is strategically located near the area, and data from the station was collected to support some of the discussions based on the results.

Data recording and statistical analysis

Monitoring crop growth to record the effect of the treatments was conducted through observations on pegs and destructive sampling. Pegs were used to mark the position of plants, and measurements of heights and productive and unproductive tillers were recorded throughout the experiment. Harvest data were collected and included root length, aboveground dry biomass, and yield. Plant height was measured by holding a meter stick from the soil surface to the tip of the tallest plant. The length of roots was monitored through the destructive sampling of five plants per plot. Final yields were obtained from the 2 x 2.5 square meters allocated for harvest data, and the fresh yield was adjusted to 14% moisture content. The aboveground biomass of the rice crop was monitored through destructive sampling. Fresh biomass was oven-dried at 70°C for 48 hours and then weighed to obtain dry biomass data. The experiment was laid out in a Randomized Complete Block Design, and the data were analysed through analysis of variance. In cases of significant variability, Tukey's all-pairwise comparison of means was used to determine significant differences across treatments.

Results

During the wet season, rice crops in upland areas received a total rainfall of 621.6 mm, while those in lowland areas received 552 mm. The average temperature in the first cropping season was 28.6°C and 27.2°C in the upland and lowland ecosystems, respectively. Average wind speeds were 1.2 and 1.3 meters per second for the upland and lowland ecosystems, respectively. Flowering commenced at 70 DAP with intermittent rainfall. Two typhoons affected the upland crops, striking at 93 DAP and 97 DAP, bringing rainfall amounts of 61.3 mm and 78 mm, respectively, and wind speeds of 4 meters per second and 10 meters per second. These typhoons substantially emptied most of the grains. Lowland crops were still at their seedling stage when the typhoons hit, and there were no weather disturbances in the rainfed lowlands thereafter. During the dry season, rice crops in upland areas received a total of 781.3 mm of rainfall, and those in lowland areas received 770 mm. The average temperature during the dry cropping season was 27.3 °C and 28.2 °C in the upland and lowland ecosystems, respectively. In terms of wind speed, the average was 1.23 meters per second in the upland and 1.2 meters per second in the lowland ecosystems. The highest daily rainfall received throughout the dry cropping season for both the upland and lowland ecosystems was 70.4 mm.

Agronomic response of upland rice to the treatments

Plant height

The response of rice growth to the treatment was more frequent during the wet seasons (Fig. 1). However, based on the weather data, wet seasons had lower total rainfall compared to dry seasons. There was no significant difference in plant height across treatments, seasons, and ecosystems during 30 DAP. In the lowland ecosystem, plant height ranged from 27.13 to 44.93 cm, while in the upland ecosystem, it ranged from 28.03 to 54.27 cm. During the dry season, inoculation had an impact on plant height only at 60 and 90 DAP. The impact of inoculation on rice growth was also apparent during the vegetative and reproductive stages, manifesting at 60 DAP. There were no significant variations in height at Lowland Site 1 during the dry season. However, during wet seasons, the inoculant-treated plants significantly differed from the control and full-rate

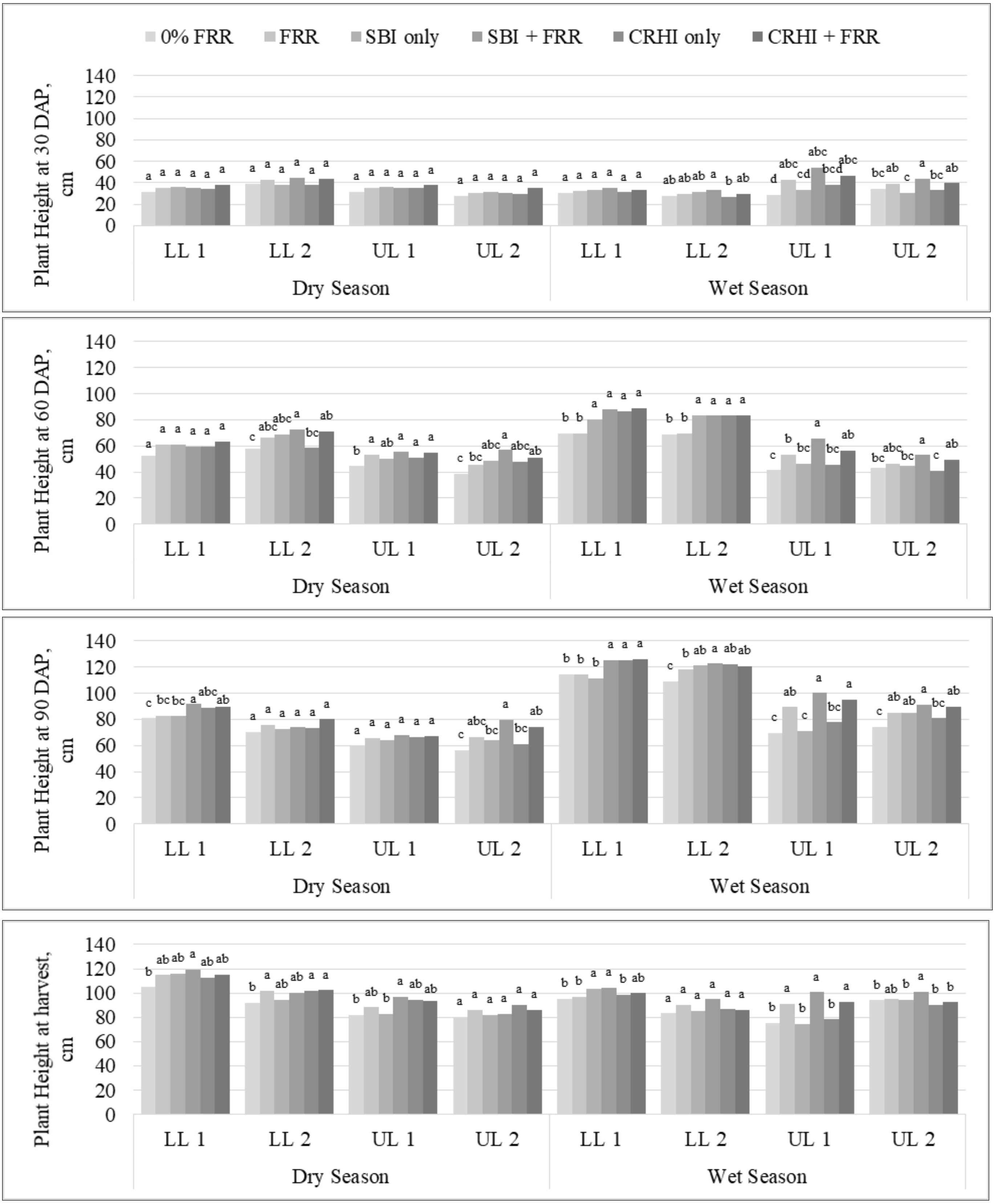

Fig. 1. Observed plant height at 30 DAP, 60 DAP, 90 DAP, and at harvest during the wet and dry seasons. Note: LL = Lowland and UL = Upland. FRR = Full rate of fertilization (120-60-60, NPK), SBI = Soil-based inoculant, CRHI = Carbonized Rice Hull-based inoculant

fertilization. Notably, all the inoculated treatments were comparable during wet seasons at the Lowland sites. Compared with the control, the SBI and CRHI alone significantly improved plant height by 16-21% and 21-24% in the lowlands. Compared with the FRR, SBI + FRR and CRHI + FRR significantly improved plant height by 20-27% and 22-28%, respectively. In the meantime, in the upland sites, inoculation was observed to be significantly effective in improving plant height. During the dry season, inoculation using CRH alone provided taller rice by 15% in Upland Site 1, while SBI + FRR boosted plant heights significantly by 24% compared to the FRR-treated plants. During the wet season, SBI + FRR improved plant heights by 14-23% relative to FRR. At 90 DAP half of the experimental plots were still responsive to treatments. During the dry seasons, the inoculation significantly improved plant height only at

Lowland Site 1 and Upland Site 2. In this field experiment, SBI + FRR increased plant height significantly by 11% relative to FRR and 13% relative to the 0% FRR. The inoculation, together with the full rate of fertilization, substantially improved growth. The CHRI + FRR improved plant height considerably, by 11% relative to the control. In Upland Site 2, inoculant as a supplement to FRR significantly improved plant heights using SBI and CRHI by 42% and 33%, respectively, relative to the control. The soil-based inoculant was proven to be an effective carrier of actinomycete. The SBI-only treatment improved plant heights in Lowland Site 2 by 11% and by 15% in Upland Site 2 during wet seasons. Relative to the control, SBI + FRR improved plant heights significantly by 9-13% in the lowlands and by 23-45% in the uplands. The carbonized rice hull was demonstrated to be a good carrier of actinomycete inoculant. The CRHI alone also improved plant heights by 12% at Lowland Site 2. Moreover, the CRHI + FRR boosted plant heights significantly relative to the control by 10-11% in the Lowlands and 21-38% in the Uplands. Relative to FRR, SBI + FRR and CRHI only improved heights by 10%, and CRHI + FRR by 11%. During harvest, the inoculated treatments still affected plant heights when compared with the non-inoculated treatments. For example, in the uplands, 7-34% taller rice crops compared to the control were observed when inoculation was added to FRR. In lowland site 1, the impact of inoculation on plant height was 9%. Notably, across stages, the inoculated treatments are prevalently comparable with the FRR in terms of plant heights. It can be concluded that inoculants, whether CRH or SBI-based, are both effective growth enhancers, and actinomycete inoculants can improve the growth of rice in actual field conditions in both lowland and upland ecosystems. The effect of inoculation with a full rate of fertilization on rice growth relative to the full recommended rate of fertilization was more prominent in the Lowland Sites and during the wet cropping season.

Root length and tiller number

The effect of treatments on root length, productive and non-productive tillers of rice crops during harvest across ecosystems is shown in Table 3. Analyses revealed significant differences primarily during the wet seasons, with growth parameters at harvest predominantly reflecting the effects of inoculation with fertilization and inoculation alone during the season. During the dry season, a significant benefit of inoculation was observed in the mean

Table 3. Effect of actinomycete inoculant and fertilizer on the agronomic traits of upland rice

Location	Treatment	Dry Season			Wet Season		
		Root length, cm	Productive Tiller	Unproductive Tiller	Root length, cm	Productive Tiller	Unproductive Tiller
Lowland Site 1	0% FRR	30.4^{a}	10^{b}	0.9^{a}	36.2^{c}	11^{b}	2.3^{a}
	FRR	33.6^{a}	12^{ab}	0.2^{a}	38.3^{ab}	12^{b}	2^{ab}
	SBI only	30.4^{a}	11^{b}	0.5^{a}	38.1^{abc}	14a^{b}	1.3^{b}
	SBI + FRR	29.1^{a}	14^{a}	0.5^{a}	37.6^{bc}	15^{a}	2^{ab}
	CRHI only	34.4^{a}	12^{ab}	1.1^{a}	39.2^{ab}	15^{a}	2^{ab}
	CRHI + FRR	33.9^{a}	12^{ab}	0.7^{a}	39.9^{a}	15^{a}	2^{ab}
Lowland Site 2	0% FRR	26.0^{b}	9^{a}	0.5^{a}	35.2^{a}	13^{b}	2.3^{a}
	FRR	29.6^{ab}	11^{a}	0.9^{a}	38.0^{a}	13^{b}	2^{ab}
	SBI only	33.7^{ab}	10^{a}	0.7^{a}	37.6^{a}	15^{ab}	2^{b}
	SBI + FRR	37.6^{a}	13^{a}	0.6^{a}	37.6^{a}	16^{a}	2^{ab}
	CRHI only	34.0^{ab}	13^{a}	0.7^{a}	39.0^{a}	14^{ab}	2^{ab}
	CRHI + FRR	32.7^{ab}	12^{a}	1.1^{a}	37.9^{a}	14^{ab}	2^{ab}
Upland Site 1	0% FRR	23.8^{a}	14^{b}	0.7^{a}	17.2^{c}	5^{c}	2.3^{a}
	FRR	27.9^{a}	16^{ab}	0.7^{a}	23.3^{ab}	11^{b}	2.4^{a}
	SBI only	27.4^{a}	18^{ab}	0.4^{a}	23.6^{ab}	14^{ab}	2.3^{a}
	SBI + FRR	35.0^{a}	19^{a}	1^{a}	26.5^{a}	19^{a}	2.1^{a}
	CRHI only	32.2^{a}	20^{a}	1^{a}	17.3^{c}	14^{ab}	2.1^{a}
	CRHI + FRR	34.7^{a}	18^{ab}	0.4^{a}	21.5^{bc}	10^{bc}	2.2^{a}
Upland Site 2	0% FRR	24.6^{a}	12^{a}	1.1^{a}	19.0^{c}	7^{c}	2.2^{a}
	FRR	26.2^{a}	12^{a}	0.7^{ab}	26.8^{bc}	11^{bc}	2.5^{a}
	SBI only	23.1^{a}	15^{a}	0.6^{ab}	21.8^{c}	14^{ab}	2.4^{a}
	SBI + FRR	22.6^{a}	16^{a}	0.6^{ab}	33.3^{a}	16^{a}	2.7^{a}
	CRHI only	24.0^{a}	15^{a}	0.4^{b}	19.7^{c}	9^{c}	2.1^{a}
	CRHI + FRR	26.8^{a}	16^{a}	0.4^{b}	20.6^{c}	11^{bc}	2.1^{a}

Note: Means followed by a common letter are not significantly different at the 5% level, Tukeys HSD count of non-productive tillers. There was a notable 74% reduction in non-productive tillers as a result of the application of soil-based inoculant in addition to the full recommended rate of fertilization at harvest in Upland Site 2. In the Lowland sites, non-productive tillers were substantially reduced by 13-43% due to soil-based inoculation during the wet season. The difference in unproductive tiller between treatments was not significant in the upland sites during the wet season. However, during the dry season, there were no significant variations in the number of unproductive tillers across treatments in the study sites, except in Upland Site 2. In Uplands Site 2, where differences in the number of unproductive tillers were significant, 0% FRR had significantly more unproductive tillers relative to CRHI only and CRHI + FRR, which had the least number of unproductive tillers. The effect of inoculation combined with fertilizer was significant on productive tillers during the wet season. Productive tillers were 23-25% significantly higher in Lowland Sites and 45-73% significantly higher in Upland sites when using SBB+FRR relative to FRR. Inoculant alone substantially improved productive tillers in Lowland Site 1 by 36% (CRHI), by 180% (both CRHI and SBI) in Upland Site 1, and by 100% (SBI) in Upland Site 2. The mean productive tiller had a maximum number of 13-14 in the lowlands and 16-20 in the uplands during the dry season. During the wet season, the maximum productive tiller was 15-16 in the lowlands and 16-19 in the uplands. Uplands have closer plant spacing, which consequently has a higher plant population, resulting in a higher tiller number compared to the lowlands. Root length showed a more significant difference caused by inoculation and fertilization in the Upland Sites during wet seasons. A 37% significantly longer root length relative to the control was observed because of soil-based inoculation in Upland Site 1, and a 75% deeper root length as a benefit of inoculation with fertilization in Upland Site 2.

Above-ground biomass

Generally, CRHI alone is more effective than SBI alone during the dry season, while SBI is more beneficial when added to FRR. In terms of the aboveground biomass, SBI alone significantly increased AGB only during wet seasons, ranging from 26% in Upland Site 2 to 75% in Lowland Site 2 (Table 4). CRHI alone improved AGB by 20% in Lowland Site 1 during the dry season and 22% in Upland Site 2 during the wet season. SBI + FRR improved AGB by 21% in Upland Site 1 during the dry season only. The above-ground biomass for the six treatments is shown in Table 2. SBI alone significantly increased AGB only during wet seasons, from 26% in Upland Site 2 to 75% in Lowland Site 2. CRHI alone improved AGB by 20% and 24% in Lowland Site 1 and Upland Site 1, respectively, during the dry season

Table 4. Effect of inoculation and fertilization on mean aboveground biomass and mean yield during the wet and dry season

Location	Treatment	Dry Season Aboveground biomass, g/plant	Wet Season Aboveground biomass, g/plant	Dry Season Yield (tons/ha)	Wet Season Yield (tons/ha)
Lowland Site 1	0% FRR	22.7^{c}	16.3^{b}	2.1^{d}	4.0^{c}
	FRR	27.7^{ab}	20.1^{ab}	3.1^{bc}	4.9^{abc}
	SBI only	24.2^{bc}	19.5^{ab}	2.8^{c}	5.3^{ab}
	SBI + FRR	29.7^{a}	24.4^{a}	3.6^{a}	6.1^{a}
	CRHI only	27.3^{ab}	18.6^{ab}	3.1^{bc}	4.8^{bc}
	CRHI + FRR	26.9^{abc}	20.2^{ab}	3.5^{ab}	4.8^{bc}
Lowland Site 2	0% FRR	15^{a}	5.5^{c}	2.0^{b}	1.2^{c}
	FRR	17.5^{a}	9.4^{ab}	3.1^{a}	2.9^{ab}
	SBI only	17.3^{a}	9.6^{ab}	3.0^{a}	2.0^{c}
	SBI + FRR	21.2^{a}	12.9^{a}	3.6^{a}	3.3^{a}
	CRHI only	17.2^{a}	7.7^{bc}	2.8^{ab}	2.6^{bc}
	CRHI + FRR	21.7^{a}	9.3^{b}	3.3^{a}	3.3^{a}
Upland Site 1	0% FRR	12.5^{c}	12.6^{b}	0.9^{c}	0.3^{d}
	FRR	13.9^{bc}	15.3^{ab}	1.1^{bc}	1.0^{bc}
	SBI only	14.4^{bc}	15.3^{ab}	1.6^{ab}	0.6^{cd}
	SBI + FRR	16.8^{a}	16.4^{a}	2.0^{a}	1.5^{a}
	CRHI only	15.5^{ab}	15.5^{ab}	1.5^{abc}	0.5^{d}
	CRHI + FRR	15.3^{ab}	15.8^{a}	1.5^{abc}	0.9^{bc}
Upland Site 2	0% FRR	12.9^{b}	11.7^{c}	0.9^{b}	0.3^{c}
	FRR	14.5^{ab}	15.5^{ab}	1.4^{ab}	0.5^{bc}
	SBI only	14.1^{ab}	14.7^{b}	1.4^{ab}	0.4^{bc}
	SBI + FRR	16.2^{ab}	17.4^{a}	2.0^{a}	0.7^{a}
	CRHI only	14.5^{ab}	14.3^{b}	1.2^{b}	0.3^{c}
	CRHI + FRR	16.8^{a}	14.9^{b}	1.5^{ab}	0.4^{bc}

Note: Means followed by a common letter are not significantly different at 5% level, Tukeys HSD and 22% in Upland Site 2 during the wet season. AGB in SBI+FRR is significantly higher by 21% relative to FRR in Upland Site 1.

Grain Yield

In terms of grain yield, SBI alone significantly increased yield by 33% during the wet season and 33 to 50% during the dry season in the lowland sites, and by 78% during the dry season in Upland site 1. CRHI alone substantially increased yield by 48% in Lowland Site 1 during the dry season. SBI inoculation with FRR increased yield by 16% in Lowland Site 1 and by 82% in Upland Site 1 during the dry season. It also increased yield by 50% in Upland Site 1 and 24% in Upland Site 1 during the wet season, while it enhanced AGB by 22% in Upland Site 2 during the wet season. The combination of CRHI and FRR was not effective in increasing yield across sites and seasons. Yields in the lowlands were higher by 48-59% relative to the uplands. While this yield gap between lowlands and uplands is normal, factors that may explain the difference include variation in water retention, soil, and crop management. Moreover, the inoculant considerably improved the yield of both lowland and upland rice. Both soil-based and CRH were found to be effective carriers of actinomycetes.

Discussion

Actinomycete inoculants have been proven to enhance the growth of upland and rainfed lowland rice production. Plant height, root length, and the number of tillers were significantly improved by the actinomycete inoculant. Additionally, it considerably increased the yield of both lowland and upland rice. Both soil and CRH were found to be effective carriers of actinomycetes. Inoculation alone significantly increased yield by up to 48% in lowland Site 1, 50% in lowland Site 2, 78% in upland Site 1, and 43% in upland Site 2. Furthermore, inoculation alone increased growth by as much as 50% in lowland site 1, 75% in lowland site 2, 24% in upland site 1, and 26% in upland site 2 compared to the control. These results demonstrate that actinomycetes inoculant is a promising intervention for better production in water-scarce rice areas and during low-rainfall cropping seasons. Inoculant studies have also shown a similar positive impact on the growth and yield of crops. A study indicated that bioinoculants are more effective in improving lowland rice production during the wet season, as more biofertilizer is recommended in addition to the application of bio-inoculants during dry seasons (23). In legumes, Rhizobia, like the actinomycete, create nitrogen-fixing nodules that transform atmospheric nitrogen into ammonia that plants can use, increasing plant growth and crop productivity (24). For green leafy vegetables, the application of fertilizer with a microbial inoculant yielded the highest mean head weight of cabbage (25). In this study, the effect of inoculation with a full rate of fertilization on rice growth relative to the full recommended rate of fertilization was more prominent in the Lowland Sites and during the wet cropping season. This could mean that the effect of inoculation on top of fertilization might have the best benefit on rice crops in the lowlands during the wet season, implying that it may have the optimum benefit in a fully irrigated rice field. To further validate these results, testing it in fully irrigated rice fields is recommended. The significant benefit of inoculation with fertilization was most prevalent at 60 DAP. In most of the dry environmental conditions, the observed rice growth from the inoculation with fertilization was comparable to the full rate of fertilization. Also, inoculation alone failed to increase the growth of the rice crops in most of the observations and experimental locations. However, it can be noted that the total rainfall amount throughout the cropping seasons is higher during the dry seasons with 781.3 mm in the Uplands and 770 mm in the Lowlands compared to the wet season, with 621.6 mm in the uplands and 552mm in the lowlands.

Numerous bacterial species reside in the complex zone known as the soil rhizosphere, located around plant roots, providing both direct and indirect benefits to host plants (26). Rhizobacteria, commonly known as root-colonizing bacteria, are essential for the growth and development of plants and can shield their hosts from soil-borne pathogens. The application of Bradyhizobium inoculants in soybean and wheat crops was found to be effective in increasing rhizobial populations, nodulation, crop yield, soil organic matter, and nitrogen content (27). Similar results were noted by (28) when they employed seed inoculation in wheat and cowpea, which increased microbial groups of actinomycetes, nitrogen fixers, and producers of siderophores. Plant growth and development in natural ecosystems depend heavily on interactions between microorganisms and plants (29,30). According to a screenhouse study, inoculants with half the fertilization rate can achieve growth promotion equal to fertilization at full rate in terms of root fresh weight, shoot and root oven-dry weights, plant height, productive tiller count, and grain yield (22). In the present study, the crops experienced environmental stresses during the cropping periods, but the inoculant-treated plants still significantly improved in terms of plant height, root length, productive tiller number, and yield. Moreover, rice crops in this study received less total rainfall during the wet seasons compared to the dry seasons. Despite this, inoculation during wet seasons provided more frequent and significant improvements in growth. Also, the rice crops experienced mechanical stress during wet seasons due to two successive typhoons. Efforts have been undertaken to explain the molecular processes involved in plants and rhizosphere microbes' resistance to biotic and abiotic stress (31, 32).

Numerous microorganisms from the rhizosphere of crop plants, such as bacteria, actinomycetes, fungi, viruses, protozoa, and nematodes, have been discovered to reduce both biotic and abiotic stressors (33-35). It has also been demonstrated that rhizobacteria promoting plant growth can produce 1-aminocyclopropane-1-carboxylate (ACC) deaminase. The production of this enzyme in the host plants results in reduced levels of the stress-causing hormone ethylene (36). Developing the ACC deaminase hydrolytic enzyme can be a valuable strategy to mitigate plant stress caused by unfavorable climatic conditions (37).Since actinomycete inoculant was found to significantly boost growth and yield even in challenging weather conditions, it makes it a potential supplement in farm fertilizer management.

Conclusion

This study revealed that actinomycete inoculant enhances the growth and yield of rainfed lowland and upland rice crops in actual field conditions. Inoculated rice crops have yields higher than the control by as much as 50% in the lowlands and 78% in the uplands. Plant height, root length, and the number of tillers were improved in all treatments compared to the control. Therefore, actinomycetes inoculant is a promising alternative and supplemental strategy to increase production and farm income in rice-growing regions, especially now that inorganic fertilizer prices have increased globally. Future directions include the development of a technology package for the actinomycete inoculant, testing of the inoculant by rice farmers, and commercialization of the technology.

Acknowledgements

This research work was funded and supported by the Philippine Rice Research Institute and Department of Agriculture - Bureau of Agricultural Research.

Authors contributions

L.A. Alejo conceptualized and designed the study, prepared and wrote the article, and J.A. Cruz conceptualize and design the study, and contributed to the article.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None.

References

1 Suwanmontri P, Kamoshita A, Fukai S. Recent changes in rice production in rainfed lowland and irrigated ecosystems in Thailand. Plant Prod Sci. 2020;1-14. https://doi.org/10.1080/1343943X.2020.1787182

2. Dianga AI, Musila RN, Joseph KW. Rainfed rice farming production constrains and prospects, the Kenyan situation. Integrative Advances in Rice Research [Internet]. 2021 Jul 29 [cited 2022 Jul 28]. https://doi.org/10.5772/intechopen.98389

3. Saito K, Asai H, Zhao D, Laborte AG, Grenier C. Progress in varietal improvement for increasing upland rice productivity in the tropics. Plant Prod Sci. 2018 Jul 3;21(3):145-58. https://doi.org/10.1080/1343943X.2018.1459751

4. Bas-Ong JY. Upland rice cultivation practices in Cagayan Province, Philippines International Journal of Biosciences | IJB |. Int J Biosci. 2019;14(1):454-67. https://doi.org/10.12692/ijb/14.1.454-467

5. De Datta SK. Principles and practices of rice production. New York: John Wiley & Sons. 1981;1-546 p.

6. Maheshwari DK. Bacteria in agrobiology: Plant nutrient management. Springer Berlin Heidelberg. 2011;345 p. https://doi.org/10.1007/978-3-642-21061-7

7. dos Santos RM, Diaz PAE, Lobo LLB, Rigobelo EC. Use of plant growth-promoting rhizobacteria in maize and sugarcane: Characteristics and applications. Front Sustain Food Syst. 2020 Sep 29;4:136. https://doi.org/10.3389/fsufs.2020.00136

8. Bashan Y, Holguin G. Azospirillum – plant relationships: Environmental and physiological advances (1990–1996). 1997;43(2):103-21. https://doi.org/101139/m97-015

9. Alipour Kafi S, Karimi E, Akhlaghi Motlagh M, Amini Z, Mohammadi A, Sadeghi A. Isolation and identification of *Amycolatopsis* sp. strain 1119 with potential to improve cucumber fruit yield and induce plant defense responses in commercial greenhouse. Plant and Soil. 2021 Aug 26;468(1):125-45. https://doi.org/10.1007/s11104-021-05097-3

10. Gopalakrishnan S, Vadlamudi S, Apparla S, Bandikinda P, Vijayabharathi R, Bhimineni RK et al. Evaluation of *Streptomyces* spp. for their plant-growth-promotion traits in rice. 2013;59(8):534-39. https://doi.org/101139/cjm-2013-0287

11. Akbari A, Gharanjik S, Koobaz P, Sadeghi A. Plant growth promoting *Streptomyces* strains are selectively interacting with the wheat cultivars especially in saline conditions. Heliyon. 2020 Feb 1;6(2):e03445.https://doi.org/10.1016/j.heliyon.2020.e03445

12. Aldesuquy HS, Mansour FA, Abo-Hamed SA. Effect of the culture filtrates of *Streptomyces* on growth and productivity of wheat plants. Folia Microbiologica. 1998;43(5):465-70. https://doi.org/10.1007/BF02820792

13. Grzesik M, Rudnicki RM. The use of growth regulators in nursery production of woody ornamental Plant-I. Application of growth habit control of some woody ornamental plants. Acta Hortic. 1985 Apr;(167):401. https://doi.org/10.17660/ActaHortic.1985.167.44

14. Paterno ES. Enhancement of plant growth and production of plant growth regulators by soil bacteria. Inaugural Professorial Lecture. UPLB College, Laguna, SEARCA. 2004; p. 3-9.

15. Jeon WT, Seong KY, Lee JK, Oh IS, Lee YH, Ok YS. Effects of green manure and carbonized rice husk on soil properties and rice growth. Korean J Soil Sci Fert. 2010;43(4):484-89.

16. Kim BH, Sa TM, Chung JB. Effect of inoculation of *Azospirillum brasilense* and *Methylobacterium oryzae* on the growth of red pepper plant. Korean Journal of Environmental Agriculture. 2011 Jun 30;30(2):223-28. https://doi.org/10.5338/KJEA.2011.30.2.223

17. Alen'kina SA, Kupryashina MA, He X, Alen'kina SA, Kupryashina MA, He X. Influence of *Azospirillum* lectins on the antioxidant system response in wheat seedling roots during abiotic stress. Soil Research [Internet]. 2021 Nov 8 [cited 2022 Jul 28];60(2):197-209. https://doi.org/10.1071/SR21092

18. Tien TM, Gaskins MH, Hubbell DH. Plant growth substances produced by *Azospirillum brasilense* and their effect on the growth of pearl millet (*Pennisetum americanum* L.). Appl Environ Microbiol. 1979 May;37(5):1016. https://doi.org/10.1128/aem.37.5.1016-1024.1979

19. Jacoby R, Peukert M, Succurro A, Koprivova A, Kopriva S. The role of soil microorganisms in plant mineral nutrition—Current knowledge and future directions. Front Plant Sci. 2017 Sep 19;8:1617. https://doi.org/10.3389/fpls.2017.01617

20. Bashan Y, Holguin G, De-Bashan LE. *Azospirillum*-plant relationships: Physiological, molecular, agricultural and environmental advances (1997-2003). 2004 [cited 2022 Jul 28]. https://doi.org/10.1139/w04-035

21. Cruz JA, Delfin EF, Paterno ES. Promotion of upland rice growth by actinomycetes under growth room condition. Asia Life Sciences Volume. 2015;24(1):87-94.

22. Cavite HJM, Mactal AG, Evangelista E V, Cruz JA. Growth and yield response of upland rice to application of plant growth-promoting rhizobacteria. Journal of Plant Growth Regulation. 2020 Apr 18;40(2):494-508. https://doi.org/10.1007/s00344-020-10114-3

23. Sta Cruz PC, Banayo NC, Marundan SR, Magnaye AA, Lalican DJ, Hernandez JE. Bio-inoculant and foliar fertilizer in combination with soil-applied fertilizer on the yield of lowland rice. Philippine Journal of Crop Science. 2012;37(3):55-63.

24. Sindhu S, Dahiya A, Gera R, Sindhu SS. Mitigation of abiotic stress in legume-nodulating rhizobia for sustainable crop production. Agricultural Research. 2020 Jul 18;9(4):444-59. https://doi.org/10.1007/s40003-020-00474-3

25. Kumari C, Markar A, Karuna K, Solankey S, Singh V. Effect of different levels of nitrogen and microbial inoculants on yield and quality of cabbage (*Brassica oleracea* var *capitata*) cv pride of India. The Indian Journal of Agricultural Sciences. 2015;85(4):515-18. https://doi.org/10.56093/ijas.v85i4.47930

26. Wani SP, Gopalakrishnan S. Plant growth-promoting microbes for sustainable agriculture. Plant Growth Promoting Rhizobacteria (PGPR): Prospects for Sustainable Agriculture. 2019;19-45. https://doi.org/10.1007/978-981-13-6790-8_2

27. Kumar V, Rawat AK, Rao DLN. Improving the performance of *Bradyrhizobium japonicum* by double inoculation in non-fertilized and fertilized wheat–soybean rotation. Agricultural Research. 2021 Sep 17;1-11. https://doi.org/10.1007/s40003-021-00600-9

28. Kumar A, Chandra D, Pallavi, Sharma AK. Impact of seed applied rhizobacterial inoculants on growth of wheat (*Triticum aestivum*) and cowpea (*Vigna unguiculata*) and their influence on rhizospheric microbial diversity. Agricultural Research. 2021 Apr 25;11(1):1-14. https://doi.org/10.1007/s40003-021-00546-y

29. Pii Y, Mimmo T, Tomasi N, Terzano R, Cesco S, Crecchio C. Microbial interactions in the rhizosphere: Beneficial influences of plant growth-promoting rhizobacteria on nutrient acquisition process. A review. Biology and Fertility of Soils. 2015 Jan 31;51(4):403-15. https://doi.org/10.1007/s00374-015-0996-1

30. Adesemoye AO, Kloepper JW. Plant-microbes interactions in enhanced fertilizer-use efficiency. Appl Microbiol Biotechnol. 2009 Nov;85(1):1-12.https://doi.org/10.1007/s00253-009-2196-0

31. Meena KK, Sorty AM, Bitla UM, Choudhary K, Gupta P, Pareek A et al. Abiotic stress responses and microbe-mediated mitigation in plants: The omics strategies. Front Plant Sci. 2017 Feb 9;8:172. https://doi.org/10.3389/fpls.2017.00172

32. Enebe MC, Babalola OO. The influence of plant growth-promoting rhizobacteria in plant tolerance to abiotic stress: A survival strategy. Appl Microbiol Biotechnol. 2018 Sep 1;102(18):7821-35. https://doi.org/10.1007/s00253-018-9214-z

33. Khan N, Asadullah, Bano A. Rhizobacteria and abiotic stress management. 2019;65-80. https://doi.org/10.1007/978-981-13-6536-2_4

34. Selvakumar G, Panneerselvam P, Ganeshamurthy AN. Bacterial mediated alleviation of abiotic stress in crops. Bacteria in Agrobiology: Stress Management. 2012 Jul 1;9783642234651:205-24. https://doi.org/10.1007/978-3-642-23465-1_10

35. Grover M, Ali SZ, Sandhya V, Rasul A, Venkateswarlu B. Role of microorganisms in adaptation of agriculture crops to abiotic stresses. World Journal of Microbiology and Biotechnology. 2010 Oct 5;27(5):1231-40. https://doi.org/10.1007/s11274-010-0572-7

36. Karthikeyan B, Joe MM, Islam MR, Sa T. ACC deaminase containing diazotrophic endophytic bacteria ameliorate salt stress in *Catharanthus roseus* through reduced ethylene levels and induction of antioxidative defense systems. Symbiosis. 2012 Mar 30;56(2):77-86. https://doi.org/10.1007/s13199-012-0162-6

37. Chandra D, Srivastava R, Sharma AK. Influence of IAA and ACC deaminase producing fluorescent *Pseudomonads* in alleviating drought stress in wheat (*Triticum aestivum*). Agricultural Research. 2018 Apr 23;7(3):290-99. https://doi.org/10.1007/s40003-018-0305-y