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Improving the Sustainability of Rice Cultivation in Central Thailand with Biofertilizers and Laser Land Leveling

Anny Ruth P. Pame [1,*], Duangporn Vithoonjit [2], Nisa Meesang [3], Carlito Balingbing [1], Martin Gummert [1], Nguyen Van Hung [1], Grant R. Singleton [1,4] and Alexander M. Stuart [1]

[1] International Rice Research Institute, Los Baños 4031, Philippines
[2] Chainat Rice Research Center, Chai Nat 17000, Thailand
[3] Land Development Department, Bangkok 10900, Thailand
[4] Natural Resources Institute, University of Greenwich, Chatham Maritime, Kent ME4 4TB, UK
* Correspondence: a.pame@irri.org

Abstract: Rice production in the Central Plains of Thailand plays a key role in the country's food security. However, the overuse of inputs coupled with the rising production costs are making it increasingly difficult for smallholder rice farming to remain economically and environmentally sustainable. Replicated production-scale field trials of Cost Reduction Operating Principles (CROP)—Thailand's national package of best management practices for rice production—were established in tandem with laser land leveling (LLL), mechanical drum seeder, and the application of two biofertilizer products (i.e., PGPR II, that contains *Azospirillum brasilense* Sp. TS29 and *Burkholderia vietnamiensis* S45; and LDD #12, that contains *Azotobacter tropicalis*, *Burkholderia unamae* and *Bacillus subtilis*) and compared with farmer's practices (FP). Performance indicators (PI) promoted by the Sustainable Rice Platform (SRP) were used to assess economic and environmental indicators. CROP + PGPR had significantly higher net income (79%) and nitrogen-use efficiency (57%) compared with FP. Pesticide use (28%), seed (60%), inorganic fertilizer N (41%) and total production costs (19%) were reduced in all CROP treatments compared with FP. These results demonstrate that the application of CROP, LLL, mechanical drum seeder, and biofertilizers can substantially improve the economic and environmental sustainability of rice production in the Central Plains of Thailand.

Keywords: food security; natural resource management; plant growth promoting rhizobacteria; resource use efficiency; smallholder farmers; sustainable rice production

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1. Introduction

Rice is the daily staple for more than 3.5 billion people, accounting for 19% of dietary energy globally [1], and will continue to be of high importance to global diets [2]. With the global population estimated to reach over nine billion by 2050 [3], the total global food demand is expected to increase by 35% to 56% between 2010 and 2050 [4]. However, rice production faces many serious challenges including the loss of agricultural land because of urban growth [5,6], overuse of inputs [7–10] and negative effects on production related to climate change [11–15]. In addition, an increased awareness of the benefits of faunal and floral biodiversity at a landscape level [16,17] has led to a greater focus on the need to sustainably produce food in the remaining agricultural lands [1,18].

To address these challenges, many countries have developed national programs for rice production that include a set of best management practices (BMPs), such as Vietnam's "1 Must Do, 5 Reductions (1M5R)" [19], China's "3 Controls Technology (3CT)" [20] and Thailand's "Cost Reduction Operating Principles (CROP)" [21]. On a global scale, sustainable agricultural practices and programs are also being promoted, including Global GAP and the Sustainable Rice Platform (SRP) [22–25]. The Closing Rice Yield Gaps in Asia Project with a reduced environmental footprint (CORIGAP) is providing one avenue to address these challenges in rice production [7–10,26]. The objectives of CORIGAP include improving food security and alleviating poverty through optimizing the productivity and sustainability of irrigated rice production systems in six countries in Asia—China, Indonesia, Myanmar, Sri Lanka, Thailand and Vietnam. Through its adaptive farmer participatory research platform and in collaboration with country partners, CORIGAP has conducted several farmer participatory field trials. One of its key approaches is to identify gaps and constraints for rice production through needs assessment surveys and focus group discussions and then conduct farmer participatory adaptive research that provide evidence to help strengthen national programs for rice. For example, in Vietnam, the application of 1M5R practices with clear limits for input use (i.e., seeds and pesticides) in rice production in the Mekong River Delta resulted in a 23% decrease in the mean total production cost per season and an increase in the mean net income by 19% [8]. In addition, farmer participatory rice field trials of CROP in the Central Plains of Thailand resulted in reduced seed and chemical fertilizer inputs by 60–67% and 50–64%, respectively, without compromising the yield, and increased the net income by 26% compared with farmers' practices [7]. These studies have clearly demonstrated that the application of BMPs can substantially improve the sustainability of intensive lowland irrigated rice production.

Thailand is one of the major exporters of rice in the world [27]. Thus, it plays a key role in global food security. Based on the results of the farmer participatory field trials in the central plains [7] and recognizing the need for sustainably produced rice, Thailand's Rice Department (RD) added the following to their CROP recommendations: (1) reduce the seed rate through the application of drum seeding technology, and (2) install field water tubes as a tool to indicate when to irrigate and reduce water use [7]. In the current study, we evaluate further modifications to CROP recommendations that were based on farmer feedback and the results of previous field trials. These include the use of a mechanized drum seeder that is pulled by a two-wheeled tractor; the application of laser land leveling (LLL); and the application of biofertilizers. In the recent years, Thailand has been experiencing irrigation water scarcity [28]. LLL provides high precision in leveling rice fields and leads to reduced water use (1.5–2.8 m^3 water per ha), improved fertilizer and herbicide use efficiency, and reduced greenhouse gas emissions by 20–40% [29,30]. A life-cycle assessment on energy use for lowland irrigated rice production reported that LLL reduces energy use by 20–30% [29]. Biofertilizers, meanwhile, are substances that contain beneficial microorganisms that increase the availability of nutrients to the plant, e.g., by biological nitrogen fixation, thus reducing the inorganic fertilizer use requirements [31]. They can also promote fibrous roots and enlarge the root surface area, which enhance the ability of the plants to absorb water and nutrients [32].

In the current study, the performance of a modified CROP complemented with a mechanical drum seeder, laser land leveling and two biofertilizer products was assessed compared to current farmer practices. The key agronomic practices and production outputs were assessed against the SRP performance indicators [33]. We test the hypothesis that the combination of improved CROP recommendations and new crop establishment and biofertilizer practices will provide both economic and environmental benefits to smallholder farmers in the central plains of Thailand.

2. Materials and Methods

2.1. Field Trial Sites and Farmer Selection

Farmer participatory field trials were established in Nong Jikree and Wat Prakeaw villages in the Nakhon Sawan and Chainat provinces, respectively, in the Central Plains of Thailand. The climate is tropical, with one pronounced wet and dry season each year. The soil type is mostly clay [26]. Rice is grown twice a year in these sites: the wet season (WS) crop is from June to October while the dry season (DS) crop is from January to May [7,26]. Data were collected across three cropping seasons—2016 WS, 2016–17 DS and 2017 WS.

Farmers were selected based on their motivation to participate in the trials and willingness to follow the protocols and provide field plots of at least 1–4 rai (1 rai = 1600 m^2)

for each treatment. These included some farmers who are members of groups that form the Community Rice Centers registered with the government extension office [7]. The selected individuals served as treatment farmers while neighboring farmers, whose fields were adjacent to the treatment farmers' fields, served as control farmers who applied the usual farmer's practices in these areas (Table 1). Preliminary on-site briefing and training sessions on the protocols were conducted before the start of the trials.

Table 1. Summary of field activities for the four field trial treatments in Nakhon Sawan and Chainat provinces during the 2016 WS, 2016–17 DS and 2017 WS.

Activity/Operation	CROP	CROP + PGPR	CROP + BIO	FP
Plot size (ha)	0.32–0.64	0.32–0.64	0.16–0.48	0.48–3.20
No. of replicates	6–8	6–8	6–8	6–8
Soil preparation	CROP recommendations	CROP recommendations	CROP recommendations	Farmer practice
Soil surface leveling	Laser land leveling	Laser land leveling	Laser land leveling	Farmer practice
Crop establishment [a]	Mechanical drum seeding	Mechanical drum seeding	Mechanical drum seeding	Direct broadcasting
Cultivar				
2016 WS	RD41, PTT1	RD41, PTT1	RD41, PTT1	RD41, RD57, SPR1, PTT1, KDML 105
2016–17 DS	RD41, PTT1	RD41, PTT1	RD41, PTT1	RD41, RD57, PTT1
2017 WS	RD41, PTT1, KDML105	RD41, PTT1, KDML105	RD41, PTT1, KDML105	RD41, RD57, PTT1, Khao Jow Hawm Suphan Buri
Seed quality	Certified seeds	Certified seeds	Certified seeds	Certified seeds
Seed rate (kg ha^{-1})				
2016 WS	37.50–62.50	37.50–62.50	37.50–62.50	43.75–156.25
2016–17 DS	37.50–75.00	37.50–75.00	37.50–75.00	62.50–468.75
2017 WS	31.25–75.00	31.25–75.00	31.25–75.00	50.00–156.25
Date sown				
2016 WS	12 July–14 August	12 July–14 August	12 July–14 August	5 July–7 August
2016–17 DS	18–28 December	18–28 December	18–28 December	11–21 December
2017 WS	8 May–5 July	8 May–5 July	8 May–5 July	1 May–28 June
Fertilizer application rate (kg ha^{-1})				
2016 WS	37.38–74.75	28.03–56.35	39.28–67.60	20.00–128.88
2016–17 DS	37.38–86.25	28.03–67.85	39.28–79.10	47.63–220.88
2017 WS	54.63–92.00	46.00–77.63	54.63–92.00	43.75–131.23
Date harvested				
2016 WS	18 October–6 December	18 October–6 December	18 October–6 December	11 October–29 November
2016–17 DS	15 April–9 May	15 April–9 May	15 April–9 May	8 April–2 May
2017 WS	21 August–10 November	21 August–10 November	21 August–10 November	14 August–3 November

[a] Two CROP farmers in Wat Prakeaw used mechanical transplanter (1 each for 2016–17 DS and 2017 WS). WS = wet season; DS = dry season; CROP = Cost Reduction Operating Principles; CROP + PGPR = CROP plus Department of Agriculture's (DA) "plant growth promoting Rhizobacteria" (PGPR) II biofertilizer; CROP + BIO = CROP plus Land Development Department's (LDD) #12 biofertilizer; FP = Farmer's Practice.

2.2. Field Trial Design and Treatment Details

A randomized complete block design was applied to account for spatial variability. Four treatments were replicated during the 2016 WS, 2016–17 DS and 2017 WS, respectively. The treatments implemented were: (i) Cost Reduction Operating Principles (CROP), (ii) CROP plus (PGPR) II biofertilizer (CROP + PGPR), (iii) CROP plus LDD #12 biofertilizer (CROP + BIO), and (iv) Farmer's practices (FP). Eight selected farmers participated in the 2016 WS following the four treatments. In the second season (2016–17 DS), only seven of eight farmers from the previous season were able to continue participating in the trials. Meanwhile, only six farmers participated in the last season (2017 WS).

Farmers who were selected to implement modified CROP treatments (Table 1) followed the recommended practices of CROP (Table 2) for seed quality, seed rate for mechanical drum seeding, soil preparation, weed control, pest management, fertilizer application, water management, harvesting and record keeping (see Stuart et al. [7] for further details). Laser land leveling [29] also was conducted in their fields during the 2016 WS. It was performed once in the three cropping seasons because field leveling with the laser system is best applied once every 5 years [30]. Meanwhile, neighboring farmers followed their own practices in the FP fields.

For the CROP + PGPR treatment, farmers were required to follow the above practices for CROP. In addition, they applied the biofertilizer, PGPR II, which was acquired from the Thailand Department of Agriculture (DA). This product contains two species of "plant growth promoting Rhizobacteria" (PGPR) that were identified from Thai rice, namely *Azospirillum brasilense* Sp. TS29 and *Burkholderia vietnamiensis* S45, which have the ability to fix atmospheric nitrogen and transform it to an ammonium form usable by the plant [34]. Based on the Thailand DA's initial studies, application of this biofertilizer decreases the requirement for inorganic fertilizer use by at least 25% [35–37]. PGPR II was mixed with rice seeds prior to seeding or transplanting following the recommended application rate of 500 g (equivalent to 1 bag) for every 10–15 kg of seed per rai (1 rai = 1600 m^2). This biofertilizer can be purchased by farmers in its available form and can be used directly without the need for further incubation.

For the CROP + BIO treatment, farmers also followed the above practices for CROP and, in addition, they applied the biofertilizer LDD #12. The LDD #12 starter culture is produced by the Thailand Land Development Department (LDD). This product contains asymbiotic dinitrogen fixing bacteria (*Azotobacter tropicalis*), phosphate solubilizing bacteria (*Burkholderia unamae*), potassium solubilizing bacteria (*Bacillus subtilis*; which can generate organic acid to solubilize potassium compounds of the mica group such as biotide, muscovite and feldspar as microcline orthoclase into forms that plants can absorb), and plant hormones such as auxin, gibberelin, and cytokinin. One of the advantages in applying this biofertilizer is its ability to reduce the use of inorganic fertilizers by at least 25–30% [38]. The LDD #12 starter culture was acquired from the LDD. Next, 100 g of LDD #12 was mixed with 3 kg rice bran in 20 L water, stirred for 5 min, and was left to ferment. The solution was then mixed with 300 kg of compost and incorporated into the soil during land preparation.

In the CROP + PGPR and CROP + BIO treatments, the inorganic fertilizer application rates obtained from the CROP recommendations following field-specific soil testing, were reduced by 25%. Due to lower than expected yields in some fields during the first two seasons, the applied fertilizer rates for CROP + PGPR were increased to 84% (rather than 75%) of the CROP recommended rates in the 2017 WS. Meanwhile, in CROP + BIO treated plots, farmers followed the 100% CROP fertilizer recommendation. Farmers in Chainat did not apply PGPR II and LDD #12 during the 2017 WS.

2.3. Soil Sampling and Analysis

Soil samples from the two villages were collected in each rice field plot during land preparation before the treatments were imposed. Soil fertility was assessed from organic matter, phosphorus (P), and potassium (K) content, and CROP recommendations for fertilizer application were provided for each field based on these results [39]. For the FP fields, the farmers followed their own practices of fertilizer application.

2.4. Measurements and Data Collection

The farmers were asked to record all their inputs (seeds, fertilizers, and pesticides), operations, labor inputs in all farm activities, and all other costs in the farmer diary. Phenological dates of the rice crop were also recorded. Yields from all treatment fields (both from crop cut and whole field yield) were recorded, while only the whole field yields were recorded for the farmer practice fields. At the end of the season, meetings were held with participating farmers to evaluate the technologies and practices and to facilitate farmer learning in an adaptive research approach [40,41]. A farmer field day was also held at the end of 2016 WS to promote the CROP that includes LLL, mechanical drum seeding, and biofertilizers to the wider community.

Table 2. Recommended practices based on the Cost Reduction Operating Principles (CROP) [a].

Practice	Recommendation
Seed quality	Use certified seed
Seed rate (kg ha^{-1}) [b]	Broadcasting: 94–125
	Transplanting: 44
	Parachute transplanting: 31
	Drum seeding: 50
Soil preparation [b]	No straw burning
	Soil plowing and turn over to promote straw decomposition
	Irrigate to accelerate straw degradation
	Laser land leveling (LLL)
Weed control	Pre-emergence herbicide application after sowing
	Appropriate herbicide for the type of weed
	Herbicide application if weed spread is more than 20% of total field area
	No rain/irrigation in the field during herbicide application
Pest management	Regular field inspection
Fertilizer application	Follow recommendation based on results from soil analysis (see Rice Department [39])
	Conduct soil analysis every three years
Water management [b]	Drain water before sowing
	Water levels: 5 cm above soil surface during early tillering stage 10–15 cm above soil surface during mid-tillering to milky-ripe stages
	Install field water tubes in all CROP treatment fields as a tool to decide when to irrigate
Harvesting	Drain water from the field two weeks after flowering
	Harvest at physiological maturation stage
Recording	Regular recording of production costs

[a] Adapted from Stuart et al. [7]. [b] Improved practice for this field trial.

2.5. Rice Production Inputs and Costs

We calculated the key rice production inputs and costs. Seed rate was computed by converting the local unit (rai) to per ha. Fertilizer application rates (N, P and K) were computed by multiplying the amount of fertilizer applied with the percentage of the elemental form of the nutrient present in the fertilizer. Since P and K were still in their compound forms (P_2O_5 and K_2O), these were converted into their elemental forms by multiplying by a factor of 0.4364 and 0.8302, respectively. The number of individual product applications of different pesticide categories (i.e., herbicide, insecticide, fungicide, rodenticide and molluscicide) was counted for each season. The benefit cost ratio was computed by dividing the gross income by the total production cost. Cost per kg paddy was computed by dividing the total production cost by the grain yield.

2.6. Calculation of SRP Performance Indicators

The SRP PIs were developed to assess improvements in sustainability following the adoption of best management practices [33,42,43]. We were able to compute seven PIs from a total of 12 SRP PIs. Profitability: net income, labor productivity, productivity: grain yield, nitrogen-use efficiency (NUE), phosphorus-use efficiency (PUE), pesticide use (biodiversity) and greenhouse gas emissions (GHGE) were computed using the procedures defined by SRP version 2.0 [33]. SRP PI water productivity and quality could not be calculated due to a lack of information, such as regular measurements of irrigation water levels in the field. CROP farmers used the field water tubes to check when their fields needed to be irrigated, but did not record the water levels before and after irrigation. Instead, we calculated the water pumping fuel cost to see whether there was a reduction under LLL and CROP compared with FP. Questions relating to the remaining SRP PIs, i.e., food safety; health and safety; child labor and youth engagement; and women's empowerment were not included as part of this study.

I Profitability: net income was computed using the formula:

$$NI = GI - TPC \tag{1}$$

where: NI means net income, GI means gross income, and TPC means total production cost. Gross income was computed based on the grain yield (at 14% moisture content (MC)) and the farm-gate price reported by each farmer. The total production costs included costs for all inputs, labor, machine and land rent required for all farm activities from land preparation to harvesting. These also included non-paid out costs that were imputed from family labor, the land rental equivalent for the cost of lost opportunity and the depreciation cost for the machinery and equipment. The cost for LLL (Appendix A Table A1) was excluded in the calculation of the total production cost as this was covered by the adaptive research platform of CORIGAP in cooperation with Thailand's RD.

II Labor productivity—to compute labor productivity, grain yield was divided by the number of labor days per season. Labor days include all activities from land preparation until harvest and regular field visits by farmers. This was estimated by dividing the total labor cost per season by the average daily wage rate at the time taken across all activities (i.e., THB 50 or USD 1.45 for Nakhon Sawan and THB 60 or USD 1.75 for Chainat).

III Productivity: grain yield—to compute grain yield (expressed as kg ha^{-1}), wet grain harvested from the whole field was measured in kilograms and the MC was also recorded at harvest. Then, the whole harvest was divided by the total land area, converted to a per ha basis and 14% MC.

IV Nutrient-use efficiency: N—to compute NUE, the total grain yield harvested (kg ha^{-1} at 14% MC) was divided by the total amount of N (kg ha^{-1}) applied.

V Nutrient-use efficiency: P—to compute PUE, the total grain yield harvested (kg ha^{-1} at 14% MC) was divided by the total amount of P (kg ha^{-1}) applied.

VI Pesticide use (biodiversity)—pesticide use is defined by SRP as an intermediate indicator for biodiversity, i.e., as an indicator of the potential negative impacts of rice cultivation on biodiversity. The basis for this indicator is the total number of individual pesticide products applied per season.

VII Greenhouse gas emissions—GHGEs (expressed as CO_2 equivalent emission) were calculated following the IPCC [44] formula as described by Stuart et al. [8].

2.7. Data Analysis

Linear mixed models with the maximum likelihood of estimation were used to analyze differences between treatments over the three cropping seasons using SPSS version 18 (SPSS Inc., Chicago, IL, USA). The fixed effects entered into the model included season (as a repeated variable with diagonal repeated covariance), treatment and treatment-by-season interaction. Site was included as a random effect with no intercept to account for the block design. Dependent variables that produced non-normally distributed residuals were analyzed using rank transformation. Pairwise comparisons of the main effects were conducted using the Bonferroni test.

3. Results

3.1. Rice Production Inputs and Costs

The mean seed, nitrogen and phosphorus application rates were lower by 60, 41 and 80%, respectively, in all CROP treatments compared with FP ($p < 0.05$; Table 3 and Table 6). The mean total production cost was significantly lower in both CROP and CROP + PGPR, by an average of 19%, compared with FP ($p < 0.05$; Table 4 and Table 6). The cost per kg paddy was also 29% lower in CROP + PGPR compared with CROP + BIO ($p < 0.05$; Table 4 and Table 6). Meanwhile, the mean BCR was significantly higher in CROP and

CROP + PGPR compared with FP, with differences of 20% and 23% ($p < 0.05$; Table 4 and Table 6).

Table 3. Key inputs (mean values followed by standard error in parenthesis) of rice production across four field trial treatments over three seasons.

	CROP			CROP + PGPR			CROP + BIO			FP		
2016 WS:												
Seed rate (kg ha^{-1})	52.54	(3.42)	a	52.54	(3.42)	a	52.54	(3.42)	a	103.13	(16.79)	b
Nitrogen application rate (kg ha^{-1})	47.25	(6.01)	a	35.47	(4.53)	b	46.72	(4.53)	a	69.93	(14.44)	c
Phosphorus application rate (kg ha^{-1}) [a]	2.20	(1.44)	a	1.65	(1.08)	a	3.28	(1.08)	a	8.81	(1.95)	b
Potassium application rate (kg ha^{-1})	7.78	(2.94)	a	5.84	(2.21)	a	10.51	(2.21)	a	11.72	(3.35)	a
Pesticide application (no.)	3.25	(0.45)	a	3.25	(0.45)	a	3.25	(0.45)	a	3.25	(0.65)	a
Herbicide	2.63	(0.32)		2.63	(0.32)		2.63	(0.32)		2.00	(0.38)	
Fungicide	0.50	(0.33)		0.50	(0.33)		0.50	(0.33)		0.00	(0.00)	
Insecticide	0.13	(0.13)		0.13	(0.13)		0.13	(0.13)		1.25	(0.41)	
2016–17 DS:												
Seed rate (kg ha^{-1})	58.04	(4.46)	a	58.04	(4.46)	a	58.04	(4.46)	a	191.96	(48.43)	b
Nitrogen application rate (kg ha^{-1})	50.00	(7.98)	a	37.95	(6.33)	a	51.26	(6.13)	a	103.31	(22.19)	b
Phosphorus application rate (kg ha^{-1}) [a]	1.25	(1.25)	a	0.94	(0.94)	a	2.58	(0.94)	a	13.10	(3.44)	b
Potassium application rate (kg ha^{-1})	6.67	(3.14)	a	5.00	(2.36)	a	9.67	(2.36)	a	3.58	(3.55)	a
Pesticide application (no.)	4.29	(0.68)	a	4.29	(0.68)	a	4.29	(0.68)	a	5.57	(0.69)	a
Herbicide	2.43	(0.37)		2.43	(0.37)		2.43	(0.37)		2.29	(0.36)	
Fungicide	1.00	(0.38)		1.00	(0.38)		1.00	(0.38)		2.00	(0.00)	
Insecticide	0.86	(0.34)		0.86	(0.34)		0.86	(0.34)		1.29	(0.42)	
2017 WS:												
Seed rate (kg ha^{-1})	59.38	(6.80)	a	59.38	(6.80)	a	59.38	(6.80)	a	133.33	(17.43)	b
Nitrogen application rate (kg ha^{-1})	67.81	(7.68)	a	56.60	(5.87)	a	71.56	(6.70)	a	84.30	(13.25)	a
Phosphorus application rate (kg ha^{-1}) [a]	1.88	(1.88)	a	1.67	(1.67)	a	2.43	(1.80)	a	8.58	(2.61)	b
Potassium application rate (kg ha^{-1})	7.26	(4.59)	a	6.23	(3.94)	a	8.82	(4.19)	a	9.22	(6.10)	a
Pesticide application (no.)	2.83	(0.54)	a	2.83	(0.54)	a	2.83	(0.54)	a	6.00	(0.73)	b
Herbicide	1.67	(0.49)		1.67	(0.49)		1.67	(0.49)		3.00	(0.45)	
Fungicide	0.17	(0.17)		0.17	(0.17)		0.17	(0.17)		1.83	(0.17)	
Insecticide	0.83	(0.65)		0.83	(0.65)		0.83	(0.65)		1.17	(0.31)	

Means within a row followed by the same letter are not different at the 0.05 probability level following pairwise comparisons. [a] Analyzed using log-transformed data.

The CROP farmers applied a significantly lower rate of N (by 29%) during the 2016 WS than in 2017 WS (Table 3 and Table 6). The water pumping fuel cost was also 74% lower during the 2016 WS than in 2016–17 DS (Table 4 and Table 6). Meanwhile, 2017 WS had the highest BCR and lowest cost per kg paddy (Table 4 and Table 6). Farmers in Nakhon Sawan applied 4% less K than farmers in Chainat (Table 3 and Table 6).

3.2. SRP Performance Indicators

The mean net income and NUE were highest in CROP + PGPR by 79% and 57%, respectively, over FP. The mean number of pesticide applications in all CROP treatments was reduced by 28% compared to FP. However, no significant differences in treatments were observed in labor productivity, grain yield and GHGE ($p < 0.05$; Tables 5 and 6).

Significant differences were also observed between seasons. Labor productivity and NUE were higher by 33% and 36%, respectively, during the 2016 WS. Net income and grain yield were 149% and 20% higher, respectively, during the 2017 WS. Additionally, farmers applied significantly fewer pesticides (mean difference of 30%) during the 2016 WS than in the 2016–17 DS. GHGE was 27% lower during the 2016–17 DS.

Table 4. Economic analysis (mean values followed by standard error in parenthesis) of rice production across four field trial treatments over three seasons.

	CROP			CROP + PGPR			CROP + BIO			FP		
2016 WS:												
Seed cost (USD ha^{-1})	27.51	(1.79)	a	27.51	(1.79)	a	27.51	(1.79)	a	50.04	(8.40)	b
Fertilizer cost (USD ha^{-1})	47.70	(6.66)	a	35.74	(5.03)	a	35.74	(5.03)	a	97.68	(18.08)	b
Pesticide cost (USD ha^{-1})	36.19	(6.40)	a	36.19	(6.40)	a	36.19	(6.40)	a	45.79	(10.96)	a
Herbicide	31.21	(5.83)		31.21	(5.83)		31.21	(5.83)		30.76	(5.01)	
Insecticide	0.85	(0.85)		0.85	(0.85)		0.85	(0.85)		15.03	(7.83)	
Fungicide	4.14	(2.71)		4.14	(2.71)		4.14	(2.71)		0.00	(0.00)	
Water pumping fuel cost (USD ha^{-1})	10.98	(2.55)	a	10.98	(2.55)	a	10.98	(2.55)	a	11.29	(8.94)	a
Labor cost (USD ha^{-1})	236.77	(20.60)	a	236.54	(20.60)	a	264.15	(20.60)	a	267.37	(17.48)	a
Total production cost (USD ha^{-1})	548.86	(23.53)	a	541.23	(23.39)	a	782.45	(23.69)	c	676.68	(39.79)	b
Gross income (USD ha^{-1}) [a]	895.14	(80.94)	a	895.00	(92.64)	a	919.04	(71.99)	a	899.96	(46.40)	a
Cost per kg paddy (USD ha^{-1})	0.13	(0.01)	a	0.13	(0.01)	a	0.18	(0.01)	b	0.14	(0.01)	a
Benefit: Cost ratio	1.65	(0.17)	c	1.67	(0.19)	c	1.18	(0.09)	a	1.35	(0.08)	b
2016–17 DS:												
Seed cost (USD ha^{-1})	32.07	(2.47)	a	32.07	(2.47)	a	32.07	(2.47)	a	84.01	(20.86)	b
Fertilizer cost (USD ha^{-1})	50.46	(8.00)	a	38.44	(6.15)	a	38.44	(6.15)	a	111.51	(23.45)	b
Pesticide cost (USD ha^{-1})	41.09	(6.14)	a	41.09	(6.14)	a	41.09	(6.14)	a	82.16	(20.84)	b
Herbicide	24.68	(3.35)		24.68	(3.35)		24.68	(3.35)		29.80	(4.30)	
Insecticide	7.98	(3.00)		7.98	(3.00)		7.98	(3.00)		25.21	(14.22)	
Fungicide	8.43	(3.87)		8.43	(3.87)		8.43	(3.87)		27.15	(7.26)	
Water pumping fuel cost (USD ha^{-1})	40.70	(10.41)	a	40.70	(10.41)	a	40.70	(10.41)	a	49.07	(13.77)	a
Labor cost (USD ha^{-1})	316.02	(27.51)	a	316.56	(27.79)	a	340.10	(27.37)	a	290.38	(39.29)	a
Total production cost (USD ha^{-1})	618.48	(56.27)	a	611.54	(57.31)	a	848.68	(55.08)	b	735.60	(60.57)	b
Gross income (USD ha^{-1}) [a]	860.69	(67.49)	a	867.73	(66.25)	a	856.83	(58.92)	a	900.78	(97.81)	a
Cost per kg paddy (USD ha^{-1})	0.17	(0.03)	ab	0.16	(0.02)	a	0.23	(0.03)	bc	0.19	(0.04)	ab
Benefit: Cost ratio	1.45	(0.14)	b	1.47	(0.11)	b	1.03	(0.09)	a	1.32	(0.23)	b
2017 WS:												
Seed cost (USD ha^{-1})	30.15	(4.19)	a	30.15	(4.19)	a	30.15	(4.19)	a	59.29	(6.41)	b
Fertilizer cost (USD ha^{-1})	65.25	(10.54)	a	54.89	(8.67)	a	65.25	(10.54)	a	109.85	(22.66)	b
Pesticide cost (USD ha^{-1})	27.07	(4.05)	a	27.07	(4.05)	a	27.07	(4.05)	a	73.18	(9.99)	b
Herbicide	17.85	(5.29)		17.85	(5.29)		17.85	(5.29)		38.64	(6.19)	
Insecticide	8.19	(6.02)		8.19	(6.02)		8.19	(6.02)		17.47	(4.31)	
Fungicide	0.40	(0.40)		0.40	(0.40)		0.40	(0.40)		17.07	(3.01)	
Water pumping fuel cost (USD ha^{-1})	4.95	(1.75)	a	4.95	(1.75)	a	4.95	(1.75)	a	6.99	(4.65)	a
Labor cost (USD ha^{-1})	302.55	(24.78)	a	302.91	(24.71)	a	311.66	(26.03)	a	369.19	(57.19)	a
Total production cost (USD ha^{-1})	558.61	(24.09)	a	550.12	(24.94)	a	640.44	(65.65)	ab	707.22	(88.91)	b
Gross income (USD ha^{-1}) [a]	1052.47	(47.12)	a	1076.66	(47.16)	a	1058.49	(52.39)	a	943.05	(86.10)	a
Cost per kg paddy (USD ha^{-1})	0.12	(0.01)	ab	0.11	(0.00)	a	0.13	(0.01)	b	0.15	(0.02)	b
Benefit: Cost ratio	1.90	(0.10)	a	1.97	(0.10)	a	1.72	(0.016)	a	1.44	(0.21)	a

Means within a row followed by the same letter are not different at the 0.05 probability level following pairwise comparisons. [a] Actual income farmers received for fresh grain. 1 USD = 34.38 THB.

A trade-off comparison among the different performance indicators and the four treatments per season (Figure 1) showed that during all three seasons, CROP + PGPR had the highest net income and NUE, while CROP + BIO had the lowest net income for the 2016 WS and 2016–17 DS. FP had the lowest net income during the 2017 WS and lowest NUE for all three seasons. However, across all seasons, FP had the highest PUE. All CROP treatments received a lower number of pesticide applications compared to FP, especially during the 2016–17 DS and 2017 WS.

Table 5. Key SRP performance indicators (mean values followed by standard error in parenthesis) of rice production across four field trial treatments over three seasons.

	CROP			**CROP + PGPR**			**CROP + BIO**			**FP**		
2016 WS:												
Profitability: net income (USD ha^{-1})	346.27	(82.30)	b	353.77	(90.86)	b	136.59	(69.60)	a	223.27	(51.30)	a
Labor productivity (kg day^{-1})	29.91	(2.96)	a	29.56	(2.91)	a	27.05	(1.95)	a	29.33	(2.87)	a
Productivity: grain yield (t ha^{-1}) [a]	4.24	(0.27)	a	4.23	(0.32)	a	4.40	(0.31)	a	4.72	(0.22)	a
Nutrient-use efficiency: N (grain kg N kg^{-1})	96.32	(9.88)	a	127.36	(13.63)	b	99.37	(10.80)	a	94.78	(19.83)	ab
Nutrient-use efficiency: P (grain kg P kg^{-1}) [b]	96.70	(63.44)	a	125.70	(82.94)	a	2273.15	(426.17)	b	4971.84	(4428.91	b
Nutrient-use efficiency: K (grain kg K kg^{-1}) [c]	131.25	(51.08)	a	177.17	(69.81)	a	610.29	(140.37)	b	1958.82	(1522.25)	b
No. of pesticide applications	3.25	(0.45)	a	3.25	(0.45)	a	3.25	(0.45)	a	3.25	(0.65)	a
Greenhouse gas emission (kg CO_2 equivalent ha^{-1})	3629.75	(398.86)	a	3628.88	(409.80)	a	3824.60	(451.80)	a	3765.40	(387.72)	a
2016–17 DS:												
Profitability: net income (USD ha^{-1})	242.21	(80.41)	b	256.19	(67.27)	b	8.15	(72.23)	ba	165.18	(132.21)	ab
Labor productivity (kg day^{-1})	29.91	(2.96)	a	29.56	(2.91)	a	27.05	(1.95)	a	29.33	(2.87)	a
Productivity: grain yield (t ha^{-1}) [a]	4.00	(0.48)	a	3.99	(0.39)	a	3.89	(0.29)	a	4.42	(0.53)	a
Nutrient-use efficiency: N (grain kg N kg^{-1})	92.87	(18.06)	b	119.41	(19.92)	b	83.33	(12.38)	b	55.32	(12.49)	a
Nutrient-use efficiency: P (grain kg P kg^{-1}) [b]	46.63	(46.63)	c	59.11	(59.11)	c	2136.14	(334.00)	a	663.96	(330.41)	b
Nutrient-use efficiency: K (grain kg K kg^{-1}) [c]	106.93	(52.67)	a	148.62	(70.75)	a	588.18	(138.72)	bc	6622.71	(6600.55)	ac
No. of pesticide applications	4.29	(0.68)	a	4.29	(0.68)	a	4.29	(0.68)	a	5.57	(0.69)	a
Greenhouse gas emission (kg CO_2 equivalent ha^{-1})	2727.92	(228.30)	a	2690.27	(204.13)	a	2750.37	(181.68)	a	2707.48	(201.67)	a
2017 WS:												
Profitability: net income (USD ha^{-1})	493.86	(43.08)	b	526.54	(41.93)	c	418.05	(58.77)	b	235.82	(109.52)	a
Labor productivity (kg day^{-1})	20.94	(2.42)	ab	20.92	(2.07)	ab	18.97	(1.54)	a	26.36	(3.99)	bc
Productivity: grain yield (t ha^{-1}) [a]	4.85	(0.31)	a	4.97	(0.33)	a	4.90	(0.39)	a	4.81	(0.39)	a
Nutrient-use efficiency: N (grain kg N kg^{-1})	76.97	(10.57)	ab	93.37	(12.41)	bc	72.43	(9.41)	ab	65.18	(12.49)	a
Nutrient-use efficiency: P (grain kg P kg^{-1}) [b]	74.09	(74.09)	c	83.27	(83.27)	c	1302.70	(758.85)	a	562.66	(225.46)	b
Nutrient-use efficiency: K (grain kg K kg^{-1}) [c]	66.18	(42.20)	a	79.61	(50.87)	a	492.09	(255.84)	b	55.00	(0.45)	a
No. of pesticide applications	2.83	(0.54)	a	2.83	(0.54)	a	2.83	(0.54)	a	6.00	(0.73)	b
Greenhouse gas emission (kg CO_2 equivalent ha^{-1})	3740.38	(588.67)	a	3777.21	(601.57)	a	3806.92	(641.86)	a	3597.70	(482.40)	a

Means within a row followed by the same letter are not different at the 0.05 probability level following pairwise comparisons. [a] Adjusted to 14% MC. [b] Analyzed using log-transformed data. [c] KUE is not a SRP performance indicator, but is important for rice production.

Table 6. Linear mixed model results of the interaction effects of field trial treatment and season on input, output and economic variables.

Dependent Variable	**Treatment**		**Season**		**Treatment × Season**	
	F	p	F	p	F	p
Seed rate (kg ha^{-1})	24.401	***	3.582	*	1.610	ns
Nitrogen rate (kg ha^{-1})	11.176	***	6.295	**	0.932	ns
Phosphorus rate (kg ha^{-1}) [a]	7.913	***	0.460	ns	0.386	ns
Potassium rate (kg ha^{-1})	1.043	ns	5.144	*	0.957	ns
Nutrient-use efficiency: N (grain kg N kg^{-1})	6.744	***	3.719	*	0.650	ns
Nutrient-use efficiency: P (grain kg P kg^{-1}) [a]	12.048	***	0.132	ns	0.073	ns
Nutrient-use efficiency: K (grain kg K kg^{-1})	15.587	***	2.991	ns	1.356	ns
No. of pesticide applications (biodiversity)	6.799	***	7.267	**	2.590	*
Water pumping fuel cost (USD ha^{-1})	0.205	ns	49.139	***	0.177	ns
Labor productivity (kg day^{-1})	0.592	ns	12.236	***	0.666	ns
Greenhouse gas emission (kg CO_2 equivalent ha^{-1})	0.285	ns	41.476	***	0.355	ns
Productivity: grain yield (t ha^{-1})	0.756	ns	10.376	***	0.414	ns
Total production cost (USD ha^{-1})	15.287	***	2.599	ns	1.603	ns
Profitability: net income (USD ha^{-1})	6.749	***	8.197	***	1.143	ns
Cost per kg paddy (USD kg^{-1})	3.928	*	8.605	***	1.717	ns
Benefit: Cost ratio	7.715	***	6.484	**	0.849	ns

ns = $p > 0.05$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. [a] Analyzed using log-transformed data.

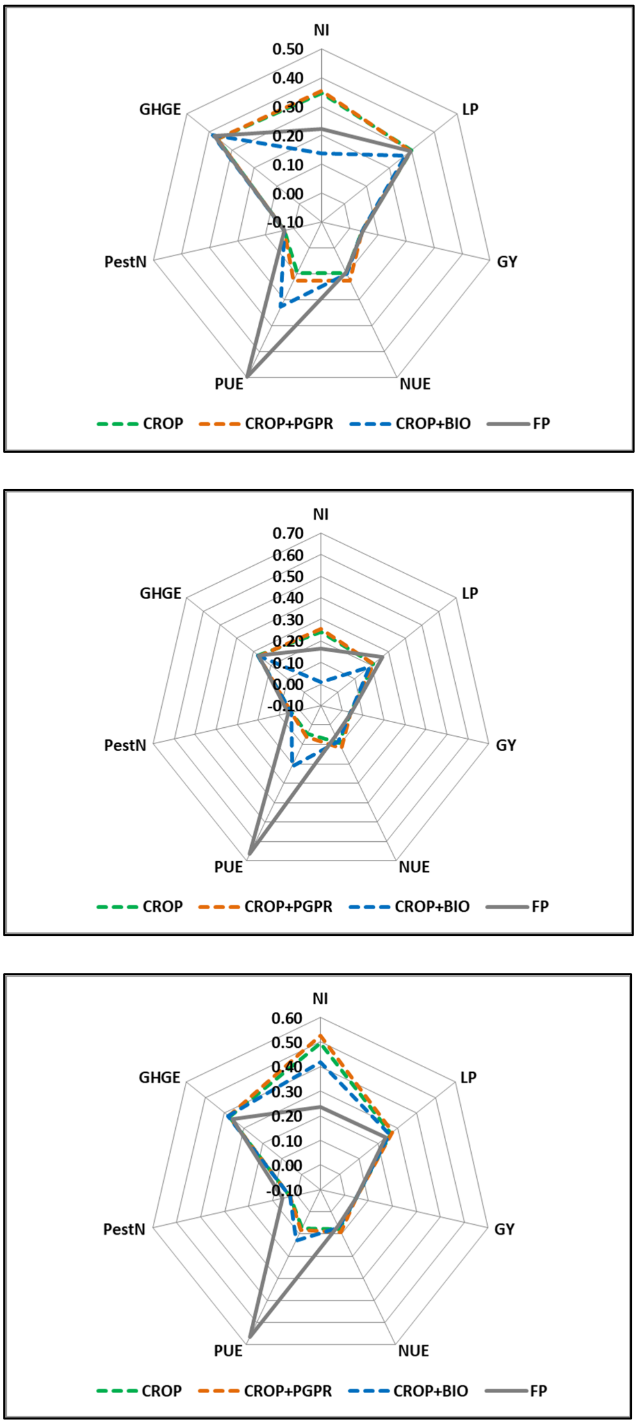

Figure 1. Trade-off comparison among the different performance indicators during: (upper) 2016 WS, (middle) 2016–17 DS and (lower) 2017 WS across four field trial treatments in the Central Plains Thailand. Symbols and units: NI = net income (USD ha^{-1}); LP = labor productivity (kg day^{-1}); GY = grain yield (t ha^{-1}); NUE = nitrogen-use efficiency (grain kg N kg^{-1}); PUE = phosphorus-use efficiency (grain kg P kg^{-1}); PestN = no. of pesticide applications; and GHGE = greenhouse gas emission (kg CO_2 equivalent ha^{-1}).

4. Discussion

The application of CROP combined with the biofertilizer—PGPR II and BIO (LDD #12), provided significant economic and environmental benefits to smallholder farmers whilst maintaining yields compared to current farmers' practices in the Central Plains. Through the application of these best management practices (BMPs), there were significant reductions in production costs and significant increases in the net income and NUE for CROP and CROP + PGPR treatments versus FP. In addition, the mean number of pesticide applications, an indicator for potential biodiversity loss [33], was significantly reduced under all CROP treatments. Meanwhile, there was no significant difference in labor productivity, grain yield and GHGE between treatments. Rice production inputs (seed and N rates) were also reduced under CROP treatments. Similar findings have been observed in previous participatory field trials in lowland irrigated rice crops in Thailand [7] and in other irrigated rice-producing regions in Asia [8,10,45–49] following the application of BMPs. However, this is the first of such studies to include biofertilizer in combination with BMPs. This is also the first study to document the benefits of LLL in Thailand rice cultivation.

The significant increase in net income in CROP and CROP + PGPR was due to the reduction in the total production costs over FP with no yield penalty, with the CROP + PGPR having the biggest reduction. Net income in CROP + PGPR was 370.60 USD ha^{-1}, compared to FP at 207.50 USD ha^{-1} across three seasons, which is an increase of 79%. This far exceeds the CROP objectives of an increased income by 20% [7]. Such an increase in net income can make a substantial difference to the livelihoods of smallholder farmers focusing on cereals, whom generally depend on their crops for nourishment and some income. An increase in income will contribute to purchasing other food that would supplement the necessary nutrients required for a family that rice lacks [2].

The majority of the cost savings obtained in CROP + PGPR was met through reductions in inputs—seeds (60%), inorganic fertilizers (50%) and pesticides (28%)—which contributed to 20% of the total production costs across three seasons. With these reductions in inputs, farmers were able to save USD 34, 64 and 31 ha^{-1} on seeds, inorganic fertilizers and pesticides, respectively, across three seasons. These savings comprised 9, 17, and 8% of farmer's net income across three seasons. Meanwhile, the reduction in the total production cost in CROP + PGPR contributed to a lower cost per kg paddy by an average of 29% over CROP + BIO while no increase over FP was observed because the grain yields were maintained. Furthermore, the reduction in total production cost coupled with no loss in gross income resulted in a higher BCR by an average of 22%. Although LLL costs (Appendix A Table A1) were not factored into the calculation of the total production cost, the average LLL cost only ranged from USD 45.89–94.86 ha^{-1} season^{-1}.

The application of BMPs contributed to the reduction in inputs and consequently the costs in this study. The use of drum seeding for crop establishment reduced seed input in all CROP treatments. Similar findings were observed by Stuart et al. [7]. However, in this study we were able to demonstrate that the innovative development of a mechanical drum seeder also was effective. This is vitally important due to the lack of labor required for manual drum seeding in the region. Aside from reducing the seed input and cost, sowing seeds in rows also provides other benefits through reducing plant density; providing better plant spacing, good plant aeration and light penetration [50,51]. The application of biofertilizers was demonstrated to reduce the inorganic fertilizer input rates without a yield penalty. In addition to reducing the use of inorganic fertilizers and increasing nutrient-use efficiency [52], biofertilizers can also be beneficial by restoring and preserving soil nutrient richness and reducing nutrient losses in the environment [53–58]. The added advantages of applying the PGPR II biofertilizer is that it is already in its biological available form, therefore farmers can purchase and apply it directly to their field by mixing with rice seeds without further incubation needed, and at a low cost. This, however, is not the case for LDD #12 because of the need for other raw materials and the labor intensive process needed, which then equates to more input and labor costs.

The nutrient-use efficiency observed in this study had varying results. CROP + PGPR had significantly higher NUE compared with CROP + BIO and FP, while it consistently had the lowest N fertilizer application rates across three cropping seasons. A high N fertilizer input leads to low NUE due to the rapid N losses from ammonia volatilization, denitrification, surface runoff, and leaching in the soil–flood water system [59,60]. The application of the PGPR II biofertilizer could have also contributed to the high NUE in CROP + PGPR due to the presence of two groups of PGPRs—*Azospirillum brasilense* and *Burkholderia vietnamiensis*. These PGPRs have the ability to fix atmospheric nitrogen and transform it into an ammonium form usable by plants [34]. Other studies using PGPRs also reported increases in NUE [56,57]. A significant reduction in N fertilizer inputs is beneficial to the environment as excessive use of this input could lead to serious environmental issues such as surface water eutrophication and groundwater pollution [61–64]. Meanwhile, the seasonal difference in NUE between 2016 WS and 2017 WS was mainly due to the higher N application rates during the 2017 WS when fertilizer application rates in CROP + PGPR were reduced from 25 to only 16%, while in CROP + BIO, farmers followed the 100% CROP fertilizer recommended rates due to concerns of applying fertilizer at too low a rate.

FP had the highest PUE and KUE among the four treatments while CROP + BIO had the highest PUE and KUE among CROP treatments. The high PUE and KUE values in FP could be due to the relatively higher mean yields during the 2016 WS and 2016–17 DS. Meanwhile, the lower K application rate in Nakhon Sawan could be due to the straw management practice in this area. According to Dobermann and Fairhurst [65], the removal of rice straw from the field removes 14–20 kg K_2O ha^{-1} or 12–17 kg K ha^{-1}. Farmers in Nakhon Sawan left the straw in the field to decompose and then incorporated the remaining straw during land preparation, which could have contributed to the lower K application rate required. This practice was also observed by Moya et al. [66]. Between seasons, farmers applied a significantly lower K application rate during the 2016–17 DS (21% lower) than in the 2017 WS. This could be due to the length of time for straw incorporation before soil cultivation. Between harvest of the 2016 WS crop and the start of the 2016–17 DS, straw was left in the field for more than 30 days, hence a longer time for straw decomposition.

We found no difference in labor productivity between CROP and FP. Meanwhile, the difference in labor productivity between seasons was mainly due to the lower total labor cost in Chainat during the 2017 WS due to no LDD #12 biofertilizer use in that season. A recent study comparing countries in Southeast Asia concluded that farmers in Thailand were amongst the most labor efficient due to a high level of mechanization [67]. Manalili et al. [68] also reported that the majority of the farmers in Suphanburi, in the central plains of Thailand, used a combination of two-wheel and four-wheel tractors for land preparation. All farmers also used combine harvesters for harvesting and threshing. They also had the most advanced model of combine harvester, which includes storage bins for the grains, thus eliminating the need for bagging and hauling. In addition, farmers also used engine-powered sprayers for direct seeding and pesticide application.

Stuart et al. [26] identified a 23% exploitable yield gap in the Nakhon Sawan province, suggesting that yields can be increased in the region through improvements in crop management practices. However, the results in our study showed no grain yield increase for farmers implementing CROP over FP. This could suggest that the mean yield attained by farmers involved in this study may already be close to the attainable yield given the local socio-economic and biophysical conditions (including the rice varieties grown). Similar results were also observed in the irrigated rice areas of the Mekong River Delta in Vietnam [8] and in previous participatory field trials in the central plains of Thailand [7].

The seasonal difference in the number of pesticide applications was mainly due to an outbreak of Asian rice gall midge (*Orseolia oryzae*) that affected a large rice growing area in the Central Plains during the 2016–17 DS. This was first noticed at around 50 DAS after an unusual rainfall event. The farmers also commented that golden apple snails (*Pomacea* spp.) were causing significant damage during the seedling stage in the region for the first time in over five years, possibly as a result of fewer avian predators (e.g., *Anastomus oscitans*) observed following two years of drier than normal conditions and reduced planting area, which were also consequences of the dry conditions. Because molluscicides were no longer locally available, many farmers resorted to using broad-spectrum insecticides to control snails during the seedling stage. By following the recommendations provided by CROP on weed and pest management, the CROP farmers in this study were able to successfully manage pests and diseases with reduced pesticide use. These findings support previous studies of CROP in Thailand [7]. In addition, LLL could have contributed to a further reduction in pesticide use as farmers reported reduced weeds and herbicide use as a result of more uniform flooding following LLL, with only one pre-emergence herbicide application needed instead of two (one pre-emergence and one post-emergence). Studies have shown the role of LLL in controlling weeds. Rickman [69] reported a reduction in the labor requirement for weeding due to precision land leveling while Jat et al. [70] also reported a reduction in the weed population in wheat after 30 days of sowing compared to traditionally leveled fields.

The difference in GHGE between villages is mainly due to differences in rice straw management. While no straw burning was observed in our study, farmers from Nakhon Sawan would leave the straw in the field to decompose and incorporate these during land preparation. On the other hand, farmers from Chainat, who had 41% less GHGE, would remove the straw from the field after harvest by using balers and sell this for THB 30 per bale. Meanwhile, the seasonal differences in GHGE, with 27% lower GHGE during the 2016–17 DS, are mainly due to the different lengths of time provided for straw incorporation before soil cultivation. Between harvest of the 2016 WS crop and the start of the 2016–17 DS, straw was left in the field for more than 30 days, while the interval between the harvest of the 2016–17 DS crop and the start of the 2017 WS was less than 30 days.

While no differences were observed in water pumping fuel costs between treatments, water pumping costs in FP were higher by 18% across three seasons. The costs were higher (by 21%) during the 2016–17 DS. Individual costs during the 2016–17 DS showed that farmers spent 15.27–82.63 and 23.63–126.04 USD ha^{-1} under CROP and FP, respectively. When discussing the benefits of LLL during a focus group discussion, the farmers reported that the application of LLL led to lower water pumping fuel cost. Other benefits of LLL reported by the farmers included reduced time for water pumping (reduced from 24 h to 5 h per irrigation); reduced weeds and herbicide use from uniform flooding; and uniform drainage at harvest leading to uniform crop maturity. Such benefits have also been observed in other studies on LLL [30,71].

5. Conclusions

The findings from this study provide on-farm field-based evidence of multiple economic and environmental benefits from applying a combination of technologies for rice production in the Central Plains of Thailand that include CROP (i.e., a package of BMPs), LLL, mechanical drum seeder, and biofertilizers. There were significant improvements in three out of the seven SRP PIs assessed in this study while no trade-offs were observed for the other three PIs. Net income, NUE and pesticide use were all improved, while no differences were observed for labor productivity, grain yield and GHGE. CROP + PGPR (i.e., PGPR II biofertilizer) had the largest improvement among the CROP treatments over FP, and produced a significantly higher net income (79%) and nitrogen-use efficiency (57%), while pesticide use was reduced by 28%. The added advantages of this treatment are that the PGPR II biofertilizer is available in its biologically active form, which farmers can purchase and apply directly to their fields at minimal cost. Thus, CROP together with the PGPR II biofertilizer, mechanical drum seeder, and laser land levelling, is a readily available technology package that could be promoted to alleviate the burden of rising input costs for smallholder farmers and improve the sustainability of Thailand's rice production.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

1M5R	1 Must Do, 5 Reductions
3CT	3 Controls Technology
CO2	Carbon dioxide
CORIGAP	Closing Rice Yield Gaps in Asia Project with reduced environmental footprint
CROP	Cost Reduction Operating Principles
CROP + PGPR	CROP plus Department of Agriculture's plant growth promoting Rhizobacteria II biofertilizer
CROP + BIO	CROP plus Land Development Department's #12 biofertilizer
DA	Department of Agriculture
DS	Dry season
FP	Farmer's Practice
GHGE	Greenhouse gas emissions
ha	Hectare
kg	Kilogram
K	Potassium
KUE	Potassium-use efficiency
LDD	Land Development Department
LLL	Laser land leveling
USD	US Dollars
MC	Moisture content
N	Nitrogen
NUE	Nitrogen-use efficiency
PI	Performance indicators
P	Phosphorous
PGPR	Plant growth promoting Rhizobacteria
PUE	Phosphorus-use efficiency
RD	Rice Department
SRP	Sustainable Rice Platform
t	Ton
THB	Thai Baht
WS	Wet season

Appendix A

Table A1. Breakdown of laser land leveling cost per farmer's field in Nakhon Sawan and Chainat provinces, Central Thailand.

	Nakhon Sawan				Chainat			
	F1	**F2**	**F3**	**F4**	**F1**	**F2**	**F3**	**F4**
Total area (ha)	1.60	0.80	1.60	1.60	1.44	1.76	1.28	1.92
Total amount of soil cut and moved (m^3 ha^{-1})	162.56	425.39	102.00	162.09	191.98	158.49	249.60	216.83
Total area preparation cost (USD ha^{-1})	218.15	436.30	218.15	218.15	218.15	218.15	181.79	181.79
Total topographic survey cost (USD ha^{-1})	4.84	15.16	4.71	4.09	6.75	3.26	12.57	4.54
Total fuel cost (USD ha^{-1})	17.72	60.88	9.24	34.70	41.53	23.59	17.18	42.74
Fuel (li)	48.75	82.01	12.50	46.88	59.03	33.52	23.44	58.57
Cost (USD li^{-1})	0.36	0.74	0.74	0.74	0.70	0.70	0.73	0.73
Wage for tractor driver (USD ha^{-1}) [a]	13.63	27.27	18.18	27.27	36.36	19.83	27.27	18.18
No. of hours	0.24	0.48	0.19	0.33	0.27	0.20	0.36	0.29
No. of days	0.03	0.05	0.04	0.05	0.06	0.05	0.07	0.05
Machine rent (USD ha^{-1})	204.52	409.03	272.69	409.03	454.48	247.90	340.86	340.86
Total laser leveling cost (USD ha^{-1})	458.86	948.64	522.96	693.24	757.27	512.72	579.67	588.12
Laser land leveling cost (USD ha^{-1} $season^{-1}$) [b]	45.89	94.86	52.30	69.32	75.73	51.27	57.97	58.81

[a] Nakhon Sawan: 500 THB day^{-1}. Chainat: 600 THB day^{-1}. 1 USD = 34.38 THB. [b] Based on estimates that a one-time application of laser land leveling lasts for five years [30] and with the central plains of Thailand having 2 cropping seasons per year [7].

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