SEHS science, engineering and health studies

Research Article

Science, Engineering and Health Studies
https://li01.tci-thaijo.org/index.php/sehs
ISSN (Online): 2630-0087

Impacts of precision fertilization combined with alternate wetting–drying water management on yield, production costs, and the environment in irrigated rice-growing systems

Auraiwan Isuwan[1], Wilaiwan Sirirotjanaput[1], Jeerasak Chobtang[2], and Thanawadee Promchan[1]*

[1] Faculty of Animal Sciences and Agricultural Technology, Silpakorn University, Phetchaburi 76120, Thailand
[2] Bureau of Animal Nutrition Development, Department of Livestock Development, Pathum Thani 12000, Thailand

***Corresponding author**:
Auraiwan Isuwan
isuwan_a@su.ac.th

***Received**: 9 December 2024*
***Revised**: 17 April 2025*
***Accepted**: 21 April 2025*
***Published**: 12 December 2025*

***Citation**:*
Isuwan, A., Sirirotjanaput, W., Chobtang, J., & Promchan, T. (2025). Impacts of precision fertilization combined with alternate wetting–drying water management on yield, production costs, and the environment in irrigated rice-growing systems. Science, Engineering and Health Studies, 19, 25030004.

ABSTRACT

A comparative study was conducted to investigate the effects of implementing precision fertilization (PF) practices combined with alternate wetting and drying (AWD) water management on yields, financial costs, and environmental impacts in irrigated rice growing systems. A paired comparison t-test design with 10 replications was used. Two rice-growing models were compared: Model 1 combined PF and AWD and Model 2 combined farmer-experience-based fertilization with a continuous flooding system. The PF was performed based on the recommendations of the All-rice1 smartphone app. The rice fields under Model 1 resulted in higher paddy yields (p<0.05), by 32.71% on average, compared with those under Model 2, leading to a higher net profit of 12,935 THB per ha (p<0.05). In addition, in the rice fields under Model 1, a range of 11 selected life cycle environmental impact indicators, comprising climate change (71.60%), acidification potential (52.78%), freshwater eutrophication potential (54.84%), marine eutrophication potential (62.50%), human health toxicity—cancer effects (65.56%), human health toxicity—non cancer effects (55.38%), particulate matter (56.20%), photochemical ozone formation potential (74.07%), terrestrial eutrophication potential (52.92%), ecotoxicity for aquatic freshwater (73.96%) and ozone depletion potential (77.22%) were significantly lower than those using Model 2 (p<0.05). In conclusion, the adoption of the PF combined with AWD not only increased rice production levels but also increased economic benefits and reduced the environmental impact indicators of irrigated rice growing systems.

Keywords: wetting/drying irrigation; water management; rice production; environmental impact; production cost

1. INTRODUCTION

Globally, rice growing systems are integral to food production systems, but unfortunately, they contribute to environmental degradation. Smith et al. (2007) reported that compared to other food production systems, rice growing systems emit the major greenhouse gasses (GHGs), i.e., methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O), which have serious negative effects on climate change. However, the demand for rice is increasing proportionally with the increasing world population. Thailand not only ranks as the sixth largest rice producer worldwide but is also the biggest rice exporter (Food and Agriculture Organization of the United Nations, 2017). However, the economic competitiveness of Thai rice has been decreasing over time because rice production costs have increased. Over the past 10 years, rice production costs have increased by 22.39% (Sanpakdee & Onwimon, 2021), especially the cost associated with fertilizers, which is generally one of the most substantial (Isuwan et al., 2018). In traditional rice-growing systems farmers use fertilizers based only on their experience, (i.e., amount and nutrient balance) and water management by using a continuous flooding system. It has been well recognized that over-fertilization (especially nitrogen fertilizers), results in a nutrient imbalance and the continuous flooding system (waterlogging) creates environmental issues associated with GHG emissions, e.g., N_2O emitted from use of nitrogen fertilizers and CH_4 stemming from microbial fermentation under anaerobic condition of flooding systems (Cowan et al., 2021). There have been reports indicating that precision fertilization (PF) practices that account for existing soil nutrients and the nutritional requirements of plants enhance rice productivity (Isuwan, 2013, 2014a, 2014b, 2015). Although numerous PF practices are being implemented across Thailand, one of the most recently developed and well-adopted tools to manage fertilization is a smartphone app called All-rice1. The app has been developed by a research team of Silpakorn University, Phetchaburi, Thailand (Isuwan, 2020), and can be downloaded from either the App Store or Play Store, or it can be directly used through the website www.soil.asat.su.ac.th. Practically, All-rice1 computes and recommends the total amount of chemical fertilizers and application events based on the nutrient requirements of rice and the available plant nutrients existing in soils. In a recent study by Isuwan (2020), fertilizers were applied to a rice field based on All-rice1 recommendations, and it was found that rice productivity and associated financial benefits increased compared with those obtained using traditional practices. Moreover, previous studies demonstrated that All-rice1-based fertilization could reduce the cost of rice production by 1,282 THB per ha (35 THB = 1 USD), increase paddy production by 433 kg per ha, and increase the net profit by 4,134 THB per ha. In addition, compared to traditional farmer practices, All-rice1 has the potential to decrease environmental impacts, ranging from 12.07% to 56.00%, depending on impact indicators (Isuwan et al., 2018).

In addition to fertilizer management, water management practices are also important in rice growing systems. According to a report by the Center for Applied Economics Research (2010), waterlogged (flooded) rice growing systems are responsible for more than 50% of the total CH_4 emissions in the agriculture and livestock sector of Thailand. Alternate wetting and drying (AWD) water management in rice growing systems in which the water in fields is allowed to dry over a certain time during the growing season has been scientifically proven to be effective in saving water. Additionally, other beneficial effects of AWD on rice growth have been demonstrated. For example, Carrijo et al. (2017) showed that AWD not only maintains rice productivity but also saves water and reduces GHG emissions, especially CH_4.

However, rice-growing systems generate not only GHG but also other environmental emissions, e.g., ammonia (NH_3), nitrogen oxides (NO_X) and heavy metals (Amirahmadi et al., 2022). Thus, to confirm that All-rice1 and AWD can be combined and result in financial benefits as well as an improvement in environmental performance, a life cycle assessment (LCA) should be carried out to identify all environmental emissions along the supply chain within rice production systems. LCA is an approach to quantitatively identify multiple environmental impact indicators. Therefore, the objective of the present study was to compare yields, financial benefits, and multiple life cycle environmental impact indicators between a rice growing system managed using the All-rice1 app for fertilization in combination with AWD and a system managed based on traditional farmer practices.

2. MATERIALS AND METHODS

2.1 Site and experimental procedures

Ten rice-growing farms located in Rong Khe subdistrict, Ban Lat district, Phetchaburi province, Thailand, were selected for this study (Figure 1). This area is the major rice farming area in Phetchaburi, where irrigation systems are available throughout the year.

The soil type is the Phetchaburi soil series (fine-silty, mixed, active, isohyperthermic Aquic Haplustalfs). Rice seeds (var. RD85) were sown at a rate of 156.25 kg/ha. To statistically compare rice production and environmental impacts between rice fields, two farming models were adopted. It should be noted that for each farm, the two models were performed in the two adjacent individual rice plots using the same seeding rates (i.e., planting density) and other agricultural practices (e.g., soil preparation, weeding management, and harvesting practices) except for water and fertilizer management practices. The germination rate of rice seeds was tested before spreading in order to ensure similarities of plant density between rice plots. Moreover, the two plots were separate using a 1 m width ridge with 0.5 m height above the ground surface to protect contaminations of irrigation water and fertilizer nutrients. Details associated with fertilization and water management practices (both AWD and waterlogging) can be found in Isuwan et al. (2022).

In Model 1, fertilizers were applied based on the recommendations of the All-rice1 app (downloadable from App Store, Play Store, or www.soil.asat.su.ac.th), and AWD water management was jointly adopted (referred to "All-rice1 + AWD"). The details of fertilizer use are shown in Table 1. For AWD water management, water management was carried out as described by Isuwan et al. (2022). Initially, the water level was maintained at half the rice stem height until the first fertilizer application (22-day-old rice). Subsequently, the water was allowed to evaporate naturally to a depth of 10 cm below the soil surface. Then, water was refilled up to 10 cm above the ground and allowed to evaporate again down to a depth of 10 cm below the soil surface. This procedure was performed cyclically until panicle initiation upon the second fertilizer application (55-day-old rice). The water was then maintained at a level of 5 cm above the ground until 10 days before harvest (120-day-old rice at harvest). Water levels were measured using holed PVC tubes (2.5 cm in diameter and 25 cm in length), which were inserted 15 cm below the soil surface.

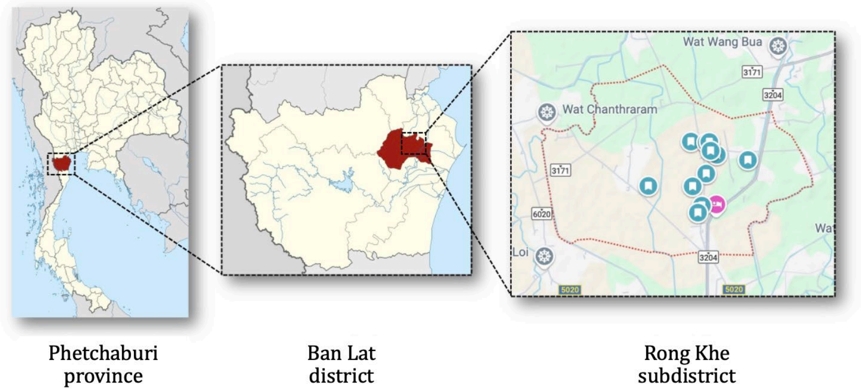

Figure 1. Map of study site in Rong Khe subdistrict, Ban Lat district, Phetchaburi province

Table 1. Details of fertilizer use in the All-rice1 + AWD model (Model 1)

Farmers	1st fertilizer spreading period (kg/ha)			2nd fertilizer spreading period (kg/ha)	N (kg/ha)	P_2O_5 (kg/ha)	K_2O (kg/ha)
	18-46-0	46-0-0	0-0-60	46-0-0			
1	31.25	55.63	41.88	55.63	31.21	14.38	25.59
2	31.25	55.63	62.50	55.63	31.21	14.38	25.59
3	31.25	55.63	62.50	55.63	31.21	14.38	25.59
4	31.25	55.63	62.50	55.63	31.21	14.38	25.59
5	31.25	55.63	62.50	55.63	31.21	14.38	25.59
6	62.50	50.31	62.50	50.31	34.39	28.75	34.39
7	62.50	50.31	20.63	50.31	34.39	28.75	34.39
8	31.25	55.63	20.63	55.63	31.21	14.38	25.59
9	31.25	55.63	20.63	55.63	31.21	14.38	25.59
10	31.25	55.63	20.63	55.63	31.21	14.38	25.59

In Model 2, fertilizers were applied according to traditional farmers' methods, in conjunction with waterlogging (F). Water was maintained continuously at a level of 5 cm above the ground for up to 10 days before harvesting. The first and second fertilizer application events occurred on the 20th and 55th day after transplantation, respectively (Table 2).

Data associated with farm activities, input use, and outputs were recorded. The farmers harvested only grains and left straws in the fields. Therefore, the only product exported from this rice growing system consisted of paddies.

Table 2. Details of fertilizer use in the F model (Model 2)

Farmers	1st fertilizer spreading period (kg/ha)		2nd fertilizer spreading period (kg/ha)		N (kg/ha)	P_2O_5 (kg/ha)	K_2O (kg/ha)
1	16-8-8	156.25	22-5-18	156.25	59.38	20.31	40.63
2	16-8-8	156.25	15-5-20	156.25	48.44	20.31	43.75
3	46-0-0	312.50	15-7-18	312.50	190.63	21.88	56.25
4	16-8-8	312.50	-	-	50.00	25.00	25.00
5	30-0-0	125.00	15-5-20	125.00	56.25	6.25	25.00
6	30-0-0	312.50	-	-	93.75	0.00	0.00
7	16-8-8	312.50	30-0-0	312.50	143.75	25.00	25.00
8	16-8-8	218.75	15-5-20	125.00	53.75	23.75	42.50
9	20-8-8	218.75	15-5-20	125.00	62.50	23.75	42.50
10	46-0-0	312.50	15-7-18	312.50	190.63	21.88	56.25

2.2 Data collection and management

2.2.1 Agronomic evaluation

Plant height was recorded at the initial panicle stage (60-day-old rice) by measuring the height of stems from the ground level to the top leaf apex or flag leaf apex. Generally, 10 plants per m^2 (620 plants in total) were measured. In addition, the number of plants per m^2 (60-day-old rice) was recorded. The same random points were used in this study as those employed in the study of rice stem height by Chumjom et al. (2017).

Yield components were determined on the 120th day after transplantation. They included the number of panicles per m^2, total number of grains per panicle, percentage of filled grains, percentage of unfilled grains, and weight of 1,000 filled grains. Paddy yield was recorded over an area of 2 × 5 m with 250 random-spots per ha and standardized to a moisture level of 14% (Ruensuk et al., 2021).

2.2.2 Economic evaluation

Two types of financial data were collected, i.e., primary and secondary data. The former were collected from the records of expenses and income, and by conducting in-depth interviews with the participating farmers. The latter were obtained from related academic papers published by various agencies, such as the Department of Agricultural Extension and the Office of Agricultural Economics.

Production costs were classified into two categories: fixed and variable costs. Fixed costs consisted of monetary expenses such as land tax and rent, and nonmonetary expenses such as the depreciation of agricultural equipment. Variable costs were further divided into monetary and nonmonetary components. The monetary variable costs included agricultural materials for rice cultivation, including seeds, fertilizers, insecticides, and herbicides; labor costs, including wages for land preparation, sowing, fertilizing, applying insecticides and herbicides, and harvesting; and other costs, such as fuel and maintenance of agricultural equipment.

The income and profit from rice cultivation were calculated using the following equations:

Total income = Total yield × Selling price

Net income = Total income − Total variable cost

Net profit = Total income − Total fixed cost − Total variable cost

The cost associated with irrigation was negligible because water was supplied free of charge through local channels, where farmers could simply open the water gates to allow water into the rice fields. Therefore, in the present study, this cost was assumed to be zero for both models.

2.2.3 Environmental assessment

The attributional LCA approach (International Organization for Standardization, 2006a, 2006b) was used to assess the environmental impacts of the rice growing systems examined in this study.

2.2.3.1 Functional unit and system boundary

One kilogram of standardized paddies was considered as the functional unit. Standardized paddies are defined as cleaned paddies with adjusted moisture at a level of 14%. The assessment of the life cycle of a rice growing system starts with the collection of data associated with the used inputs and generated pollution, beginning from the acquisition of raw materials up to the obtained rice yields at the farm gate (known as the cradle-to-farm gate perspective), as shown in (Figure 2). Note that environmental emissions associated with the manufacturing of agricultural machinery and equipment was not accounted for in the present study.

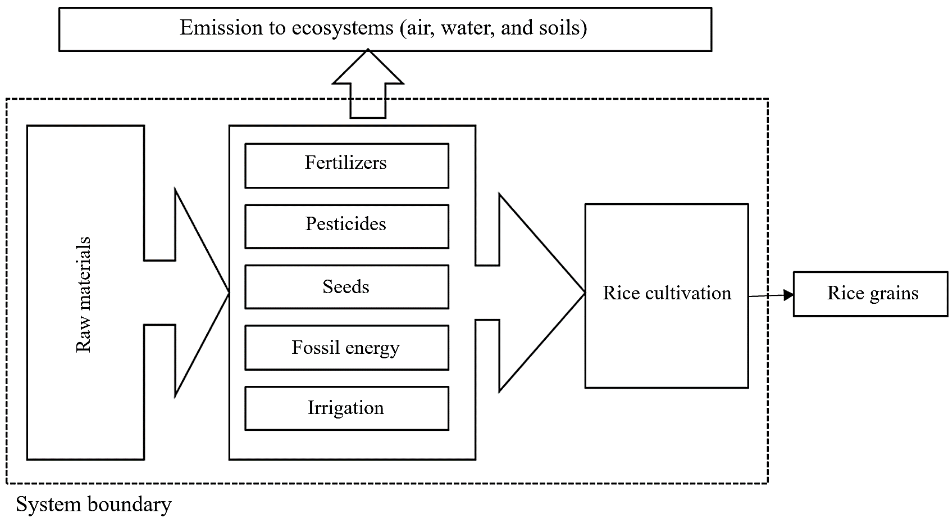

Figure 2. Elementary flow diagram and system boundary of rice growing systems examined in the present study

2.2.3.2 Life cycle inventory analysis

The data associated with the use of inputs and pollution generated to produce raw materials (e.g., chemical fertilizers, fuels, and herbicides) were obtained from the Ecoinvent database version 3.4 (www.ecoinvent.org).

The data associated with the use of inputs in rice fields were recorded, and pollution emissions due to such use were computed using relevant mathematic inventory models as suggested by De Klein et al. (2006), and other related research publications (Thanawong et al., 2014; Nemecek et al., 2016). The number of dried (aeration) and flooded days were taken into account when CH_4 emission was modeled as described by De Klein et al. (2006). The details concerning the life cycle inventory analysis and the methods used for calculating the pollution emissions in this study have been previously described by Isuwan et al. (2018) and Chobtang et al. (2016). Other farming practices, input use, and farm outputs have been detailed in Isuwan et al. (2022).

2.2.3.3 Life cycle impact assessment

Of the 15 environmental impact indicators recommended by the De Camillis et al. (2013), 11 were selected and modeled in the present study (Table 3). Therefore, this study is the most comprehensive in terms of the analysis of environmental indicators in rice growing systems. The SimaPro v3.8 software (Pré Consultants, 2018) was used to model and characterize the selected indicators.

Table 3. Environmental indicators used in the present study

Impact category	Units*	Abbreviation
Climate change	kg CO_2 equivalent	CC
Acidification potential	molc H^+ equivalent	AP
Freshwater eutrophication potential	kg P equivalent	FEP
Marine eutrophication potential	kg N equivalent	MEP
Human health toxicity – noncancer effects	CTU_h	Noncancer
Human health toxicity – cancer effects	CTU_h	Cancer
Particulate matter (PM)	kg $PM_{2.5}$ equivalent	PM
Photochemical ozone formation potential	kg NMVOC equivalent	POFP
Terrestrial eutrophication potential	molc N equivalent	TEP
Ecotoxicity for aquatic freshwater	CTU_e	Ecotox
Ozone depletion potential	kg CFC-11 equivalent	ODP

* CO_2 = carbon dioxide; molc = mole of charge; H^+ = hydrogen ion; N = nitrogen; P = phosphorus, CTU_h = comparative toxic unit for humans, $PM_{2.5}$ = particulate matter <2.5 μ diameter, NMVOC = nonmethane volatile organic compounds, CTU_e = comparative toxic unit for ecosystems, and CFC-11 = trichlorofluoromethane

2.3 Statistical analysis

The data were statistically analyzed, and average differences between the All-rice1 + AWD and F models were compared using a paired comparison t-test in R.

3. RESULTS AND DISCUSSION

3.1 Temperature, precipitation and activity

The experiment was commenced around the 4th week of January 2024. Over the course of the experiment, there were two water refilling practices; the first was around the 1st week March 2024 and the second was around the 3rd week of March 2024 (Figure 3). Finally, rice was harvested during the last week of May 2024.

3.2 Nutrient use

The total amount of nitrogen (*N*) and phosphorus (*P*) fertilizers used in the All-rice1 + AWD model was lower (p<0.05) than that used in the F model (Table 4). Traditionally, farmers apply specific amounts of fertilizers based on their experience to ensure that rice plants receive sufficient nutrients, and it is common that these amounts exceed plant requirements. The overuse of fertilizers not only increases production costs but also leads to increased environmental emissions per kg of paddy product.

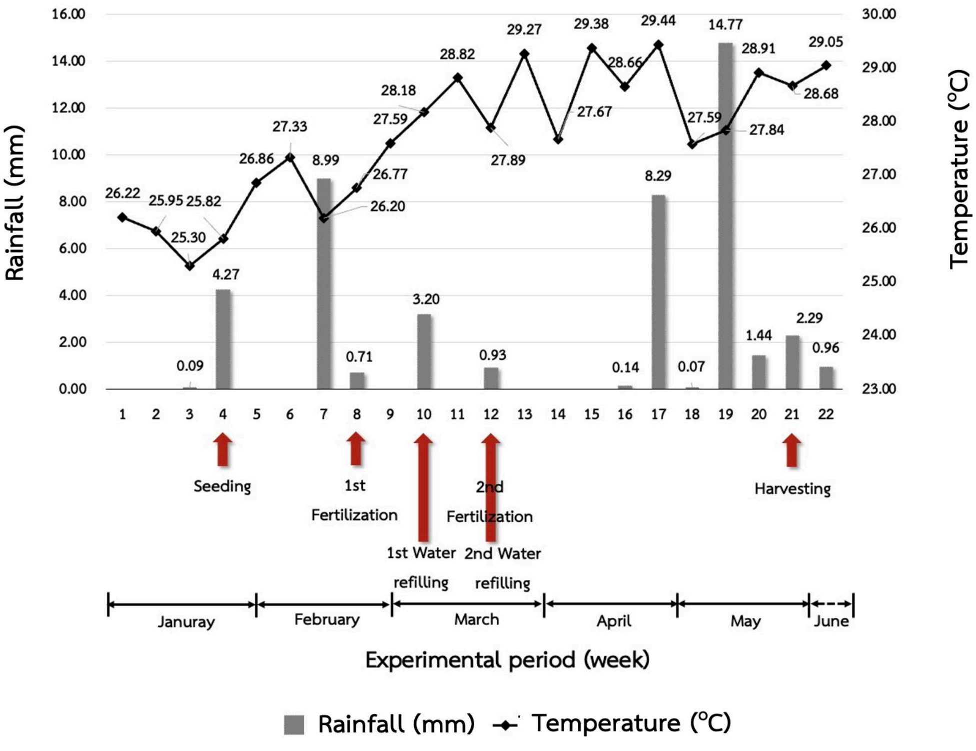

Figure 3. Temperature, precipitation and activities during the experimental period

Table 4. Total nutrient use by rice plants that received the fertilizer doses recommended by the All-rice1 app in conjunction with alternate wetting and drying water management (All-rice1 + AWD) versus traditional management practice (f)

Parameter	All-rice1 + AWD		F		p-value	All-rice1 + AWD/F
	Mean	SD	Mean	SD		(%)
Nitrogen, N (kg/ha)	31.85	1.27	33.03	4.94	<0.01	−3.57
Phosphorus, P (kg/ha)	17.25	5.75	18.19	1.79	<0.01	−5.17
Potassium, K (kg/ha)	27.35	3.52	24.44	8.62	ns	+11.91

Note: ns = nonsignificant

3.3 Agronomic trait indicators

In general, the two models applied to var. RD85 rice plants grown in the Phetchaburi soil series did not result in significant differences between agronomic traits, except for grain number per panicle and subsequently grain yields (Table 5). Interestingly, paddy yield in the All-rice1 + AWD model was significantly higher (p<0.05) than that in the F model, at an average of 32.71%. This was partly due to an increase in grain number per panicle in the rice under the All-rice1 + AWD model.

The management of fertilizer applications and water under the Model 1 was adequate in terms of the nutritional needs of rice plants; therefore, plants produced more grain numbers per panicle and hence higher grain yields (Sibayan et al., 2018; Tirol-Padre et al., 2018). In addition, Isuwan and Keawaram (2021) reported that adequate and balanced nutrient supply in accordance with nutrient requirements of rice (amounts and application events) not only results in increased grain yields but also improved nutrient use efficiency of rice.

Table 5. Growth, yield components, and grain yield of rice plants that received the fertilizer doses recommended by the All-rice1 app in conjunction with alternate wetting and drying water management (All-rice1 + AWD) versus traditional management practice (F)

Parameter	All-rice1 + AWD		F		p-value	All-rice1+ AWD/F
	Mean	SD	Mean	SD		(%)
Plant height (cm)	56.01	6.57	55.21	5.98	ns	+1.45
Plants no. per square meter	307.17	23.45	285.50	40.56	ns	+7.59
Panicle no. per square meter	282.30	34.93	271.20	60.26	ns	+4.09
Grain no. per panicle	92.91	13.08	78.71	11.66	<0.01	+18.04
1,000 grain weight (g)	30.48	1.05	29.21	1.83	ns	+4.35
Filled grain percentage (%)	67.38	6.54	64.44	7.97	ns	+4.56
Grain yield (kg/ha)	5,571.27	951.72	4,198.01	514.99	<0.05	+32.71

Note: ns = nonsignificant

3.4 Economic performance indicators

It is particularly interesting that while the fixed rice production cost components did not differ between the two models (p>0.05), the variable cost component in the All-rice1 + AWD model was lower than that in the F model (p<0.05) (Table 6). This was because the plants under the All-rice1 + AWD model used less N and P fertilizers than those under the F model (see Table 4). As the former model produced a higher paddy yield than the latter (Table 5), the total revenue derived from it was greater, which led to a higher net income and net profit (p<0.05) (Table 6).

3.5 Environmental impact indicators

It is of great interest that the 11 environmental impact indicators examined were 52.29% to 77.22% lower (depending on indicators) in the rice fields under the All-rice1 + AWD model than in those under the F model (p<0.05) (Table 7).

The three main substances contributing to the climate change (CC) indicator were CH_4, CO_2, and N_2O, with the former being the most significant, followed by CO_2 and N_2O. Approximately 70% of the total CH_4 emissions were mainly attributed to the activities of microorganisms under aerobic conditions during the waterlogging period in the growing season. The CO_2 emissions were largely due to the use of fossil energy (petrol and diesel), while the N_2O emissions were derived from the use of N fertilizers. Comparatively, the relatively significant decrease in the CC indicator was mostly due to a reduction in CH_4 emissions. According to Thanawong et al. (2014), rice farming under waterlogging conditions for the entire growing season has an average CH_4 emission factor of 0.6, whereas when AWD water management is adopted, the average CH_4 emission factor is 0.52. Similarly, Sriphirom et al. (2019) reported that although AWD during the growing season reduces CH_4 emissions, it causes an increase in N_2O emissions. However, AWD is still associated with a reduction in net GHG emissions by approximately 14% compared with the continuous waterlogging system. The results of the present study confirmed that a combination of PF technology and AWD water management could help reduce the values of the CC indicator.

Table 6. Cost components and economic returns for rice fields that received the fertilizer doses recommended by the All-rice1 app in conjunction with alternate wetting and drying water management (All-rice1 + AWD) versus traditional management practices (F)

(THB/ha)	All-rice1 + AWD		F		p-value	All-rice1 + AWD/F
	Mean	SD	Mean	SD		(%)
Total cost	26,416	6,708	31,277	9,931	<0.01	−15.54
Fixed cost	8,471	6,667	8,471	6,667	ns	0.00
Variable cost	17,945	2,188	22,806	4,209	<0.01	−21.31
Total revenue	48,216	7,639	36,396	4,588	<0.01	+32.48
Net income	30,271	8,004	13,590	8,347	<0.01	+122.74
Net profit	21,800	11,794	5,119	13,741	<0.05	+145.90

Note: ns = nonsignificant
change rate (%) = [(cost or return of All-rice1 − cost or return of F) / cost or return of F] × 100

Table 7. Environmental impact indicators in rice fields that received the fertilizer doses recommended by the All-rice1 app in conjunction with alternate wetting and drying water management (All-rice1 + AWD) versus traditional management practices (F)

	All-rice1 + AWD		F		p-value	All-rice1 + AWD/F
	Mean	SD	Mean	SD		(%)
CC	1.21E + 00	0.21E + 00	1.69E + 00	0.34E + 00	0.0017	−71.60
- CH_4 (%)	66.87	1.00	64.55	6.73		
- CO_2 (%)	23.19	1.19	24.06	3.03		
- N_2O (%)	9.75	0.44	11.17	3.88		
- Other (%)	0.21	0.02	0.22	0.03		
AP	1.90E − 02	0.30E − 02	3.60E − 02	0.22E − 02	0.0376	−52.78
- NH_3 (%)	87.85	0.84	89.18	3.66		
- SO_x (%)	6.79	0.47	6.28	2.07		
- NO_x (%)	5.36	0.41	4.54	1.60		
FEP	1.70E − 04	0.20E − 04	3.10E − 04	0.90E − 04	0.0011	−54.84
- P (%)	100		100			
MEP	2.50E − 03	0.40E − 03	4.00E − 03	1.90E − 03	0.0283	−62.50
- NO_3 (%)	58.43	1.01	57.68	1.17		
- NO_x (%)	21.11	1.39	19.08	4.61		
- NH_3 (%)	20.08	0.49	22.85	4.24		
- Other (%)	0.38	0.03	0.39	0.02		
Noncancer	5.71E − 07	1.13E − 07	10.31E − 07	2.80E − 07	0.0013	−55.38
- Zn (%)	69.56	2.13	55.28	13.08		
- Hg (%)	18.71	1.68	32.37	12.93		
- Other (%)	11.72	0.50	12.35	0.73		
Cancer	2.57E − 08	0.52E − 08	3.92E − 08	0.90E − 08	0.0021	−65.56
- Cr (%)	88.54	0.39	84.83	2.88		
- Hg (%)	3.50	0.30	7.47	3.25		
- Other (%)	7.96	0.09	7.70	0.57		
PM	6.80E − 04	1.20E − 04	12.10E − 04	6.40E − 04	0.0258	−56.20
- NH_3 (%)	53.56	1.60	56.31	8.14		
- $PM_{2.5}$ (%)	35.86	1.17	34.00	5.78		
- SO_2 (%)	9.00	0.49	8.36	2.05		
- Other (%)	1.57	0.09	1.33	0.36		

Table 7. Environmental impact indicators in rice fields that received the fertilizer doses recommended by the All-rice1 app in conjunction with alternate wetting and drying water management (All-rice1 + AWD) versus traditional management practices (F) (continued)

	All-rice1 + AWD		F		p-value	All-rice1 + AWD/F
	Mean	**SD**	**Mean**	**SD**		**(%)**
POFP	2.00 E – 03	0.40 E – 03	2.70 E – 03	0.60E – 03	0.0051	−74.07
- CH_4 (%)	12.67	0.97	12.85	1.63		
- NO_x (%)	68.25	0.92	67.80	1.23		
- NMVOC (%)	12.82	0.23	12.66	0.26		
- Other (%)	6.26	0.21	6.69	0.41		
TEP	8.00E – 02	1.30E – 02	15.30E – 02	10.00E – 02	0.0395	−52.29
- NH_3 (%)	92.71	0.57	93.81	2.26		
- NO_x (%)	7.29	0.57	6.19	2.26		
Ecotox	4.09E + 00	0.95E + 00	5.53E + 00	1.27E + 00	0.0051	−73.96
- Herbicides (%)	38.66	5.36	33.58	6.82		
- Cu (%)	8.56	0.87	9.36	1.08		
- Zn (%)	25.32	2.56	28.96	4.21		
- Other (%)	27.46	1.99	28.10	2.04		
ODP	7.29E – 08	1.96E – 08	9.44E – 08	2.47E – 08	0.0114	−77.22
- Halon 1301 (%)	39.67	7.15	44.24	8.65		
- CFC 10 (%)	52.65	8.46	46.98	10.35		
- Other (%)	7.58	1.31	8.79	1.72		

The three main substances contributing to the acidification potential (AP) indicator were NH_3, SO_2, and nitrogen oxides (NO_x). NH_3 emissions originated mainly from the use of N fertilizers (approximately 80% of the AP indicator) and fossil fuels (approximately 3% of the AP indicator). Similarly, a previous study of rice growing systems in China reported that the main contributor to the AP indicator originated from the use of nitrogen fertilizers (Wang et al., 2010).

The only contributor to the freshwater eutrophication potential (FEP) indicator was the contamination of freshwater ecosystems with P compounds (De Camillis et al., 2013). Therefore, the use of P fertilizers in the rice growing system was the single main contributor (a hotspot). Wang et al. (2010) reported that the contamination of freshwater ecosystems with P compounds is closely related to algal blooms, which negatively affect freshwater animals. The lower use of these fertilizers under the All-rice1 + AWD model and the higher paddy yield obtained led to relatively lower FEP values compared with the F model.

The three main contributors to the marine eutrophication potential (MEP) indicator were NO_3, NO_x, and NH_3. These substances largely originated from the use of N fertilizers (approximately 60% of the MEP indicator), followed by the use of fossil energy (approximately 10% of the MEP indicator). Kitsiou and Karydis (2011) reported that N contamination in marine ecosystems leads to algal blooms, which negatively affect ecosystem balances.

For the human health toxicity-noncancer effect indicator, Zn and Pb were the two main contributing substances. These heavy metals mainly originated from the use of fossil fuels (approximately 60% of the indicator) and chemical fertilizers (approximately 25% of the indicator).

For the human health toxicity-cancer effect indicator, Cr and Pb were the two main contributing substances, deriving largely from background processes, for example, with the production of fossil fuels and chemical fertilizers.

The three main substances contributing to the PM indicator were NH_3, chemical dust (diameter < 2.5 µm), and SO_2. The use of N fertilizers was the largest source (approximately 50% of the indicator), followed by emissions originating from the use of fossil fuels (approximately 5% of the indicator).

For the photochemical ozone formation potential (POFP) indicator, the three main contributing substances were NO_x, CH_4, and nonmethane volatile organic compounds (NMVOC), deriving mainly from the use of fossil fuels in rice fields and transportation processes.

Two main contributing substances were identified for the terrestrial eutrophication potential (TEP) indicator, i.e., NH_3 and NO_x, which originated primarily from the use of N fertilizers (>90% of the indicator) and fossil fuels (approximately 3% of the indicator).

Contamination by herbicide derivatives and heavy metals (e.g., Cu and Zn) in freshwater ecosystems was the major contributor to the ecotoxicity for aquatic freshwater indicator. The use of herbicides was the main activity contributing to this indicator (approximately 25% of the indicator), followed by contamination with heavy metals derived from the use of fossil fuels (about 4% of the indicator). Ueji and Inao (2001) reported that herbicide derivatives could be detected in natural rivers 3 months after their use. Similarly, Ali et al. (2019) found that the bioaccumulation of heavy metals in the trophic web is highly toxic to ecosystems and poses a great risk to human health as these compounds can be transported up the food chain.

For the ozone depletion potential (ODP) indicator, the main contributing substances were Halon-1301 and CFC-10, which primarily originated from background processes associated with the production of petrochemicals.

4. CONCLUSION

The present study compared yield, financial aspects, and cradle-to-farm gate life cycle environmental impact indicators of the irrigated rice growing systems that adopted fertilizer management practices as recommended by the All-rice1 application (precision fertilizer management) coupled with the AWD water management practices or followed the regular farmers' practices (farmer's experience). It was concluded that the use of the All-rice1 app in conjunction with AWD water management led to increases in paddy yields of 32.71% on average, resulting in an increased net profit of 12,935 THB per ha. Additionally, the values of all 11 environmental impact indicators of the rice in Model 1 were reduced when compared to those in Model 2, i.e., climate change (71.60%), acidification potential (52.78%), freshwater eutrophication potential (54.84%), marine eutrophication potential (62.50%), human health toxicity-cancer effects (65.56%), human health toxicity-non cancer effects (55.38%), particulate matter (56.20%), photochemical ozone formation potential (74.07%), terrestrial eutrophication potential (52.92%), ecotoxicity for aquatic freshwater (73.96%) and ozone depletion potential (77.22%). Therefore, using All-rice1 associated with AWD water management is a promising farming practice for improving the sustainability of irrigated rice growing systems.

ACKNOWLEDGMENT

This study was supported by the Office of the Ministry of Higher Education, Science, Research and Innovation in the fiscal year of 2020, grant number FF65: 168420.

REFERENCES

Ali, H., Khan, E., & Ilahi, I. (2019). Environmental chemistry and ecotoxicology of hazardous heavy metals: Environmental persistence, toxicity, and bioaccumulation. *Journal of Chemistry*, *2019*, Article 6730305. https://doi.org/10.1155/2019/6730305

Amirahmadi, E., Moudrý, J., Konvalina, P., Hörtenhuber, S. J., Ghorbani, M., Neugschwandtner, R. W., Jiang, Z., Krexner, T., & Kopecký, M. (2022). Environmental life cycle assessment in organic and conventional rice farming systems: Using a cradle to farm gate approach. *Sustainability*, *14*(23), Article 15870. https://doi.org/10.3390/su142315870

Carrijo, D. R., Lundy, M. E., & Linquist, B. A. (2017). Rice yields and water use under alternate wetting and drying irrigation: A meta-analysis. *Field Crops Research*, *203*, 173–180. https://doi.org/10.1016/j.fcr.2016.12.002

Center for Applied Economics Research. (2010). *Preparation of the second national report for further submission to the UNFCCC*. Office of Natural Resources and Environmental Policy and Planning (ONEP).

Chobtang, J., Ledgard, S. F., McLaren, S. J., Zonderland-Thomassen, M., & Donaghy, D. J. (2016). Appraisal of environmental profiles of pasture-based milk production: A case study of dairy farms in the Waikato region, New Zealand. *The International Journal of Life Cycle Assessment*, *21*(3), 311–325. https://doi.org/10.1007/s11367-016-1033-9

Chumjom, S., Kerdsom, U., Phantharak, R., Patanapichai, S., Sucharit, M., & Wongsupaluk, N. (2017). *The test and technology transfer of economical water management in rice fields by alternate wetting and drying with farmer participation (Year 1)*. Ministry of Agriculture and Cooperatives. [in Thai]

Cowan, N., Bhatia, A., Drewer, J., Jain, N., Singh, R., Tomer, R., Kumar, V., Kumar, O., Prasanna, R., Ramakrishnan, B., Kumar, D., Bandyopadhyay, S. K., Sutton, M., & Pathak, H. (2021). Experimental comparison of continuous and intermittent flooding of rice in relation to methane, nitrous oxide and ammonia emissions and the implications for nitrogen use efficiency and yield. *Agriculture, Ecosystems & Environment*, *319*, Article 107571. https://doi.org/10.1016/j.agee.2021.107571

De Camillis, C., Bauer, C., Schenker, U., Martin, N., King, H., Blomsma, C., Bligny, J.-C., Lundquist, L., Vessia, Ø., Papagrigoraki, A., Unger, N., & Sueys, R. (2013). *ENVIFOOD protocol, environmental assessment of food and drink protocol*. European Food Sustainable Consumption & Production Round Table. https://doi.org/10.13140/2.1.1042.2404

De Klein, C., Novoa, R. S. A., Ogle, S., Smith, K. A., Rochette, P., Wirth, T. C., McConkey, B. G., Mosier, A., Rypdal, K., Walsh, M., & Williams, S. A. (2006). N_2O emissions from managed soils, and CO_2 emissions from lime and urea application. In S. Eggleston, L. Buendia, K. Miwa, T. Ngara, & K. Tanabe (Eds.), *2006 IPCC guidelines for national greenhouse gas inventories, Vol. 4: Agriculture, forestry and other land use* (pp. 11.1–11.54). Institute for Global Environmental Strategies.

Food and Agriculture Organization of the United Nations. (2017). FAOSTAT. http://www.fao.org

International Organization for Standardization. (2006a). *ISO 14040: Environmental management—Life cycle assessment—Principles and framework*. ISO. https://www.iso.org/standard/37456.html

International Organization for Standardization. (2006b). *ISO 14044: Environmental management—Life cycle assessment—Requirements and guidelines*. ISO. https://www.iso.org/standard/38498.html

Isuwan, A. (2013). Effects of a combination of nitrogen fertilizer and composted manure on production and nitrogen use efficiency of paddy rice. *Thai Agricultural Research Journal*, *31*(3), 270–281. https://doi.org/10.14456/thaidoa-agres.2013.9 [in Thai]

Isuwan, A. (2014a). Effects of compost and site-specific fertilization regimes on growth and grain yield of Pathum Thani rice grown in Sappaya soil series. *Khon Kaen Agriculture Journal*, *42*(3), 369–374. [in Thai]

Isuwan, A. (2014b). Site-specific fertilizer management on growth, yield, and agronomic nitrogen use efficiency of rice grown in Sapphaya soil series. *Journal of Agriculture*, *30*(2), 133–140. [in Thai]

Isuwan, A. (2015). Effects of site-specific fertilization on yields and chemical properties of rice (Pathum Thani) grown in Sapphaya soil series. *Khon Kaen Agriculture Journal*, *43*(3), 423–430. [in Thai]

Isuwan, A. (2020). *Precision soil and fertilizer management for rice production using All-rice1 application (P-18-52860)*. The National Science and Technology Development Agency. [in Thai]

Isuwan, A., Chobtang, J., & Sirirotjanaput, W. (2018, October 17–19). *Economic and environmental sustainability of rice farming systems in Thailand: Adoption of site-specific fertilization practice* [Conference session]. 11th International Conference on Life Cycle Assessment of Food 2018 (LCA Food), Bangkok, Thailand.

Isuwan, A., & Keawaram, T. (2021). Effects of fertilization regimes on grain yields and economic returns of Pathum Thani 1 rice grown on Sapphaya soil series. *Walailak Journal of Science and Technology*, *18*(2), Article 6838. https://doi.org/10.48048/wjst.2021.6838

Isuwan, A., Promchan, T., & Chobtang, J. (2022). Rice growth, yield composition and water efficiency in different soil series using alternate wetting and drying water management. *Science, Engineering and Health Studies*, *16*, Article 22030010. https://doi.org/10.14456/sehs.2022.55

Kitsiou, D., & Karydis, M. (2011). Coastal marine eutrophication assessment: A review on data analysis. *Environment International*, *37*(4), 778–801. https://doi.org/10.1016/j.envint.2011.02.004

Nemecek, T., Schnetzer, J., & Reinhard, J. (2016). Updated and harmonised greenhouse gas emissions for crop inventories. *The International Journal of Life Cycle Assessment*, *21*(9), 1361–1378. https://doi.org/10.1007/s11367-014-0712-7

Pré Consultants. (2018). *SimaPro 8.0* [Computer software]. Pré Consultants. https://simapro.com/

Ruensuk, N., Rossopa, B., Channu, C., Paothong, K., Prayoonsuk, N., Rakchum, P., & Malumpong, C. (2021). Improving water use efficiency and productivity in rice crops by applying alternate wetting and drying with pregerminated broadcasting in farmers' fields. *Agriculture and Natural Resources*, *55*(1), 119–130.

Sanpakdee, P., & Onwimon, N. (2021). Cost and return on investment from Jasmine rice farming of the farmers in Sam Chuk district, Suphan Buri province. *Journal of Humanities and Social Sciences*, *Rajapruk University*, *7*(1), 121–135. [in Thai]

Sibayan, E. B., Samoy-Pascual, K., Grospe, F. S., Casil, M. E. D., Tokida, T., Padre, A. T., & Minamikawa, K. (2018). Effects of alternate wetting and drying technique on greenhouse gas emissions from irrigated rice paddy in Central Luzon, Philippines. *Soil Science and Plant Nutrition*, *64*(1), 39–46. https://doi.org/10.1080/00380768.2017.1401906

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., & Sirotenko, O. (2007). Agriculture. In B. Metz, O. Davidson, P. Bosch, R. Dave, & L. Meyer (Eds.), *Climate change 2007: Mitigation. Contribution of working group III to the 4th Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 497–540). Cambridge University Press.

Sriphirom, P., Chidthaisong, A., & Towprayoon, S. (2019). Effect of alternate wetting and drying water management on rice cultivation with low emissions and low water use during wet and dry season. *Journal of Cleaner Production*, *223*, 980–988. https://doi.org/10.1016/j.jclepro.2019.03.212

Thanawong, K., Perret, S. R., & Basset-Mens, C. (2014). Eco-efficiency of paddy rice production in Northeastern Thailand: A comparison of rain-fed and irrigated cropping systems. *Journal of Cleaner Production*, *73*, 204–217. https://doi.org/10.1016/j.jclepro.2013.12.067

Tirol-Padre, A., Minamikawa, K., Tokida, T., Wassmann, R., & Yagi, K. (2018). Site-specific feasibility of alternate wetting and drying as a greenhouse gas mitigation option in irrigated rice fields in Southeast Asia: A synthesis. *Soil Science and Plant Nutrition*, *64*(1), 2–13. https://doi.org/10.1080/00380768.2017.1409602

Ueji, M., & Inao, K. (2001). Rice paddy field herbicides and their effects on the environment and ecosystems. *Weed Biology and Management*, *1*(1), 71–79. https://doi.org/10.1046/j.1445-6664.2001.00002.x

Wang, M., Xia, X., Zhang, Q., & Liu, J. (2010). Life cycle assessment of a rice production system in Taihu region, China. *International Journal of Sustainable Development & World Ecology*, *17*(2), 157–161. https://doi.org/10.1080/13504501003594224