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Improvement of rice farming through use of biomass waste-derived biochar in combination with soil analysis-based fertilization and wetting and drying water

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Abstract Improvement of rice farming through use of biomass waste-derived biochar in combination with soil analysis-based fertilization (recommended by All-rice1 application) and alternate wetting and drying water management (AWD) is an important and essential approach for Thai agriculture and the utilization of biomass waste, especially in rice production, which is found to be the main occupation and an important economic crop of the country. For the use of 2,000 kg/ha biochar at the rate (All-rice1+AWD+Biochar) and not (All-rice1+AWD) in the farmer's paddy, both management forms were not affected the height of 35- and 65-day-old rice. In addition, the rice yield components of the All-rice1+AWD+Biochar rice cultivation were 100.32 grains/panicle, resulting in a rice yield (6,453.75 kg/ha), which increased by 10.04%. The All-rice1+AWD+Biochar had a higher total cost and variable cost than the rice cultivation according to the All-rice1+AWD, an average of 40,018.81 Thai baht/ha., It was found that All-rice1+AWD+Biochar rice cultivation had an average net loss of 15,121.25 Thai baht/ha. Although using biochar as a production factor in All-rice1+AWD+Biochar rice cultivation resulted in higher yields and total incomes more than All-rice1+AWD cultivation, it was still not worth the higher production costs of All-rice1+AWD+Biochar rice cultivation. For the environmental impact, the CC index of rice cultivation using biochar was 52.71% lower than without biochar. The AP index of the rice cultivation system slightly increased, with ammonia emissions (83.09% AP index) resulting from nitrogen fertilizer application, sulfur dioxide emissions (9.35% AP index), and nitrogen oxides (7.28% AP index).

Keywords: Biochar, Biomass waste, Rice farming, Soil analysis-based fertilization, Wetting and drying water management

Introduction

Traditional rice production systems or lowland paddy field rice farming emit high levels of greenhouse gases, mainly methane and nitrous oxide, which have global warming potentials 21 and 265 times higher than carbon dioxide, respectively (Myhre *et al.*, 2013). In addition to the greenhouse gas effects, the increased application of fertilizers (especially nitrogen and phosphorus fertilizers) (Isuwan, 2016; 2015) results in increased leaching of

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nitrogen compounds such as nitrate, ammonium and phosphorus compounds (such as phosphate and phosphoric acid). These pollutants make the Thai rice farming system less environmentally sustainable (Thanawong *et al.,* 2014), and contribute to global warming and climate change. Fertilizer management considering soil analysis results will help to use fertilizers efficiently.

Isuwan *et al*. (2019) reported that rice that received fertilizers based on soil analysis values had high yields and could control chemical fertilizer costs, resulting in higher net profits than other fertilizer management methods. In addition, Isuwan *et al*. (2021b) found that fertilizer management based on soil analysis values along with alternate wet and dry water management (AWD) not only helped rice to have high yields but also helped reduce water use in rice farming by up to 24%.

The transformation and reuse of biomass waste is an approach to add value to waste and increase agricultural production efficiency, especially the transformation of biomass waste into biochar. Biochar is of interest in agriculture, such as its use in soil improvement to increase crop yields. It is produced from various types of natural materials such as wood, leaves, branches, fruit peels, animal waste, or agricultural waste (i.e., rice husks, bagasse, corn cobs, and cassava roots. It is a high-carbon material produced by pyrolysis or thermochemical decomposition of biomass under conditions with limited oxygen (Charoensri *et al.,* 2017). It is a thermal decomposition, which has two methods: rapid decomposition at an average temperature of 700 °C and slow decomposition at an average temperature of 500 °C (Winsley, 2007).

The pyrolysis process can produce 60% bio-oil, 20% syngas including H_2, CO and CH_4, and 20% biochar consisting of C, H, O, N, S and ash. Each pyrolysis process gives different ratios of products. Total Carbon is in the range of 172-905 g/kg, Total Nitrogen is in the range of 1.8-56.4 g/kg, Phosphorus is in the range of 2.7-480 g/kg and Potassium is in the range of 1.0-58.0 g/kg. Cation exchange capacity (CEC) is about 40 milligram equivalents per gram, and the acidity (pH) of 6.2-9.6, depending on the materials used to make biochar (Verheijen *et al*., 2010).

In addition, the pyrolysis process makes biochar porous, which can absorb fertilizer molecules and gradually release them, allowing plants to increase the efficiency of fertilizer usage. Research has found that the use of biochar increases the efficiency of fertilizer usage in rice (Hemwong, 2014; Wijitkosum and Sriburi, 2018; Zhang *et al.,* 2011). It also provides nutrients such as phosphorus, potassium, calcium, and magnesium, as well as silicon, to the soil (Harsono *et al*., 2013) and is a source of nutrients for soil microorganisms (Lehmann *et al*., 2011), resulting in increased efficiency of plant production.

Therefore, the research aimed to evaluate the productivity, economic characteristics, and environmental impact of rice production when using biochar with fertilizer and AWD management.

Materials and methods

Five rice growing farms located in Ban Lat district, Phetchaburi province, Thailand, were selected for this study. The soil type is the Phetchaburi soil series (fine-silty, mixed, active, isohyperthermic Aquic Haplustalfs). Rice seeds (var. Pathum Thani 1) 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.

Model 1, fertilizers were applied based on the recommendations of the All-rice1 application (downloadable from App Store, Play Store, or www.soil.asat.su.ac.th), and Alternate wetting and drying (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, use water pipes made from 25 cm high PVC pipes installed in the rice fields with the mouth of the pipe 5 cm above the ground surface (as shown in Figure 1.), 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 until the soil's moisture was reduced to 70%. Then, water was refilled up to 10 cm above the ground and allowed to evaporate again down to 70% soil moisture content. This procedure was performed until panicle initiation upon the second fertilizer application (55-day-old rice). The water was maintained at a level of 5 cm above the ground until 10 days before harvest (120-day-old rice at harvest).

Table 1. Details of fertilizer use in the Model 1 and 2

Farmers	1st fertilizer spreading period (kg/ha)			2nd fertilizer spreading period (kg/ha)
	18-46-0	**46-0-0**	**0-0-60**	**46-0-0**
1	13.75	58.44	41.88	958.44
2	26.88	55.94	41.88	55.94
3	26.88	55.94	62.50	55.94
4	13.75	58.44	62.50	58.44
5	26.88	55.94	62.50	55.94

In Model 2, fertilizers and water management were applied according to Model 1 and added biochar 2,000 kg/ha in soil preparation (referred to "All-rice1 + AWD + Biochar").

The chemical and physical properties of the soil were analyzed before and after the experiment, as shown in Table 2 and Table 3.

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

Table 2. Soil analysis results prior to experiment

Farm	Total N (%)	Avai. P (mg/kg)	Ex. K (mg/kg)	pH	EC 1:5 (dS/m)	Sand (%)	Silt (%)	Clay (%)	Texture
1	0.06	42.096	60.54	5.332	2.58	83.46	15.75	0.8	Loamy Sand
2	0.14	12.158	66.15	5.027	1.23	83.37	13.83	2.8	Loamy Sand
3	0.06	18.508	55.76	5.299	1.4	75.37	21.75	2.79	Loamy Sand
4	0.07	252.992	49.77	5.828	1.09	81.75	7.83	10.79	Loamy Sand
5	0.06	15.228	0.61	4.826	0.39	83.71	13.71	2.77	Loamy Sand
Methods	Bremner and Mulvaney (1982)	Bray and Kurtz (1995)	Peech *et al.* (1947)	McLean (1982)	Jackson (1958)				Dewis and Freitas (1970)

Table 3. Soil analysis results after to experiment

Farm	Treatment	Total N (%)	Avai. P (mg/kg)	Ex. K (mg/kg)	pH	EC 1:5 (dS/m)	OM
1	All-rice1+AWD	0.03	42.49	54.22	5.763	0.7165	1.11
	All-rice1+AWD+Biochar	0.03	40.28	46.23	5.558	0.9436	1.14
2	All-rice1+AWD	0.03	13.39	35.6	5.208	0.347	1.07
	All-rice1+AWD+Biochar	0.02	10.97	31.51	5.236	0.3658	0.85
3	All-rice1+AWD	0.02	19.98	36.76	5.438	0.378	0.99
	All-rice1+AWD+Biochar	0.02	29.51	33.78	5.453	0.3564	0.65
4	All-rice1+AWD	0.02	272.50	40.56	5.371	0.2216	0.74
	All-rice1+AWD+Biochar	0.02	246.91	43.33	5.444	0.3318	0.74
5	All-rice1+AWD	0.03	13.84	45.64	4.572	0.5985	1.15
	All-rice1+AWD+Biochar	0.03	20.44	52.36	4.715	0.8144	1.35
Methods		Bremner and Mulvaney (1982)	Bray and Kurtz (1995)	Peech *et al.* (1947)	McLean (1982)	Jackson (1958)	Walkley (1947); FAO (1974)

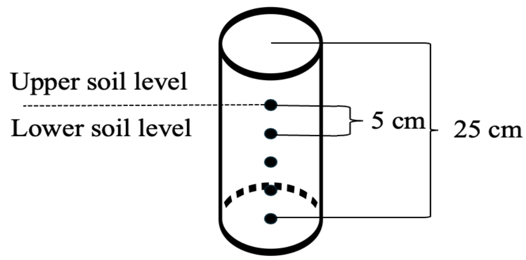

Figure 1. Water pipes for water level checking

Data collection and management

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/m^2 were measured. In addition, the number of plants/m^2 (60-day-old rice) was recorded. Note that the same random points used in the study of rice stem height by Chumjom *et al.* (2017) were used in the present study.

Yield components were determined on the 120-day-old after sowing. They included the number of panicles/m^2, total number of grains/panicles, % filled grains, % unfilled grains, and 100-filled grains weight. Yield was recorded over an area of 2 × 5 m with 250 random spots/ha and standardized to 14% moisture level (Ruensuk *et al*., 2021).

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. The fixed costs consisted of monetary costs, such as land tax and land rent, and nonmonetary costs, such as the depreciation of agricultural equipment and land rent. Similarly, the variable costs were divided into monetary and nonmonetary.

Cost of agricultural materials for rice plantation, i.e., the cost of seeds, fertilizers, insecticides, and weedicides.

Cost of labor, including wages for preparing the soil, sowing, fertilizing, spreading insecticide and weedicide, and harvesting the rice.

Other costs included fuel and repairing agricultural equipment.

The income and profit obtained from rice cultivation were analyzed 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

Environmental assessment

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

Functional unit and system boundary

One kg of standardized paddies was considered as the functional unit. Standardized paddies are defined as cleaned paddies with adjusted 14% moisture level. 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. Data collected was environmental emissions associated with the manufacturing of agricultural machinery and equipment were not accounted for in the present study.

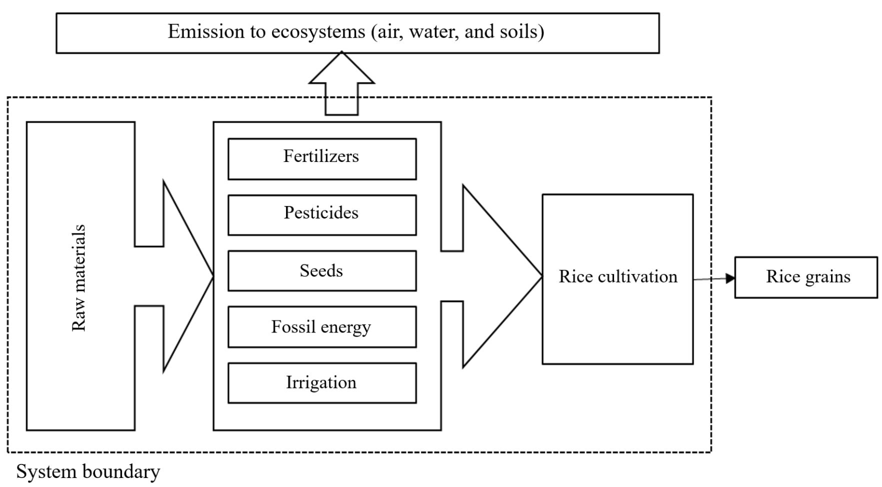

Figure 2. Elementary flow diagram and system boundary of rice growing systems examined in the present study

Life cycle inventory analysis

The data associated with the use of inputs and pollution generated to produce raw materials (i.e., chemical fertilizers, fuels, and herbicides) were obtained from the Ecoinvent database version 3.4 (www.ecoinvent.org). (Ecoinvent Centre, 2018)

The unit process selected for this study was obtained from the ecoinvent v. 3.4 database as shown in Table 4.

Table 4. Processes used to assess the environmental impact of biochar production and rice farming systems

List	Selected Process
Biochar production	
-Transportation	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {GLO}| market for | Alloc Rec, U
-Electricity generation	Electricity, low voltage {TH}| market for | Alloc Rec, U
- Diesel oil	Diesel, low sulfur {RoW}| market for | Alloc Rec, U
- Gasoline	Petrol, low sulfur {RoW}| market for | Alloc Rec, U
- Diesel combustion	Diesel, burned in agricultural machinery {GLO}| market for diesel, burned in agricultural machinery | Alloc Rec, U
- Gasoline combustion	Petrol, unleaded, burned in machinery {GLO}| market for petrol, unleaded, burned in machinery | Alloc Rec, U
Rice farming	
- Nitrogen fertilizer	Urea, as N {GLO}| market for | Alloc Rec, U
- Phosphorus fertilizer	Phosphate fertiliser, as P_2O_5 {GLO}| market for | Alloc Rec, U
- Potassium fertilizer	Potassium chloride, as K_2O {GLO}| market for | Alloc Rec, U
- Seeds	Rice seed, for sowing {RoW}| production | Alloc Rec, U
- Diesel oil	Diesel, low sulfur {RoW}| market for | Alloc Rec, U
- Gasoline	Petrol, low sulfur {RoW}| market for | Alloc Rec, U
- Transportation	Transport, freight, light commercial vehicle {GLO}| market for | Alloc Def, U
- Diesel combustion	Diesel, burned in agricultural machinery {GLO}| market for diesel, burned in agricultural machinery | Alloc Rec, U
- Gasoline combustion	Petrol, unleaded, burned in machinery {GLO}| market for petrol, unleaded, burned in machinery | Alloc Rec, U
- Pesticides	Acetamide-anillide-compound, unspecified {GLO}| market for | Alloc Rec, U
- Insecticide	Benzoic-compound {GLO}| market for | Alloc Rec, U

The accounting of pollutants directly related to the rice production system (foreground process) inventory models were used together with the use of relevant constants (inventory factors) as follows:

- Methane emissions from rice farming with alternate wetting and drying management and Assess carbon loss from chemical fertilizer use according to IPCC (2006) recommendations.

- Nitrogen loss from chemical fertilizer application was assessed according to the recommendations of Nemecek *et al.* (2016).

- Nitrogen loss from aboveground and underground parts of rice plants was assessed according to the recommendations of Yodkhum *et al.* (2018) and Cha-un *et al.* (2017).

- Rice straw volume was estimated according to the recommendations of Yan *et al*. (2009).

- Phosphorus loss from rice fields was assessed according to the recommendations of Wang *et al.* (2014)

- Emissions of greenhouse gases and other related pollutants were assessed according to the recommendations of IPCC (2006), Isuwan *et al.* (2018), and Thanawong *et al.* (2014).

Life cycle impact assessment

Four environmental impact indicators recommended by the Food SCP RT (2013) (Table 5) were used in this study. 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 5. Environmental indicators used in the present study

Impact Category	Units [1/]	Abbreviation	Source
Climate Change	kg CO_2 equivalent	CC	Myhre *et al.* (2013)
Acidification Potential	molc H^+ equivalent	AP	Posch *et al.* (2008); Seppälä *et al.* (2006)
Freshwater Eutrophication Potential	kg P equivalent	FEP	Struijs *et al*. (2009)
Marine Eutrophication Potential	kg N equivalent	MEP	Struijs *et al*. (2009)

[1/] CO_2 = carbon dioxide; molc = mole of charge; H = $^+$hydrogen ion; N = nitrogen; P = phosphorus.

Statistical analysis

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

Ethics statements

This study was approved by the ethics committee of Silpakorn University (Approval no. COE 65.1128-201)

Results

Growth characteristics

The precision fertilizer management according to the All-rice1 + AWD and All-rice1 + AWD + Biochar (2,000 kg/ha) had not affected in the number of seeding (Table 5). Other than that, both management methods had not affected in height at 35- and 65-day-old rice (Table 6).

The number of plants/m^2 was significantly differed (P<0.05) at 35-day-old rice using fertilizer according to the All-rice1 + AWD. The average number of plants/m^2 was 355.33 ± 70.92 plants.

Table 6. Growth, yield components, and grain yield of rice plants that received the fertilizer doses recommended by the All-rice1 application, and Alternate wetting and drying (AWD) water management was jointly adopted (referred to "All-rice1 + AWD") versus added biochar 2,000 kg/ha (referred to "All-rice1 + AWD + Biochar")

Parameter	All-rice1 + AWD (T1)		All-rice1 + AWD + Biochar (T2)		*P*-value[1/]	T2/T1
	mean	±SD	mean	±SD		(%)
7-day-old						
Number of seeding	384.07	127.96	335.84	97.00	ns	
35-day-old						
Plant height (cm)	50.11	3.53	52.09	4.58	ns	
Plants no./m^2	266.40	56.04	355.33	70.92	*	
65-day-old						
Plant height (cm)	88.33	8.43	88.49	9.25	ns	
Plants no. /m^2	268.40	38.50	273.53	25.90	ns	
Yield components						
Panicle no. /m^2	261.90	19.85	246.90	33.42	ns	-5.73
Grain no. /spike	89.24^b	17.41	100.32^a	17.56	**	12.42
100 grain weight (g)	3.31	0.18	3.32	0.17	ns	0.30
% Filled grain (%)	78.34	7.35	79.76	6.32	ns	1.81
Grain yield (kg/ha)	3,732.19^b	273.56	4,106.94^a	426.38	*	10.04

[1/]ns = nonsignificant, * = significant at 0.05, and ** = significant at 0.01

Yield and rice yield components

For yield components, it was found that both management methods had no effect (P>0.05) on the number of panicles/m^2, 100-grain weight, % good grains, and % deflated grains, with values ranging from 213.48-281.75, 3.15-3.49, 70.99-86.08, and 13.92-29.01, respectively (Table 5). However, it was found that the All-rice1 + AWD +Biochar (2,000 kg/ha) resulted in the 100.32 grains/ panicle, resulting in a rice yield (4,106.94 kg/ha) increased ($P<0.05$) by 10.04%, compared to the All-rice1 + AWD, which gave a paddy yield of only 3,732.19 kg/ha.

Economic performance indicators

For the comparison of production costs between rice cultivation using biochar made from biomass waste (All-rice1+AWD+Biochar) in combination with the All-rice1+AWD on average/ha/production cycle (Table 6), it was found that rice cultivation in the All-rice1+AWD+Biochar had a higher total cost and variable costs than rice cultivation in the All-rice1+AWD, with an average of 49,018.81 Thai baht/ha, or 255.30% ($P>0.05$), with the same fixed cost for both patterns, and with an average of 12,988.44 Thai baht/ha, because rice cultivation in the All-rice1+AWD+Biochar had higher chemical fertilizer costs and increased biochar costs.

However, when the income and variable costs were used to calculate net income, it was found that the All-rice1+AWD+Biochar rice cultivation had a lower net income than the All-rice1+AWD rice cultivation by an average of 43,077.81 Thai baht/ha, or 105.21% ($P>0.05$). The total income and costs were used to calculate net profit, and it was found that the All-rice1+AWD+Biochar rice cultivation had an average net loss of 15,121.25 Thai baht/ha, while the All-rice1+AWD rice cultivation had an average net profit of 27,956.63 Thai baht/ha (Table 8).

The cost of biochar production from biomass waste was used as a production factor for rice cultivation using biochar combined with fertilizer management based on soil analysis values and alternating wet and dry water management (All-rice1+AWD+Biochar). This is the total cost of producing 1,000 kilograms of biochar and is calculated as the average cost of producing biochar/ kg. The costs include labor costs for cutting wood, burning charcoal and grinding charcoal, fuel and lubricant costs for transportation and sawing wood, electricity costs for sawing wood and grinding charcoal, and kiln equipment costs (Table 7).

Table 7. Cost of production of biochar made from biomass waste

List	Thai baht
Labor cost	1,875.00
Fuel cost	11,101.20
Lubricant cost	454.00
Electricity cost	894.55
Kiln equipment cost	9,800.00
Total (Thai baht)	24,124.75
Biochar yield (kg)	1,000.00
Biochar production cost (Thai baht/kg)	24.12

Table 8. Cost components and economic returns for rice fields that received the fertilizer doses recommended by the All-rice1 application, and Alternate wetting and drying (AWD) water management was jointly adopted (referred to "All-rice1 + AWD") versus added biochar 2,000 kg/ha (referred to "All-rice1 + AWD + Biochar")

(Thai baht/ha)	All-rice1 + AWD (T1)		All-rice1 + AWD + Biochar (T2)		*P-value*[1/]	Change rate [2/]
	mean	±SD	mean	±SD		(%)
Total cost	32,189.06	9,891.13	81,207.94	9,721.56	*	152.28
Total revenue	60,145.69	6,005.82	66,262.88	8,591.25	ns	255.30
Net income	40,945.06	8,915.63	-1,956.63	11,042.56	ns	-105.21
Net profit	27,956.63	13,979.69	-14,945.06	16,994.00	*	-154.09

[1/]ns = nonsignificant * = significant at 0.05, and ** = significant at 0.01
[2/]Change rate (%) = [(Cost or return of T2 − Cost or return of T1) / Cost or return of T1] × 100

Environmental impact indicators

The process and amount of production factors used to produce 1 kilogram of biochar. In the production process of 1 kg of biochar, 2.6 kg of wood chips are required, which requires tools for pruning trees, transportation which requires oil, and charcoal grinding which requires a grinder (Figure 3).

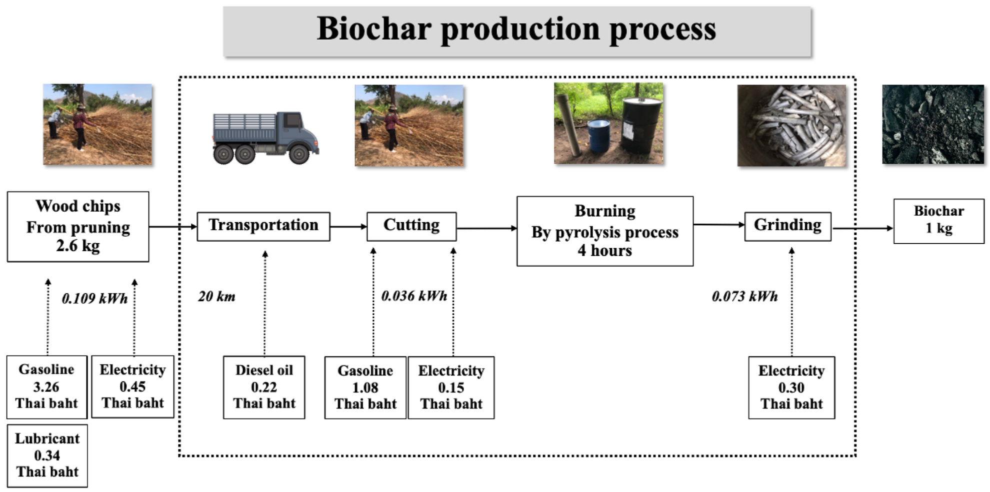

Figure 3. Biochar production process and production factor utilization

This study found that the production of 1 kg of biochar has a CC index of 0.59 kg CO_2-e (Table 9), almost all of which is carbon dioxide, accounting for 93.60 percent of the CC index. This carbon dioxide is derived from using fuel for pruning (66.70% CC index), electricity use (22.56% CC index), and transportation (4.42 % CC index). However, since biochar can store carbon for a long time (more than 100 years), the net CC index is less than zero, which means that the use of 1 kg of biochar can help store carbon at a rate of 1.76 kg CO_2-e.

The AP index is caused by nitrogen oxides (55.30% AP index) and sulfur dioxide (44.10% AP index). These two gases are caused by processes related to the use of fuel, whereas the FEP index is caused by phosphorus contamination of freshwater ecosystems, which is mostly caused by the power generation process (81.60% FEP index). The MEP index is mostly caused by nitrogen oxides (97.90% MEP index) released from activities involving the use of fuel.

Table 9. Environmental impacts of biochar

Indicator	Unit	1 kg Biochar (A)	Carbon content of biochar (B) *1/	Net Value (A – B)
CC	kg CO_2-e/kg biochar	0.59×10^0	2.35×10^0	-1.76×10^0
AP	molc H^+-e/kg biochar	4.00×10^{-3}	na	na
FEP	kg P-e/kg biochar	1.03×10^{-4}	na	na
MEP	kg N-e/kg biochar	1.19×10^{-3}	na	na

* The assumption is that biochar is 80% carbon, and after biochar is used as a soil amendment, it will degrade, and in 100 years, 80% biochar will remain. Therefore, after 100 years, 64% of the carbon in biochar will remain, and the carbon will be converted to carbon dioxide equivalent (CO_2-e) using the factor 44/12 (Woolf *et al.,* 2021).
1/na=There is no data available for use in the assessment.

Environmental impacts of rice production using biochar

Biochar application in rice fields decreased the CC index of rice (*P*<0.05) but did not affect the AP index (*P*>0.05), while the FEP and MEP indices of the biochar-treated rice system were higher (*P*<0.05) compared to the non-biochar-treated rice system with soil-based fertilizer and alternate wetting and drying water management (Table 10).

Table 10. Environmental impacts of rice cultivation systems with and without biochar

Indicator	All- rice1+AWD +Biochar (T1)		All- rice1+AWD (T2)		*P*-value[1/]	(T1-T2) /T2
	mean	±SE	mean	±SE		(%)
CC	0.61×10^{0}	0.03×10^{0}	1.29×10^{0}	0.05×10^{0}	**	-52.71
AP	2.04×10^{-2}	0.86×10^{-2}	2.03×10^{-2}	0.72×10^{-2}	ns	+0.49
FEP	2.65×10^{-4}	0.22×10^{-4}	2.32×10^{-4}	0.23×10^{-4}	*	+14.22
MEP	2.95×10^{-3}	0.12×10^{-3}	2.58×10^{-3}	0.11×10^{-3}	*	+14.34

[1/]ns = nonsignificant * = significant at 0.05, and ** = significant at 0.01

Discussion

The precision fertilizer management according to the All-rice1 + AWD and All-rice1 + AWD + Biochar (2,000 kg/ha) had no effect on the number of seeding and height at 35- and 65-day-old rice, which is consistent with Isuwan *et al.* (2022), and reported that growing Pathum Thani 1 rice in Phetchaburi soil series with fertilizer calculated using the All-rice1 + AWD resulted in rice height that was no different from that obtained with farmers' fertilizer and water management methods. Similarly, Harakotr and Thong-oon (2016) found that AWD and flooding water management had no effect on rice plant height. Manaonok *et al.* (2017) reported that the use of biochar affected the change in soil properties and affected the growth of rice in the early stage or seedling stage at 30 and 45 days after sowing, resulting in higher rice height, number of shoots/plants, leaf area, and dry weight above ground than the treatment without biochar. This is consistent with Norsuwan *et al*. (2013) who reported that biochar application at a rate of 16,000 kg/ha significantly increased the number of shoots.

For yield components, appropriate fertilizer and water management that is consistent with the needs of rice helps rice plants receive sufficient and important plant nutrients, resulting in increased rice yield (Sibayan *et al.,* 2018; Tirol-Padre *et al*., 2018). This is consistent with Wijitkosum and Kallayasiri (2015) who reported that mixing 1 kg/m^2 biochar into the planting plot resulted in better rice growth than using organic fertilizer alone at all growth stages, with the number of rice plants/tiller, the number of grains/panicles, the 1,000-grains weight, and the % good rice grains being increased when compared to rice grown using organic fertilizer alone. Norsuwan *et al.* (2013) reported that the application of 16,000 kg/ha biochar, significantly increased the number of shoots. In addition to the importance of the biochar application rate on the plant response, the management of biochar together with fertilizer management also plays an important role by applying fertilizer at the recommended rate or lower than the recommended rate for each type of plant (Vinh *et al.,* 2014), and Isuwan *et al.* (2021a), reported that fertilization using the All-rice1 application and AWD water management resulted in increased paddy yield of Pathum Thani 1 rice grown in the Phetchaburi soil series ($P<0.05$) by 39.22% compared to rice cultivation using farmers' methods.

For the comparison of production costs between rice cultivation using biochar made from biomass waste (All-rice1+AWD+Biochar) in combination with the All-rice1+AWD on average/ha/production cycle. Although the use of biochar as a production factor in the All-rice1+AWD+Biochar rice cultivation resulted in higher yields and total income than the All-rice1+AWD rice cultivation, it was still not worth the higher production costs of the All-rice1+AWD+Biochar rice cultivation. The addition of biochar reduces net profit, and if the amount added increases, the net profit would decrease accordingly (Norsuwan *et al*., 2013). The comparative analysis of total cost, total income, net income and net profit of the two rice cultivation models, it was found that the addition of biochar increased the cost but had no effect on the rice production, resulting in the same income and therefore a loss (Table 8). This is consistent with Norsuwan *et al.* (2013) who found that biochar application would decrease the net profit of rice production, and decrease with an increasing rate of biochar application. In addition, if biochar is produced in a large quantity, it would help reduce production costs for agricultural use.

The environmental impact assessment of the biochar production process determined that wood waste used for making biochar is burden-free as it is a waste. The greenhouse gas emissions of the biochar production system mainly occur from the fuel and electricity consumption processes, including greenhouse gases from incomplete combustion in the pyrolysis process (Papageorgiou *et al*., 2021).

The benefits of using biochar in rice cultivation systems are that in addition to biochar helping to fix carbon (carbon sequestration), biochar can also help reduce the emissions of nitrous oxide (Woolf *et al*., 2021) and methane (Jeffery *et al*., 2016) from rice cultivation systems. However, this study did not assess the amount of nitrous oxide and methane reduced by using biochar because there were no appropriate emission model or factor for use in the assessment. Although, after deducting the carbon fixation of biochar, the CC index of rice cultivation using biochar was 52.71% lower than that without biochar. Methane, carbon dioxide, and nitrous oxide are the major greenhouse gases affecting the CC index of rice cultivation systems. Therefore, the carbon fixation of biochar significantly reduced the CC index.

Biochar production carries an inherent AP load with charcoal; thus, the biochar application slightly increased the AP of the rice cultivation system. Ammonia emissions (83.09% AP) were caused by nitrogen fertilizer application, and sulfur dioxide (9.35% AP) and nitrogen oxides (7.28% AP) were mainly caused by the fuel oil combustion process. Similarly, biochar carries an inherent FEP and MEP load; thus, biochar application increased the FEP and MEP values.

The use of biochar in rice farming systems has significantly reduced the index values, partly due to the biochar's ability to fix carbon for a long time. However, other environmental impact indicators from non-greenhouse gas pollutants, such as FEP and MEP, have increased. Therefore, it is necessary to find a method for producing biochar that is environmentally friendly in all dimensions to truly support environmental sustainability.

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Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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