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Energy analysis and greenhouse gas emission of organic rice productions in Northern Thailand

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Abstract: Organic rice cultivation areas and organic rice market have been increasing continuously due to a rise in consumers' demand resulting in better quality of life for producers and consumers. Although there are numerous studies on organic farming involving both of production and marketing, knowledge of energy analysis and greenhouse gas emission in organic rice cultivation process have not been mentioned, especially Riceberry varieties in Thailand. To fill this gap, the energy analysis and greenhouse gas emission of organic Riceberry production in Northern Thailand was evaluated. The organic Riceberry production conducted from July 2020 to January 2021 at Lamphun province, Thailand, was analyzed. The rice variety used in this study was Riceberry. The experimental study was separated into 3 types of green manure (no green manure as control, *Crotalaria juncea*, and *Sesbania rostrata*). Each type of green manure was combined with 2 water managements (Continuous flooding; CF, and Alternative wetting and drying; AWD). The result revealed that using *Sesbania rostrata* in combination with Alternative wetting and drying water management (*Sesbania*-AWD) was the most suitable method for organic Riceberry production. The main energy consumption was from fuel and machinery (77.48 and 14.58%, respectively), whereas energy use efficiency (EUE), net energy (NE) and specific energy (SE) were 9.40, 108,123.92 MJ/ha and 3.02 MJ/kg $_{\text{paddy yield}}$, respectively. The main contributor in GHG emission was the methane (CH_4) field emission (46.16%), GHG emission from material inputs (28.86%) and nitrous oxide (N_2O) field emission (24.98%). Thus, GHG intensity was 0.62 $kgCO_{2\text{-eq}}/kg_{\text{paddy yield}}$.

Keywords: Organic farming, riceberry, *Sesbania rostrata*, *Crotalaria juncea*, alternate wetting and drying.

1. Introduction

The world had been facing an energy shortage and growing greenhouse gas emissions situations. The main reason for the increasing greenhouse gas emissions is the combustion of CO_2-containing fuels for transportation, industry and agriculture. In other words, reducing energy consumption can solve the energy shortage and reduce greenhouse gas emissions. The number of wasteful energy sources has declined in contrast to the continued rising demand for energy due to economic expansion [1]. In Thailand, energy consumption continued to increase according to economic growth, where fuel products were the most used energy, accounting for 49.0% of the total final energy consumption [2]. Agriculture is currently one of the main factors affecting energy consumption and GHG emissions [3-5]. Each year the agricultural sector emits 10–12% of estimated total greenhouse gas emissions (5.1–6.1×10^3 $MtCO_{2\text{-eq}}$/yr) [6]. Rice fields is a major source of agricultural methane (CH_4) emission since rice cultivation requires a lot of water. The continuous flooding water management in rice fields produces methane, an important greenhouse gas. The information that may not be known is methane emissions from rice paddies accounting for 72% of the total agricultural sector in Thailand [7]. One of the reasons for increasing the amount of greenhouse gas emissions is that farmers have an increased rate of fertilizer use [8]. In rice production, fertilizer represents the highest contributor to the total GHG emissions. It represents 44% and 42% in transplanting and broadcasting method, respectively. Among different types of chemical fertilizers, nitrogen represents the higher contributor [9]. Over application of N fertilizer causes environmental pollution and sustainability risk, global warming and ozone layer depletion [10].

From the current crisis situation, finding a solution to reduce the use of energy and nitrogen fertilizers is important and urgent. In terms of energy consumption, organic cultivation processes affect the energy consumption of rice cultivation. This can be seen from research by Pagani et al. [1] that they compared the energy consumption in the rice planting system in Southern Europe (Piedmont, Italy) and in North America (Missouri, USA), a total of 12 rice fields where both conventional and organic farming systems were selected and information of direct and indirect energy inputs was collected. The results indicated that organic farming could reduce energy inputs by more than 50% with only 8% yield decrease. Moreover, direct energy consumption studies of farm operations suggest that pumping groundwater for irrigation is one of the most energy-intensive processes. In Thailand, rice is the most irrigated crop. Especially in the dry season, there is more water shortage. Compared to continuous flood (CF) technique, the alternative wetting and drying (AWD) technique can reduce the amount of water normally required in rice cultivation systems and methane emissions from rice fields, as well as energy consumption [11]. Malumpong et al. [11] studied the effect of AWD (10/-10 cm, 10/-15 cm and 10/-20 cm) and CF irrigation systems in combination with rice broadcasting technique on the amount of rice yield in the dry season of 2014 and 2015. AWD 10/-10 cm means when the water drops to 10 cm below the soil surface, the field is re-flooded again to maintain the water level at 10 cm above the soil surface. The results indicated that the AWD technique resulted in lower paddy yield compared to CF, but the paddy quality after milling was not significantly different. If there is a water shortage and it is necessary to plant rice in such cases, it is recommended to use the AWD10/-10 cm technique in the rice broadcasting system in Thailand. Numerous studies had estimated the energy input, energy output, energy analysis, suitable cultivation method with low energy use for rice production [1, 12-19]. Muazu et al. [16] studied and analyzed the energy used for rice cultivation in sustainable wetlands in Malaysia. The results showed that nearly 84% of all energy used in farming was from non-renewable resources (chemical fertilizers, fuels, pesticides and machinery accounting for 60, 17, 4 and 3%, respectively). Renewable resources, including seeds, human labor and organic fertilizers accounted for 15, 0.25 and 0.22%, respectively. Therefore, it can be confirmed that organic fertilizer was used much less energy than chemical fertilizer.

Green manure is one of the interesting organic fertilizers because it can reduce the use of reactive N in agriculture [20], and easily be decomposed in rice growing environment (hot humid climate and moist soil). Traditionally, *Sesbania rostrata* and *Crotalaria juncea* were used as pre-rice green manure for rice crop in Asia and Africa. This can help harvest the benefits and recycle nutrients for the rice crop. It was found that reducing energy consumption and greenhouse gas emissions require consideration of rice yields. Therefore, the purpose of this research is to explore effective ways to reduce energy and GHG emissions while maximizing the benefits of farmers who plant Riceberry rice which is a one of popular rice varieties in Thailand due to high in antioxidants, delicious taste and aroma. Most importantly, the Rice was discovered by Thai researchers. Therefore, the results of this study are novel and will benefit policy makers, researchers and farmers.

2. Material and methods

2.1 Rice variety

The rice variety used in this study was Riceberry rice that was crossbred between Thai Hom Nil (black jasmine rice) and Khao Dawk Mali 105 (KDML105) by the Rice Research Center, Kasetsart University, Thailand. Physical characteristics are dark purple rice, slender seed shape and some important chemical properties: antioxidant, omega-3, and low-medium glycemic index [21].

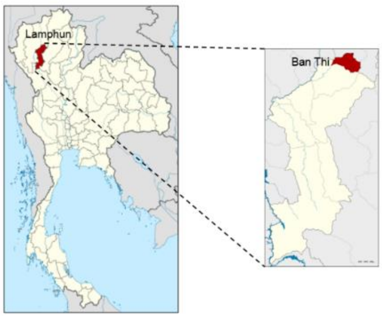

Figure 1. Location of experimental field in Ban Thi district, Lamphun, Thailand.

2.2 Site description

Field experiments were conducted in Banthi district (18°38'49.8"N, 99°04'02.9"E, 290 m above sea level), Lamphun province, Thailand (Figure 1). The Rice was planted during July 2020 to January 2021. Lamphun is located at 18° north latitude and 99° east longitude in north of Thailand. Lamphun has different 3 seasons: summer (March to April), rainy season (May to October) and winter (November to February). Winter and summer are the dry season for 6 consecutive months. During the rainy season for the next 6 months, the weather will not be as hot as in summer and not as cold as in winter. There is a moderate temperature between the two seasons. The total area of Lamphun is 4,507 km^2, of which 1,107 km^2 is agricultural area. The annual average rainfall is almost 980 mm. The highest and lowest temperatures are 38°C and 14°C. The soil of this area is clay to sandy type with a high content of total nitrogen.

2.3 Data collection

The main factors in this research were the green manure managements (no green manure; Control, *Crotalaria juncea*; *Crotalaria* and *Sesbania rostrata*; *Sesbania*). Each green manure factor was separate into 2 water managements of continuous flooding; CF, and alternative wetting and drying; AWD. Combination treatments were Control-CF, Control-AWD, *Crotalaria*-CF, *Crotalaria*-AWD, *Sesbania*-CF and *Sesbania*-AWD. All treatments were performed in triplication. Each field study was 5 m × 5 m (0.0025 ha) separated by bunds (Figure. 2). Raw data was collected in two phases. First, inputs were collected from materials used in each activity of organic Riceberry production and then separated into 5 sources of inputs (fuel, machinery, labor, fertilizer, and seed). Second, outputs were collected from paddy and straw yields after harvesting process.

Figure 2. Experimental field in Ban Thi district, Lamphun, Thailand.

Table 1. Energy equivalent of inputs and outputs**.**

Particulars	Unit	Energy equivalent (MJ/unit)	References
Inputs			
Human labor	h	1.96	[16], [22], [23]
Fuel			
- Diesel	L	43.30	[18], [22], [24]
- Gasoline	L	39.70	[18], [22], [24]
Machinery			
- Tractor	h	62.70	[22], [25], [26]
- Weed cutter	h	0.82	[22], [25], [26]
- Pumping	h	6.80	[22], [25], [26]
- Power sprayer	h	0.86	[22], [25], [26]
- Harvesting machine	h	709.96	[22], [25], [26]
Fertilizer			
- Bio-ferment fertilizer	L	0.41	[18], [22], [27]
Seed			
- Green manure seed	kg	6.10	[27]
- Rice seed	kg	14.57	[18] , [22]
Outputs			
Paddy	kg	14.57	[18] , [22]
Straw	kg	12.50	[22], [26], [28]

2.4 Crop management

Soil preparation for this study started from seeding of green manure in each experimental plot by 31.25 kg/ha. Once the green manures were 45 days, plowed the trunk and left for 3 days for fermentation. After that, the experimental plots were flooded and harrowed to break the soil colds to the smaller mass. To achieve the fermentation process, the fields were flooded and leveled water as well as left for 10 days. For the rice seedling, plowed the soil clods and residue to make them smaller. The 25-day nursery rice was used to transplant by manual transplanting for all experimental plots. To manage the water, the plots that used continuous flooding management (CF) were filled with 10 cm high water level from soil surface. AWD plots were left flooded (10 cm high from soil surface) after 45 days of transplanting. Then, AWD plots were kept wet for 15days and dry for 15 days. All experimental fields (CF and AWD) will be drained 10 days before harvest. There was herbicide spraying for all experimental plots, and twice applications were applied with bio-ferment juice by using power sprayer. For the first application, it was made at 15 days after transplanting and the second application was made at 60 days after transplanting. Finally, the rice was harvested at 120 days after transplanting [22].

2.5 Energy equivalent and Energy analysis

Energy equivalent shown in Table 1 was used to calculate the energy input and energy output. Equivalents of the machines, for those commonly used in Lamphun, Thailand, were calculated based on hourly conservation factor by [25-26]. Raw data were collected from the experimental field, and then transformed into energy input and expressed in MJ/ha. Sunlight is not considered as an energy input in this research. The energy output was obtained by multiplying paddy and straw yields for each treatment by their energy equivalents. The energy use efficiency gives an indication of how much energy was produced per unit of energy utilized, and it was determined as the ratio of energy output to energy input, Equation (1). The net energy is defined as the difference between the gross output energy produced and the total input energy for obtaining it. It was obtained by subtracting energy input from energy output, Equation (2). The specific energy gives an indication of how much energy was utilized to produce a unit of crop yield, and it was determined as the ratio of energy input to the crop yield, Equation (3). Statistical calculation was performed using SPSS 17 software (IBM SPSS Statistics Inc., Chicago., USA). Data in tables are presented as mean ± standard error of three replicates.

Energy use efficiency = (Energy output) / (Energy input) (1)
Net energy = (Energy output) - (Energy input) (2)
Specific energy = (Energy input) / (Paddy yield) (3)

2.6 Greenhouse gas emission and intensity

GHG emissions of raw material inputs were in principle calculated with emission factors in 2006 IPCC guidelines for national greenhouse gas inventories [29]. The GHG emission factors of direct energy and raw material are shown in Table 2. The GHG emissions of raw material input refer to the overall amount of GHG emission impacts of raw material production throughout the process including the emissions from mining, extraction (solid, liquid, or gas forms, e.g. steel, oil, natural gas), wastes during extraction activities and pre-treatment of raw materials and manufacturing [30]. The GHG emissions of raw material input are expressed as the following equation:

$$GHG_R = \sum A_i \cdot EF_i \quad (4)$$

Where GHG_R: The total GHG emission of raw material input ($kgCO_{2\text{-}eq}$), A_i: The amount of raw material input (i) (unit, such as kg, litter, etc.), EF_i: The GHG emission factor of raw material input (i) ($kgCO_{2\text{-}eq}$/Unit).

Table 2. Greenhouse gas emission factors of raw material inputs.

Input	Emission factor	Unit	Source of data
Gasoline (production)	0.7069	$kgCO_{2\text{-}eq}$/kg	[31]
Gasoline (combustion)	2.1896	$kgCO_{2\text{-}eq}$/L	[31]
Diesel (production)	0.3282	$kgCO_{2\text{-}eq}$/kg	[31]
Diesel (combustion)	2.7446	$kgCO_{2\text{-}eq}$/L	[31]
Rice seed	0.25	$kgCO_{2\text{-}eq}$/kg	[31]
Green manure seed	0.84	$kgCO_{2\text{-}eq}$/kg	[27]
Bio-ferment juice	0.2552	$kgCO_{2\text{-}eq}$/kg	[27]

Methane (CH_4) emissions are from field emissions of rice production. Anaerobic decomposition of organic material in flooded rice fields produces methane (CH_4), which escapes to the atmosphere primarily by transport through the rice plants. The annual amount of CH_4 emitted from a given area of rice is a function of the number and duration of crops grown, water regimes before and during the cultivation period, and organic and inorganic soil amendments. Soil type, temperature, and rice cultivar also affect CH_4 emissions. The methane emissions from rice production were calculated from equations (5) and (6), based on method IPCC tier 1, which users annual harvested area and area-based seasonally integrated emission factor. The basic equation is as follows [29]:

$$CH_{4\,Rice} = EF_i \times t \times A \quad (5)$$
$$EF_i = EF_c \times SF_w \times SF_p \times SF_o \quad (6)$$

Where $CH_{4\,Rice}$: the annual methane emissions from rice cultivation (kg CH_4/yr), EF_i: the adjusted daily emission factor for a particular harvested area (kg CH_4/ha/day), t: the cultivation period of rice (day), A: the annual harvested area of rice (ha/yr), EF_c: the baseline emission factor for continuously flooded fields without organic amendments (CH_4/ha/day), SF_w: the scaling factor to account for the differences in water regime during the cultivation period (dimensionless), SF_p: the scaling factor to account for the differences in water regime in the pre-season before the cultivation period (dimensionless), SF_o: the scaling factor that should vary for both types of the amount of organic amendment applied (dimensionless).

In this study, EF_i was calculated to be 0.63 kg CH_4/ha/day. SF_o was calculated to be 1.96 (dimensionless). Standard values were suggested by IPCC (2006) [29] for EF_c, SF_w and SF_p were adopted by considering the regions of warm temperate climate and for irrigated and continuously flooded water regimes, were 1.74 kg CH_4/ha/day, 0.27 (dimensionless) and 0.68(dimensionless), respectively. t was 100 days for CF and 70 days for AWD.

Direct and indirect Nitrous oxide (N_2O) emissions are from managed soils. The emissions of N_2O that result from anthropogenic N inputs or N mineralization occur through both a direct pathway (i.e., directly from the soils to which the N is added/released), and through two indirect pathways: (i) following volatilization of NH_3 and NO_x from managed soils and from fossil fuel combustion and biomass burning, and the subsequent redisposition of these gases and their products NH_4+ and NO_3- to soils and waters; and (ii) after leaching and runoff of N, mainly as NO_3-, from managed soils. The direct and indirect N_2O emissions can be estimated using the following equation (7) and (8), respectively, according to IPCC tier 1 [29].

$$N_2O_{Direct} = [\sum_i (F_{SN} + F_{ON}) EF_{1i} + (F_{CR} + F_{SOM}) EF_1] \times 44/28 \quad (7)$$

$$N_2O_{Indirect} = N_2O_{(ATD)} + N_2O_{(L)} \quad (8)$$

Indirect N_2O emissions of rice cultivation occurs from two field processes: (i) volatilization and (ii) leaching and runoff stages during addition of N to rice fields. The N_2O emissions from atmospheric deposition of N volatilized ($N_2O_{(ATD)}$) from managed soil are estimated using equation (9). The N_2O emissions from leaching and runoff ($N_2O_{(L)}$) of rice cultivation in regions where leaching and runoff occurs are estimated using equation (10).

$$N_2O_{(ATD)} = \left[\left(\{F_{SN} \times Frac_{GASF}\} + \{\{F_{ON} + F_{PRP}\} \times Frac_{GASM}\}\right) \times EF_4\right] \times 44/28 \quad (9)$$

$$N_2O_{(L)} = \left[(F_{SN} + F_{ON} + F_{PRP} + F_{CR} + F_{SOM}) \times Frac_{LEACH-(H)} \times EF_5\right] \times 44/28 \quad (10)$$

Where N_2O_{Direct}: the annual direct N_2O emissions from N applied to soil (kg N_2O/yr), F_{SN}: the annual amount of synthetic nitrogen fertilizers applied to soils (kg N/yr), F_{ON}: the annual amount of animal manure, compost, sewage sludge and other organic N additions applied to soils (kg N/yr), F_{CR}: the annual amount of N in crop residues returned to soils (kg N/yr), F_{SOM}: the annual amount of N in mineral soils that is mineralized, in association with loss of soil C from soil organic matter as a result of changes to land use or management (kg N/yr), EF_1: the emission factor for N_2O emissions from N inputs (kg N_2O–N/kg N input), EF_{1i}: the emission factor developed for N_2O emissions from synthetic fertilizer and organic N application under conditions i (kg N_2O–N/kg N input), $N_2O_{(ATD)}$: the annual amount of N_2O produced from the atmospheric deposition of N volatilized from managed soils (kg N_2O/yr), $FRAC_{GASF}$: the fraction of synthetic fertilizer N that volatilizes as NH_3 and NO_x (kg N volatilized/kg of N applied), F_{PRP}: the annual amount of urine and dung N deposited by grazing animals on pasture, range and paddock (kg N/yr), $FRAC_{GASM}$: the fraction of applied organic N fertilizer material (F_{ON}) and of urine and dung N deposited by grazing (F_{PRP}) that volatilizes as NH_3 and NO_x (kg N volatilized/kg of N applied or deposited), EF_4: the emission factor for N_2O emissions from the atmospheric deposition of N on soils and water surfaces [kg N–N_2O/(kg NH_3–N + NO_x–N volatilized)], $N_2O_{(L)}$: the annual amount of N_2O produced from leaching and runoff of N additions to managed soils in regions where leaching/runoff occurs (kg N_2O/yr), $FRAC_{LEACH-(H)}$: the fraction of all N additions to managed soils that is lost through leaching and runoff (kg N/kg of N addition), EF_5: the emission factor for N_2O emissions from N leaching and runoff ((kg N_2O–N/kg N leached and runoff).

In this study, standard value suggested by IPCC (2006) [29] for EF_1, EF_{1i} and EF_4 were 0.01, EF_5 was 0.0075, $FRAC_{GASF}$ was 0.1, $FRAC_{GASM}$ was 0.2, $FRAC_{LEACH-(H)}$ was 0.3. The amount of F_{ON} was calculated to be 0 in Control treatment, 84.38 in *Crotalaria* treatment and 100 in *Sesbania* treatment. The amount of F_{CR} and F_{PRP} were calculated to be 12.18 and 0.064, respectively. Therefore, F_{SN} and F_{SOM} were not considered.

Global warming potential on a 100-year horizon IPCC AR5 [32] values was used to assess the comprehensive greenhouse effect by converting emission to CO_2 equivalents (kgCO_{2-eq}/ha) as follows:

$$GHG\ emission_{Total} = GHG_R + 265N_2O_{Direct} + 265N_2O_{Indirect} + 28CH_{4\ Rice} \quad (11)$$

Greenhouse gas emission intensity (GHGI) was calculated as the CO_2 equivalent per unit of rice yield and is used as an index to evaluate the yield-scaled Global Warming Potential (GWP) and relate environmental effects to crop output [33]. This was calculated using Equation (12):

$$GHGI = GHG\ emission_{Total} / Paddy\ yield \quad (12)$$

Where $GHGI$: the total GHG emission per unit of yield (kgCO_{2-eq}/kg$_{paddy\ yield}$), $TGHG$: the total greenhouse gas emission (kgCO_{2-eq}/ha).

3. Results and Discussion

3.1 Energy input, Energy output and Energy analysis

Total energy input of organic Riceberry production ranged between 11,987.74 and 14,563.79 MJ/ha (Table 3). Energy input was highest for *Sesbania*-CF 14,563.79 MJ/ha followed by *Crotalaria*-CF 14,404.9 MJ/ha, Control-CF 13,671.9MJ/ha, *Sesbania*-AWD 12,879.54 MJ/ha, *Crotalaria*-AWD 12,720.73 MJ/ha and Control-AWD 11,987.74 MJ/ha. The average percentage of energy input for all treatments came from fuel, machinery, seed, labor and bio-ferment fertilizer, which were 79.07, 13.99, 4.36, 1.81 and 0.77%, respectively. From table 3, all energy inputs in this study were similar to that reported in Missouri, USA and ranged from 10 - 50 GJ/ha [1]. However, the energy input reported in previous studies, which were in Jhapa, Nepal 22,987 MJ/ha [34], Meerut (UP), India ranged from 25,724 to 38,879 MJ/ha [17] and 51,586 MJ/ha in Guilan, Iran [35] was higher than energy input values obtained in this study. Lower energy use has been reported for rice production in Meghalaya, India (9,162 MJ/ha) [36]. Direct energy includes energy from fuel and human labor, shared 79.43 to 82.58% (9,691.31 to 11,852.17 MJ/ha) of energy input (Table 4), whereas indirect energy includes energy from machinery, bio-ferment fertilizer and seed, shared 17.42 to 20.57% (2,296.43 to 2,711.62 MJ/ha) of energy input. Renewable energy includes energy from human labor and seed, shared 4.92 to 7.14% (672.75 to 919.48 MJ/ha) of energy input, while non-renewable energy includes energy from fuel, machinery and bio-ferment fertilizer, shared 92.86 to 95.08% (11,290.49 to 13,668.81 MJ/ha) of energy input. This is similar to the findings of Elsoragaby et al. [9], which can be attributed to the share of direct and indirect energy in transplanting method of rice production in Malaysia which were 81% and 19% of energy input, respectively. The results suggested that organic Riceberry production in Lamphun, Thailand has more energy intensive due to lower input of fuel and fertilizer than that in many other areas. The energy input of the green manure-managed treatments (*Crotalaria* and *Sesbania*) was higher than that of the control treatments (Control) since more energy input of green manure management in rice production was from machinery, fuel, labor and seed than Control. These results were in agreement with Eskandari and Attar [15], who reported that energy input of different management was significant. Differences in energy input among the two green manure managements (*Crotalaria*-CF and *Sesbania*-CF, *Crotalaria*-AWD and *Sesbania*-AWD) caused *Sesbania* need extra energy use in machinery, fuel and labor to reduce sizing of *Sesbania* branches and trunk before soil preparation [22]. By comparing treatments with two water managements (Control-CF and Control-AWD, *Crotalaria* -CF and *Crotalaria*

-AWD, *Sesbania*-CF and *Sesbania*-AWD), it was found that the energy input in CF was higher than AWD for all green manure managements. The main reason was the number of irrigation times in AWD was less than CF as a result of less energy inputs from machinery, fuel and labor. This result is in agreement with previous studies which have shown that AWD cloud be used as a water-saving technique for rice production [37].

Table 3 shows the relationship between energy output and treatments. The energy output ranges from 84,648.08 to 121,003.04 MJ/ha, while the paddy yield obtainable was 2,881.77 to 4,272.00 kg/ha. This is similar to the finding of Chaudhary et al. (2017), which can be attributed to the total energy output of rice production ranged from 115,176 to 155,033 MJ/ha in India [17]. In our study, paddy yield was similar to previous studies in Thailand (e.g. 2,946 kg/ha [38], 3,670 kg/ha [39], 3,860 kg/ha [7]). Paddy and straw yields were used to calculate the energy output. It was noted that high-productivity treatments also had high energy output. The energy output of the green manure-managed treatments was greater than C. Since, the green manure has the potential to supply the large amount of nitrogen required for the rice plant [40], which is why paddy and straw yields are also increased. Comparing treatments with both green manure managements, it was found that *Sesbania* had significantly higher energy output than *Crotalaria* because *Sesbania* unleashed more nutrient contents needed by rice plants for growth than that of *Crotalaria* [22]. In the same way, when comparing treatments with both water managements (CF and AWD), AWD treatments had greater energy outputs than CF treatments, which was connected with higher yields. These results are in agreement with previous studies which have shown that water management had a significant impact on productivity [41]. *Sesbania*-AWD treatments had the highest energy output.

Energy use efficiency (EUE) and Net energy (NE) are shown in Table 5. The EUE is one of the best indexes for input-output energy analysis in crop production to indicate the efficient use of energy. With respect to the data analysis, EUE in this study varied from 6.19 to 9.40, which averaged about 7.58 times the amount of energy invested. This result is in agreement with previous studies which have shown that the EUE in Cuttask, India of 6.22 to 7.64 [42] and Nigeria of 6.58 to 7.62 [43], but higher than that previously reported by AghaAlikhani et al. [44] of 1.72 due to higher energy output in our study. Notably, net energy (NE) showed the same trend (Table 5). NE in this study varied from 70,976.09 to 108,123.92 MJ/ha, which was higher than the result of 82,733 to 93,226 MJ/ha reported by Kosemani and Bamgboy [43]. Notably, the EUE and NE of the green manure-managed treatments was greater than C. This was due to green manure managements slightly increase energy input, but largely increase energy output. Among two green manure managements, *Sesbania* recorded significantly higher EUE and NE than *Crotalaria*, mainly since *Sesbania* needed more energy input, but can increase greater energy output than that of *Crotalaria*. In the same way, EUE and NE in all green manure management treatments combined with AWD were higher than CF (Table 5), mainly caused by AWD which needed less energy input but produced more energy output than CF. The new findings from our study suggest that the use of *Sesbania* resulted in the highest EUE and NE, while there were non-significant difference in *Crotalaria* and Control. In the same way, AWD resulted in the highest EUE compared to CF. On the other hand, the SE showed an opposite trend (Table 5). SE is an index indicating the energy use to produce one unit of the product [45]. The highest SE occurred in Control-CF 4.76 $MJ/kg_{paddy\ yield}$ and the lowest was observed in *Sesbania*-AWD 3.02 $MJ/kg_{paddy\ yield}$. In other words, one kilogram of paddy was produced by using 3.02 – 4.76 MJ of energy input from five energy sources considered in this work. The SE obtained from this study corresponds to that reported in Hubei, China by Yuan and Peng [28], in the range of 2.82 to 4.25 $MJ/kg_{paddy\ yield}$. In addition, the SE reported in Missouri, USA, was ranged from 1.5 to 3.1 $MJ/kg_{paddy\ yield}$ for farm that utilized organic rice production [1]. The lower SE indicated more paddy yields to the energy use of rice production. Compared to green manure management treatments, SE of *Crotalaria*-CF and *Sesbania*-CF were lower than Control-CF. In the same way, SE of *Crotalaria*-AWD and *Sesbania*-AWD were lower than Control-AWD due mainly to less paddy yield in Control. Comparing treatments with both green manure managements, it was found that *Sesbania* had a lower SE than *Crotalaria* since *Sesbania* produced more paddy yield than that of *Crotalaria* which had lower SE. Similarly, when compared CF and AWD water management treatments, AWD showed lower SE than that of CF. Differences in SE among the two water management treatments helped AWD increase more paddy yield while needed less energy use than those of CF. The new findings from our study suggest that the use of *Sesbania* resulted in the lowest SE, while there were non-significant difference in *Crotalaria* and C. In the same way, AWD resulted in the lowest SE compared to CF.

3.2 Greenhouse gas emission and intensity

The conversion factors shown in Table 2 were applied to calculate the material inputs GHG emissions. The equation 4 - 11 were applied to calculate the GHG emissions. The results of total GHG emissions in different managements ranged from 2,045.75 to 3,345.66 $kgCO_{2-eq}/ha$. The results from Table 6 showed that total GHG emission falls within the range of farmer traditional practices 3,027 $kgCO_{2-eq}/ha$ in Phichit, Thailand reported by Arunrat et al. [46] and 2,181 $kgCO_{2-eq}/ha$ in Chiang Mai, Thailand reported by Yodkhum et al. [39]. The main contributor for all treatments was linked to the CH_4 field emission (54.27%), mainly due to field operations. This was followed by GHG emission from material inputs (30.59%), and the N_2O field emission (15.14%). Similar results were reported by Nunes et al. [47], who reported that the shared percentage of total GHG emission was from CH_4 61%, CO_2 28% and N_2O 11% of rice production in Brazil. In this research, the total GHG emission in green manure managements was higher than in C since green manure managements need much more GHG material input than C treatment. Similar result for total GHG emission in *Sesbania* was slightly higher than *Crotalaria* since *Sesbania* needs more GHG material inputs for reduction of stem. While total GHG emission in AWD water management was lower than CF water management causing CH_4 from field emission in AWD lower than CF treatments by water drainage in experimental field. This result was in agreement with previous studies showing that AWD resulted in ≤ 12 % reductions in global warming potential [48]. Early-season plus midseason drainage can reduce global warming potential by 66% compared to CF in northern Vietnam reported by Tariq et al. [49].

Greenhouse gas emission intensity (GHGI) presented in Table 6 ranged from 0.62 to 0.99 $kgCO_{2-eq}/kg_{paddy\ yield}$. In our study, GHGI was similar to previous studies: Yodkhum et al. of 0.64 $kgCO_{2-eq}/kg_{paddy\ yield}$ in Chiang Mai province of Thailand [39], Anurat et al. of 0.82 $kgCO_{2-eq}/kg_{paddy\ yield}$ in Phichit province of Thailand [7]. GHGI in *Sesbania* was lower than *Crotalaria* and Control (Table 6) since *Sesbania* clearly gave much greater yield closely to total GHG emission than *Crotalaria* and Control. In the same way, GHGI in AWD was significantly lower than CF in Control, *Crotalaria* and *Sesbania* treatments (Table 6). The main reason was that AWD presented was lower than total GHG emission (Table 6) and had higher yield than CF (Table 3). In summary, *Sesbania*-AWD presented lowest GHGI which would be conducive to suitable practice of organic Riceberry production.

Finally, results demonstrated that energy analysis and GHG intensity in *Sesbania rostrata* as green manure in the combination with AWD water management was the most suitable method for organic Riceberry production. *Sesbania*-AWD had the highest energy use efficiency (EUE), the highest net energy (NE), the lowest specific energy (SE) and lowest greenhouse gas intensity (GHGI), which were 9.40, 108,123.92 MJ/ha, 3.02 MJ/kg$_{paddy\ yield}$ and 0.62 kgCO_{2-eq}/kg$_{paddy\ yield}$, respectively. Energy input of *Sesbania*-AWD treatment was 12,879.54 MJ/ha. The proportions of energy input were from 77.48% fuel, 14.58% machinery, 5.02% seed, 2.12% human labor and 0.80% bio-ferment fertilizer. Energy output of *Sesbania*-AWD treatment was 121,003.46 MJ/ha. The proportions of energy output were from 51.44% paddy yield and 48.56% straw yield. GHG emission of *Sesbania*-AWD treatment was 2,664.86 kgCO_{2-eq}/ha, and the proportions of GHG emission were the CH_4 field emission (46.16%), followed by GHG emission from material inputs (28.86%) and the N_2O field emission (24.98%).

Table 3. Energy input and Energy output in organic Riceberry production.

Sources of energy	**Energy input/output of treatments (MJ/ha)**					
	Control		***Crotalaria***		***Sesbania***	
	CF	**AWD**	**CF**	**AWD**	**CF**	**AWD**
Energy input						
Human labor	217.44	241.94	224.54	249.04	249.04	273.54
Fuel	11,073.13	9,449.38	11,479.06	9,855.31	11,603.13	9,979.38
Machinery	1,823.09	1,738.09	1,952.41	1,867.41	1,962.66	1,877.66
Bio-ferment fertilizer	103.02	103.02	103.02	103.02	103.02	103.02
Seed	455.31	455.31	645.94	645.94	645.94	645.94
Total energy input	13,671.99	11,987.74	14,404.98	12,720.73	14,563.79	12,879.54
Energy output						
Paddy yield	41,987.40 ± 3,384[c]	43,917.32 ± 3,429[c]	48,030.01 ± 3,169[bc]	51,436.35 ± 2,939[b]	59,740.34 ± 3,124[a]	62,243.04 ± 2,125[a]
Straw yield	42,660.68 ± 2,769[c]	43,149.22 ± 2,805[c]	46,571.09 ± 2,593[bc]	50,297.92 ± 2,404[b]	57,663.54 ±2,556[a]	58,760.42 ± 1,739[a]
Total energy output	84,648.08 ± 6,152[c]	87,066.54 ± 6,234[c]	94,601.10 ± 5,762[bc]	101,734.27 ± 5,343[b]	117,403.88 ± 5,680[a]	121,003.46 ± 3,864[a]

Table 4. Energy consumption structure in organic Riceberry production**.**

Forms of energy (MJ/ha)	**Control**		***Crotalaria***		***Sesbania***	
	CF	**AWD**	**CF**	**AWD**	**CF**	**AWD**
Direct energy	11,290.56	9,691.31	11,703.61	10,104.36	11,852.17	10,252.92
Indirect energy	2,381.43	2,296.43	2,701.37	2,616.37	2,711.62	2,626.62
Renewable energy	672.75	697.25	870.48	894.98	894.98	919.48
Non-renewable energy	12,999.24	11,290.49	13,534.50	11,825.75	13,668.81	11,960.06

Table 5. Energy analysis in organic Riceberry production.

Energy analysis	**Control**		***Crotalaria***		***Sesbania***	
	CF	**AWD**	**CF**	**AWD**	**CF**	**AWD**
Energy use efficiency (dimensionless)	6.19 ± 0.45[c]	7.26 ±0.52[bc]	6.57 ± 0.40[c]	8.00 ± 0.42[b]	8.06 ± 0.39[b]	9.40 ± 0.30[a]
Net energy (MJ/ha)	70,976.0 ± 6,152[c]	75,078.8 ± 6,234[c]	80,196.1 ± 5,762[bc]	89,013.5 ± 5,343[b]	102,840.09 ± 5,680[a]	108,123.92 ± 3,864[a]
Specific energy (MJ/kg$_{paddy\ yield}$)	4.76 ± 0.39[a]	3.99 ± 0.31[b]	4.38 ±0.29[ab]	3.61 ± 0.21[b]	3.56 ± 0.19[b]	3.02 ± 0.10[c]

Table 6. GHG emission and GHGI in organic Riceberry production.

GHG Emission	**Control**		***Crotalaria***		***Sesbania***	
	CF	**AWD**	**CF**	**AWD**	**CF**	**AWD**
GHG emission from material inputs (kgCO_{2-eq}/ha)	858.55	743.32	913.61	798.38	922.66	769.02
GHG emission from CH_4 field emission (kgCO_{2-eq}/ha)	1,757.19	1,230.04	1,757.19	1,230.04	1,757.19	1,230.04
GHG emission from N_2O field emission (kgCO_{2-eq}/ha)	72.39	72.39	573.08	573.08	665.80	665.80
Total GHG emission (kgCO_{2-eq}/ha)	2,688.14	2,045.75	3,243.89	2,601.50	3,345.66	2,664.86
GHGI (kgCO_{2-eq}/kg$_{paddy\ yield}$)	0.94 ± 0.076[ab]	0.68 ± 0.053[c]	0.99 ± 0.065[ab]	0.74 ± 0.042[bc]	0.82 ± 0.043[b]	0.62 ± 0.021[c]

4. Conclusion

The aim of this research was to assess the energy use pattern and greenhouse gas emission of organic r Riceberry production, located in Lamphun province of Thailand. Our findings showed that using *Sesbania rostrata* as green manure in combination with Alternative wetting and drying water management (*Sesbania*-AWD) was the most suitable method for organic Riceberry production, with value of energy use efficiency (EUE), net energy (NE), specific energy (SE), GHG emission and GHG intensity of 9.40, 108,123.92 MJ/ha, 3.02 MJ/kg $_{paddy\ yield}$, 2,615.98 $kgCO_{2-eq}$/ha and 0.62 $kgCO_{2-eq}/kg_{paddy\ yield}$, respectively.

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