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RESEARCH ARTICLE

Energy and environmental impact analysis of rice cultivation and straw management in northern Thailand

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Abstract
Rice cultivation and energy use for rice production can produce the environmental impacts, especially related to greenhouse gas (GHG) emissions. Also, rice straw open burning by farmers generally practiced after harvesting stage in Thailand for removing the residues in the rice field is associated with emissions of air pollutants, especially particulate matter formation that affects human health and global climate. This study assessed the environmental burdens, consisting of GHG emissions, energy use, and particulate matter formation (PM10), from rice cultivation in Thailand by life cycle assessment (LCA) and compared the environmental burdens of rice straw management scenarios: open burning, incorporation into soil, and direct combustion for electricity generation. The data were collected from the rice production cooperative in Chiang Mai province, northern Thailand, via onsite records and face-to-face questionnaires in 2016. The environmental impacts were evaluated from cradle-to-farm gate. The results showed that the total GHG emissions were 0.64 kg CO_2-eq per kilogram of paddy rice, the total energy use was 1.80 MJ per kilogram of paddy rice and the PM10 emissions were 0.42 g PM10-eq per kilogram of paddy rice. The results of rice straw management scenarios showed that rice straw open burning had the highest GHG and PM10 emissions. However, rice straw utilization by incorporation into soil and direct combustion for electricity generation could reduce these impacts substantially.

Keywords Life cycle assessment (LCA) · Rice cultivation · Rice straw management · Thailand

Introduction

Rice (*Oryza sativa* L.) is a hugely important food crop in the world, especially Asia, Latin America, and Africa (Alikhani et al. 2013). In Thailand, rice is a staple crop for domestic consumption as well as for commerce to meet the demand worldwide. Thailand is one of the largest rice-producing countries in the world. In 2015, the total rice cultivation area of Thailand was approximately 12.1 mha. Also, Thailand was the world's second largest rice exporter, the total amount of rice export being about 7.81 Mt (DFT 2015). It has the largest export product value of Thailand, contributing approximately 17.3% of the total product value of worldwide export (NFI 2015).

The prediction of total rice cultivation area and total paddy rice product of Thailand in 2016 was approximately 10 mha and 23 Mt, respectively (OAE 2015). Nevertheless, rice cultivation does not only generate affluence and employment for the cultivating regions, but also causes environmental impacts from the production practices (Fusi et al. 2014), especially greenhouse gas (GHG) emissions such as methane (CH_4) and nitrous oxide (N_2O) that are released during cultivation (Brodt et al. 2014), which is also associated with large energy and water consumption, and land use for rice cultivation and post-harvest stage (Eskandari and Attar 2015). Furthermore, there is also deposition of toxic substances such as heavy metals from inorganic fertilizers and pesticide application in cultivation stage (Garcia et al. 1996). Moreover, there is inappropriate rice straw management such as open burning after harvesting stage

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which is a general practice to remove the rice straw in many countries including Thailand. The farmers burn the rice straw in the fields for removal and weed control as also land preparation before the next cropping season. Rice straw open burning can produce several atmospheric emissions, especially carbon dioxide (CO_2) and particulate matter (PM) (Sanchis et al. 2014), that have an adverse effect on the environment.

To deal with these problems, this study has been conducted to find the appropriate practice of rice cultivation and rice straw management for rice production to mitigate the associated environmental impacts. The objective of this study was to evaluate the environmental impacts of rice cultivation and rice straw management practices, consisting of open burning, incorporation into soil, and utilization of biomass for electricity generation as well as to compare the environmental impacts from the various rice straw management scenarios. The environmental burdens included were GHG emissions, energy use, and particulate matter formation.

Methodology

Goal and scope definition

The goal of this study was to estimate the environmental impacts from rice cultivation and compare the environmental impacts of various rice straw management approaches by using life cycle assessment (LCA). The environmental impact categories were considered for assessment based on the significance of current problems being discussed in the country and region related to rice cultivation and straw management including those from GHG emissions, energy use, and particulate matter formation (leading to large-scale problems with haze). The system boundaries of this study are “cradle to farm gate” for paddy rice production, consisting of land preparation, rice planting, farming, and harvesting stage. In addition, the rice straw management scenarios including open burning, incorporation into soil, and utilization for biomass to electricity generation were also studied. The system boundary of this study is illustrated in Fig. 1. The first part of the study only considered emissions from paddy rice cultivation and the second part from straw management after the harvesting stage. The functional units (FU) of this study were (1) 1 kg of paddy rice in rice cultivation stage and (2) 1 t of rice straw (dry basis) in rice straw management stage for environmental impact comparison.

Study area and rice cultivation

The data for the study were collected from the Keelak Rice Production Cooperative (KRPC), Maerim district, Chiang Mai province, northern Thailand, by onsite records and face-to-face questionnaires in 2016. The production capacity of

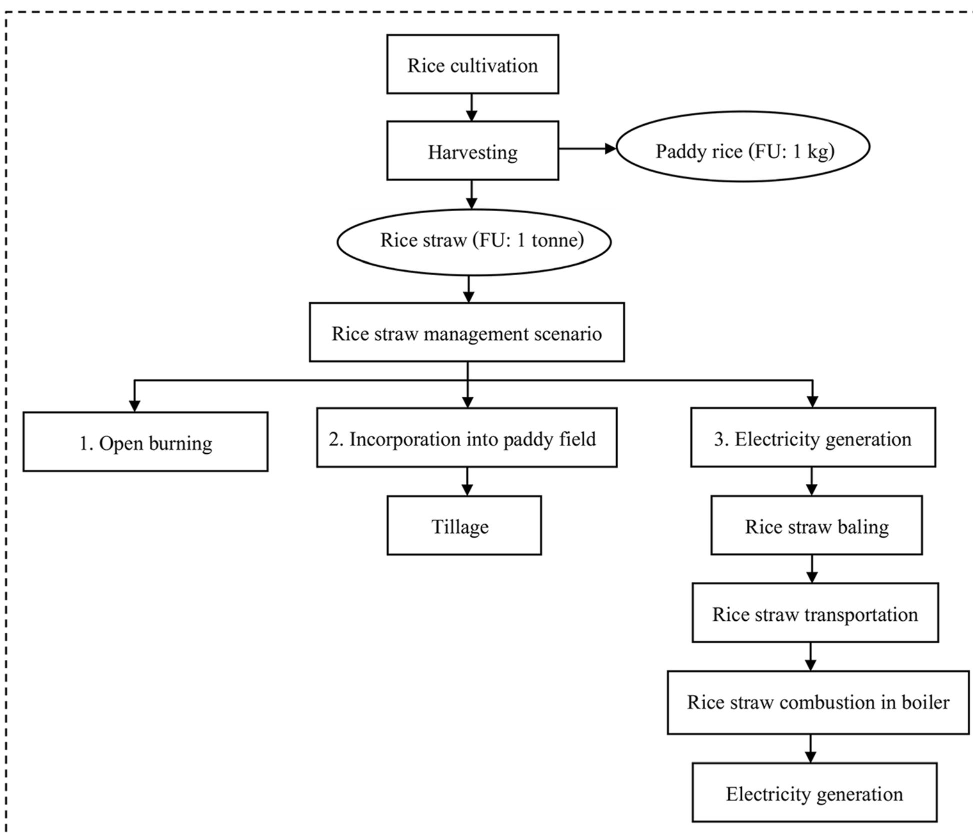


Fig. 1 System boundary of paddy cultivation and straw management

KRPC is approximately 100 t per year. The data were collected from 21 farmers. The rice variety is Khao Dawk Mali 105 (KDML 105) which is fragrant jasmine rice. It is planted and cultivated during the rainy season under flood irrigation for 120 days and harvested in the beginning of winter. Therefore, it is a rain-fed crop. The crop season starts in the middle of July with the rice seedling nursery and then the rice is planted by manual seedling transplantation practice in the first part of August. Finally, the paddy rice is harvested in the end of November by a 260-hp combined harvester. The soil tillage operations before cultivation stage consist of the first time rough plowing for incorporating biomass, such as rice straw and grass into the soil, and plowing in regular furrows for the second time by 47-hp tractor to loosen the soil. The average paddy yields of KDML rice are 3750 kg ha^{-1}.

The amount of biomass litter from rice stubble and rice root is 0.57 times of average paddy rice yields (Sukpearm and Ngerntongkhum 2012). It is incorporated into soil by tillage before the cultivation period. The amount of rice straw (top) was calculated from average paddy rice yields and straw to grain ratio (SGR). In this study, the SGR was estimated as 0.6 following Delivand et al. (2011). The rice straw was evaluated in order to compare environmental impacts of rice straw management scenarios. The material inputs of rice cultivation stage are shown in Table 1.

The environmental impacts from paddy cultivation were allocated to the paddy and straw via economic values for straw utilization including incorporation into soil and utilization for biomass. In the case of rice straw open burning, the environmental impacts were not allocated to the rice straw. The allocation factor for rice straw was calculated as defined in Eq. (1) (Silalertruksa and Gheewala 2013).

$$AF_{straw} = \frac{SGR \times P_{straw}}{P_{paddy} + SGR \times P_{straw}} \quad (1)$$

where SGR is straw to grain ratio which is 0.6, P_{straw} is the straw price which is 3.86 US$/t, P_{paddy} is the paddy rice price which is 308.57 US$/t. The price of paddy rice and rice straw were referred from the KRPC. Thus, the allocation factor of rice straw worked out to 0.007.

Rice straw management

In this study, the environmental impacts of rice straw management after the harvesting stage were estimated by scenario specification consisting of open burning, incorporation into soil, and electricity generation.

Rice straw open burning

Rice straw open burning can have considerable amounts of atmospheric emissions. The main emissions are carbon dioxide (CO_2) and particulate matter formation; also other emissions occur such as carbon monoxide (CO), methane (CH_4), nitrogen oxides (NO_X), sulfur oxides (SO_X), and non-methane hydrocarbons (NMHC) (Sanchis et al. 2014). Generally, in Thailand, the farmers manage rice straw after harvesting stage by this practice. In this study, atmospheric emissions were considered to include GHG and particulate matter emissions which are defined as PM10. For GHG emissions, the factors from rice straw open burning were estimated for gases such as CO_2, CH_4, and N_2O. Rice straw open burning emissions factors of CO_2, CH_4, and N_2O were 1460, 0.74, and 0.79 g pollutant per kilogram rice straw (dry weight), respectively (NLPSB 2013). Then, each of these gases was converted to CO_2-eq using global warming potential (GWP) values from IPCC (2007). Therefore, the GHG emissions factor of rice straw open burning was 1714 kg CO_2-eq per tonne of rice straw, dry weight. PM10 emission from rice straw open burning is concerned with other gases such as NO_2, N_2O, SO_X, NH_3, PM2.5, and PM10 (EEA 2013). These gases were converted to PM10-eq by PM10 factors according to the ReCiPe impact assessment method (Goedkoop et al. 2012). Thus, the PM10 emissions factor of a tonne of rice straw was 12.66 kg PM10-eq.

Table 1 Input inventory of rice cultivation

Rice cultivation stage	Input	Quantity	Unit
Land preparation	Herbicide	4	L ha^{-1}
	Bio-ferment juice	31	L ha^{-1}
	Gasoline	1.5	L ha^{-1}
	Diesel	26	L ha^{-1}
	Stubble and root incorporated	2138	kg ha^{-1}
Planting	Rice seed	31	kg ha^{-1}
	Fertilizer 46-0-0	3	kg ha^{-1}
Farming	Compost	62.5	kg ha^{-1}
	Fertilizer 16-20-0	31	kg ha^{-1}
	Fertilizer 13-3-21	188	kg ha^{-1}
	Pesticide	6	kg ha^{-1}
	Gasoline	7.5	L ha^{-1}
Harvesting	Diesel	26.5	L ha^{-1}

Rice straw incorporation

The rice straw comprises organic material, primary macronutrients such as N, P, and K at about 0.57, 0.14, and 1.55% per weight, respectively, and also secondary macronutrients such as Ca, Mg, and S at about 0.47, 0.25, and 0.17% per weight, respectively (LDD 2004). After harvesting by combined harvesters, the rice straw was left in the fields and then during the land preparation stage of the next crop, it was incorporated into the soil by tractor and left for approximately 14 days before the planting stage for increasing soil nutrients. Nevertheless, the rice straw incorporation contributed to CH_4 emission from the rice fields during the cultivation period. Also, the N from the rice straw incorporated into the rice fields produced N_2O emissions.

Rice straw to electricity generation

Electricity generation from rice straw consists of rice straw collection by baler machine and tractor, baling transportation, and rice straw combustion. This study defines the capacity of the biomass power plant as 10 MWe. The net electricity output to the grid is 613 kWh/t of rice straw, dry basis (Silalertruksa and Gheewala 2013). In other words, the energy output is 2207 MJ/t of rice straw, dry basis. Rice straw combustion in boiler for electricity generation produces GHG and PM10 emissions per tonne of dry rice straw at 1312 kg CO_2-eq (Shafie et al. 2013; IPCC 2007) and 1.98 kg PM10-eq (EEA 2013), respectively. The GHG emissions from rice straw combustion in boiler for electricity generation could be evaluated by using the emissions factor of each gas and the heating value of rice straw. In this study, the CO_2, CH_4, and N_2O emissions factors of rice straw combustion in boiler were 0.08384, 5.59×10^{-6}, and 9.03×10^{-6} kg per megajoule, respectively (Shafie et al. 2013). The heating value of rice straw for GHG emissions factor calculation was 15.3 MJ per kilogram of rice straw (Kargbo et al. 2010). Therefore, GHG emissions of rice straw combustion in boiler work out to 1312 kg CO_2-eq per tonne of dry rice straw.

The PM10 emissions of rice straw combustion could be estimated according to the rice straw open burning scenario, as mentioned earlier. However, emissions factors of gases such as NO_X, N_2O, and SO_X, which influenced PM10 emissions (Shafie et al. 2013), were estimated by rice straw combustion in boiler in conjunction with N_2O, NH_3, PM2.5, and PM10 emissions from biomass combustion in boiler (EEA 2013). After that, all the emissions were converted to PM10-eq. Thus, the PM10 emissions from 1 t of rice straw combustion in boiler were 1.98 kg PM10-eq (EEA 2013).

The rice straw collection process uses the small baler machine (Model Kubota HB-130) and tractor (Model Kubota L4708). The baler machine did not consume fuel as it used power from the tractor. The approximate dimensions and weight of the rice straw bale are $1.0 \times 0.45 \times 0.3$ (m) and 14 kg, respectively. Transportation distance of the rice straw bale consists of two sections: field to collection center (FC) and collection center to electricity generation plant (CE). This study assumes that FC was 10 km round-trip by a 7-t truck and CE distance was 90 km round-trip (Saramaythangkoor and Gheewala 2008) by a 16-t truck. Input inventory of rice straw management of each scenario is shown in Table 2.

Table 2 Input inventory of rice straw management scenario

Input	Rice straw management scenario		
	Open burning	Incorporation	Electricity generation
Diesel (L t^{-1} straw)		2.78	3.2
Rope (kg)			1
Transportation distance of rice straw bale (km)			10 (FC)
			90 (CE)

GHG emissions analyses

The GHG emissions were estimated according to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006). GHG emissions of rice cultivation and rice straw management were investigated including CO_2, CH_4, and N_2O and were evaluated by using GWP over a 100-year time horizon into CO_2-eq. The GWP factors of CO_2, CH_4, and N_2O are 1, 25 and 298, respectively (IPCC 2007). The GHG emissions factors of raw material inputs are shown in Table 3.

GHG emissions from field during rice cultivation stage include CH_4 and N_2O emissions which were calculated according to the 2006 IPCC Guidelines by the following Eqs. (2) to (6).

$$CH_{4\ Rice} = EF_i \times t \times A \times 10^{-6} \quad (2)$$

where $CH_{4\ Rice}$ is annual methane emissions from rice cultivation (Gg CH_4 $year^{-1}$); EF_i is adjusted daily emissions factor for a particular harvested area (kg CH_4 ha^{-1} day^{-1}), it can be calculated by Eq. (3); t is the cultivation period of rice (day) and A is annual harvested area of rice (ha $year^{-1}$). The rice cultivation period of KDML 105 rice was 120 days and the cultivation area of 1 ha was used for estimation.

$$EF_i = EF_c \times SF_w \times SF_p \times SF_o \quad (3)$$

where EF_c is baseline emissions factor for continuously flooded fields without organic amendments. This emissions factor is constant at 1.30 kg CH_4 ha^{-1} day^{-1} (IPCC 2006). SF_w is a scaling factor to account for the differences in water regime during the cultivation period, SF_p is a scaling factor to account for the differences in water regime in the pre-season before the cultivation period, and SF_o is a scaling factor that should vary for both type and amount of organic amendment applied, it can be calculated by Eq. (4).

$$SF_o = \left(1 + \textstyle\sum_i ROA_i \cdot CFOA_i\right)^{0.59} \quad (4)$$

where ROA_i is the application rate of organic amendment i, in dry weight for straw and fresh weight for others (t ha^{-1}) and $CFOA_i$ is the conversion factor for organic amendment i

Table 3 Greenhouse gas emissions factors of raw material inputs and transportation

Input	Emissions factor	Unit	Source of data
Herbicide (glyphosate)	16.0	kg CO_2-eq kg^{-1}	TGO (2016)
Pesticide	10.9	kg CO2-eq kg^{-1}	Ecoinvent (2013)
Bio-ferment juice	0.2552	kg CO_2-eq kg^{-1}	TGO (2016)
Gasoline (production)	0.7069	kg CO_2-eq kg^{-1}	TGO (2016)
Gasoline (combustion)	2.1896	kg CO_2-eq L^{-1}	TGO (2016)
Diesel (production)	0.3282	kg CO_2-eq kg^{-1}	TGO (2016)
Diesel (combustion)	2.7446	kg CO_2-eq L^{-1}	TGO (2016)
Rice seed	0.25	kg CO_2-eq kg^{-1}	TGO (2014)
Compost	0.2552	kg CO_2-eq kg^{-1}	TGO (2016)
Fertilizer 16-20-0	2.16	kg CO_2-eq kg^{-1}	Ecoinvent (2013)
Fertilizer 13-3-21	1.63	kg CO_2-eq kg^{-1}	Ecoinvent (2013)
Fertilizer 46-0-0	3.3036	kg CO_2-eq kg^{-1}	TGO (2016)
Rope	4.13	kg CO_2 kg^{-1}	TGO (2016)
Transportation by a 7-t truck	0.1402	kg CO_2 tkm^{-1}	TGO (2016)
Transportation by a 16-t truck	0.0530	kg CO_2 tkm^{-1}	TGO (2016)

(IPCC 2006). In this study, the water regime was rain-fed and deep water and non-flooded pre-season of more than 180 days, so SF_w and SF_p were 0.27 and 0.68, respectively. The N_2O emissions from rice fields consist of direct and indirect N_2O emissions. Direct N_2O emissions (kg N_2O $year^{-1}$) produced from N applied to soils can be estimated through Eq. (5).

$$N_2O_{Direct} = [(F_{SN} + F_{ON} + F_{CR}) \times 0.01] \times \frac{44}{28} \quad (5)$$

where F_{SN} is the annual amount of synthetic fertilizer N applied to soils (kg N $year^{-1}$), F_{ON} is the annual amount of organic fertilizer N addition applied to soils (kg N $year^{-1}$), and F_{CR} is the annual amount of N in crop residues returned to soils (kg N $year^{-1}$). Also indirect N_2O emissions (kg N_2O $year^{-1}$) produced from N volatilized of managed soils also leaching and runoff can be calculated following Eq. (6).

$$N_2O_{Indirect} = \{[(0.1F_{SN} + 0.2F_{ON}) \times 0.01] + [(F_{SN} + F_{ON} + F_{CR}) \times 0.3 \times 0.0075]\} \times \frac{44}{28} \quad (6)$$

Energy analyses

The energy equivalent of inputs was used for the energy use analysis. Energy use estimation consists of direct energy input as fossil fuel and indirect energy inputs from material inputs (i.e., seeds, fertilizers, compost, and pesticides). The energy use of labor and production of machinery have not been considered in this study. The energy equivalent values of raw material inputs are illustrated in Table 4.

Particulate matter formation emissions analyses

Particulate matter formation was evaluated by PM10-equivalent factors of raw material inputs and transportation. The direct PM10 creation from rice straw management scenario such as rice straw open burning and rice straw combustion in boiler for electricity generation was also estimated. PM10 factors of diesel and gasoline fuel were estimated from emissions gases that were combusted and then converted to PM10-eq by factors from the ReCiPe method. The PM10 factors of raw material inputs and transportation are presented in Table 5.

Sensitivity analysis

In this study, sensitivity analysis was performed to assess the variation of the environmental impacts and thus test the robustness of the result in cultivation stage. Methane gas in field emissions was a major contributor to GHG emissions. The variations in the emissions factor of methane thus significantly affect the GHG emissions during cultivation according to Fusi et al. (2014). The baseline emissions factor of methane for continuously flooded fields without organic amendments (EF_c) was undertaken

Table 4 Energy equivalent values of raw material inputs and transportation

Input	Energy equivalent	Unit	Reference of data
Herbicide	85	MJ kg^{-1}	Pishgar-Komleh et al. (2011)
Pesticide	229	MJ kg^{-1}	Pishgar-Komleh et al. (2011)
Fungicide	115	MJ kg^{-1}	Pishgar-Komleh et al. (2011)
Bio-ferment juice	0.408	MJ L^{-1}	Ecoinvent (2013)
Gasoline	39.7	MJ L^{-1}	Chaichana et al. (2014)
Diesel	43.3	MJ L^{-1}	Chaichana et al. (2014)
Rice seed	14.57	MJ kg^{-1}	Iqbal (2007)
Compost	2.02	MJ kg^{-1}	Sun et al. (2006)
Fertilizer N	47.10	MJ kg^{-1}	Gezer et al. (2003)
Fertilizer P	15.80	MJ kg^{-1}	Gezer et al. (2003)
Fertilizer K	9.28	MJ kg^{-1}	Gezer et al. (2003)
Rope	123	MJ kg^{-1}	Ecoinvent (2013)
Transportation of a 7-t truck	8.05	MJ tkm^{-1}	Ecoinvent (2013)
Transportation of a 16-t truck	1.4	MJ tkm^{-1}	Ecoinvent (2013)

to investigate the influence of field emissions. The error range values of EF_c were used to test the robustness of GHG emissions from field by comparison with baseline scenario where EF_c was 1.3. The minimum and maximum values of the error range of EF_c were 0.8 and 2.2, respectively (IPCC 2006).

In addition, another sensitivity analysis was conducted to assess the effect of the ranges of paddy yields from data collection. Baseline scenario for this analysis was the average paddy yield value of 3750 kg ha^{-1}. The minimum and maximum values of paddy yields were calculated by the standard deviations of the paddy yields of ± 267 kg ha^{-1}. Thus, the minimum and maximum of paddy yields were 3483 and 4017 kg ha^{-1}, respectively.

Results and discussion

Impacts of rice cultivation stage

GHG emissions

Figure 2 shows the life cycle GHG emissions of the rice cultivation stages including land preparation, planting, farming, harvesting, and field emissions. The total GHG emissions of rice cultivation were 0.64 kg CO_2-eq per kilogram of paddy rice. Field emissions are the largest contributor to the life cycle GHG emissions, at 0.45 kg CO_2-eq per kilogram of paddy rice, or 70% of the total life cycle GHG emissions of rice cultivation. Farming stage was the second largest contributor,

Table 5 Particulate matter formation (PM10) factors of raw material inputs and transportation

Input	PM10	Unit	Reference of data
Herbicide	0.0263	kg PM10-eq kg^{-1}	Ecoinvent (2013)
Bio-ferment juice	0.00014	kg PM10-eq L^{-1}	Ecoinvent (2013)
Gasoline (production)	0.00106	kg PM10-eq kg^{-1}	Ecoinvent (2013)
Gasoline (combustion)	0.0014	kg PM10-eq L^{-1}	EEA (2013)
Diesel (production)	0.00154	kg PM10-eq kg^{-1}	Ecoinvent (2013)
Diesel (combustion)	0.00954	kg PM10-eq L^{-1}	EEA (2013)
Rice seed	0.00281	kg PM10-eq kg^{-1}	Ecoinvent (2013)
Fertilizer 46-0-0	0.00787	kg PM10-eq kg^{-1}	Ecoinvent (2013)
Fertilizer 16-20-0	0.00426	kg PM10-eq kg^{-1}	Ecoinvent (2013)
Fertilizer 13-3-21	0.00252	kg PM10-eq kg^{-1}	Ecoinvent (2013)
Pesticide	0.0298	kg PM10-eq kg^{-1}	Ecoinvent (2013)
Rope	0.0085	kg PM10-eq kg^{-1}	Ecoinvent (2013)
Transportation by a 7-t truck	0.000915	kg PM10-eq tkm^{-1}	Ecoinvent (2013)
Transportation by a 16-t truck	0.000479	kg PM10-eq tkm^{-1}	Ecoinvent (2013)

at 0.13 kg CO_2-eq per kilogram of paddy rice, or 20% of the total life cycle GHG emissions of rice cultivation. The other stages consisting of land preparation, planting, and harvesting contributed approximately 10% of the total life cycle GHG emissions of rice cultivation. These results correspond to those of Brodt et al. (2014) who found that the rice field emissions was the largest contributor of life cycle GHG emissions in California rice production at about 69% of life cycle GHG emissions and followed by farming stage including using, manufacture, and distribution of fertilizers at approximately 10% of total net emissions. Nevertheless, the life cycle GHG emissions of their study were 1.50 kg CO_2-eq per kilogram of paddy rice which is more than twice of this study. This was because their study used the average field emissions factor from literature which used direct measurement by static chambers. This resulted in the field emissions of their study being approximately 2.5 times higher than this study. A carbon footprint study of grain crop production in China by Yan et al. (2015) found that total GHG emissions of paddy rice was 0.80 kg CO_2-eq per kilogram of paddy rice which is only slightly higher than our study. Field emissions from CH_4 and N_2O of their study contributed 69% of total CO_2 emissions of rice production which is again similar to this study. In addition, another similar study in Italy by Fusi et al. (2014) found that the GHG emissions of paddy rice were 0.70 kg CO_2-eq per kilogram of paddy which is quite similar to this study.

A similar study of GHG emissions of rice cultivation in Thailand by Soni et al. (2013) of rain-fed rice production system in Northeast Thailand showed life cycle GHG emissions of paddy rice slightly lower than this study at 0.42 kg CO_2-eq per kilogram of paddy. Field emissions contributed approximately 65% of overall GHG emissions of rice production. In addition, the study of the similar rice variety in Northeast Thailand by Thanawong et al. (2014), who evaluated CO_2 emissions in rain-fed agricultural production systems, reported that the life cycle GHG emissions of paddy rice was 2.97 kg CO_2-eq per kilogram of paddy which is approximately five times higher than our study because the farmers use about three times higher synthetic fertilizers than our study leading to high N_2O emissions from the field. Also their study found that field emissions were the largest contributor, at 62% of the total GHG emissions of rice cultivation. The contributions of field operations (land preparation and harvesting), chemicals (fertilizers and pesticides), and rice seed production were 27, 9, and 2% of the overall GHG emissions. However, another study with similar rice variety by Mungkung et al. (2011), who estimated CO_2 emissions of 1 kg of KDML 105 paddy rice in Northeast Thailand, showed results 12 times higher than this study because they measured field emissions by closed chamber method while this study calculated these according to the 2006 IPCC Guidelines. Furthermore, the cultivation period in Mungkung et al.'s study was much longer than in our study (240 versus 120 days for this study) probably also contributing to higher emissions; in addition, rice straw before planting stage was incorporated, so added biomass into soil could also lead to high field emissions.

The sensitivity analysis study on the methane factors showed that the GHG emissions for the minimum and maximum values of methane factor were 0.30 and 0.71 kg CO_2-eq per kilogram of paddy rice, respectively, or approximately − 32 and 58% when compared with the baseline methane factor. These results correspond to Fusi et al. (2014) who found that GHG emissions of the minimum and maximum values of methane factor when compared with their baseline factor were − 26 and + 77.2%, respectively. In addition, sensitivity analysis conducted on the range of paddy yields showed that GHG emissions of minimum and maximum paddy yield values were 0.68 and 0.61 kg CO_2-eq per kilogram of paddy rice, respectively, or approximately + 5.6 and − 4.9% when

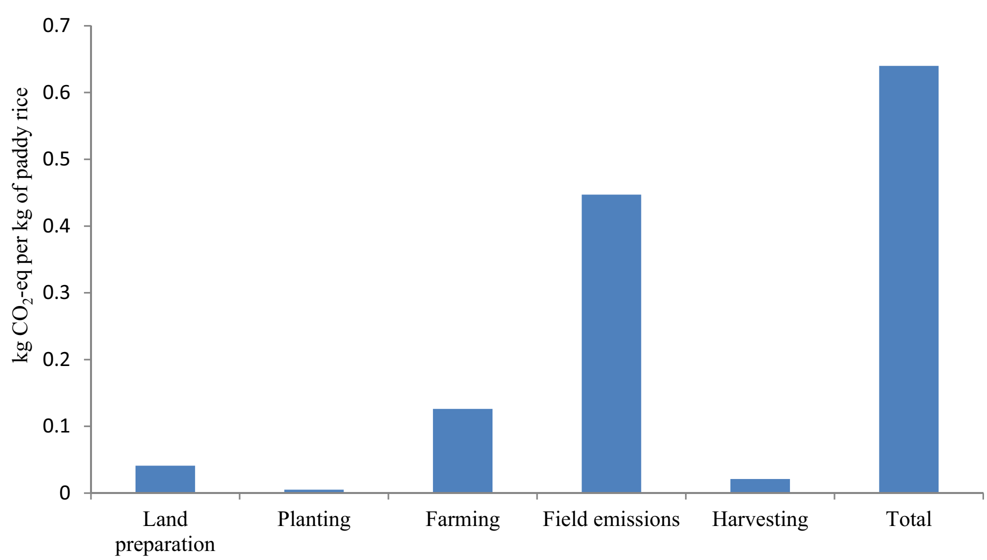
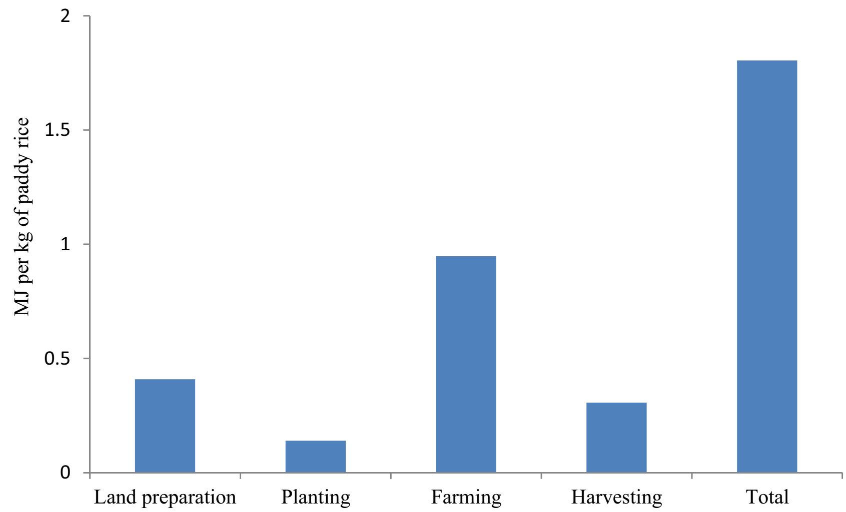


Fig. 2 GHG emissions of rice cultivation

Fig. 3 Energy use of rice cultivation



compared with the baseline paddy yields. Thus, the variation of GHG emissions with paddy yield is not so significant.

Energy use analysis

Figure 3 illustrates the energy use of rice cultivation consisting of land preparation, planting, farming, and harvesting stages. The total energy use of rice cultivation was 1.80 MJ per kilogram of paddy rice. The highest energy use was from the farming stage contributing approximately 53% of total energy use of rice cultivation. The chemical fertilizers and pesticides use in the farming stage contributed significantly. Land preparation was the second highest contributor at 0.41 MJ per kilogram of paddy rice, or 23% of total energy use of rice cultivation, followed by harvesting and planting at approximately 17 and 7%, respectively. These results are comparable to Koga and Tajima (2011) who assessed energy efficiency of rice production in northern Japan. They reported an energy use of 2.17 MJ per kilogram of paddy rice which is slightly higher than this study. This may be due to the fuel use for agricultural machinery in Japan for transplanting, fertilization, and chemical spraying; these operations are manual in Thailand. Moreover, higher amounts of fertilizer and biocides were used in their study. In addition, another study with similar rice cultivation in Thailand by Thanawong et al. (2014) found that the energy use of KDML 105 rice cultivation was 7.25 MJ per kilogram of paddy rice, approximately four times higher than this study. This was mainly because their study considered about three times more chemical fertilizers than our study. Also the paddy yield of their study was approximately 25% lower than this study.

The sensitivity analysis conducted on energy use from variation in paddy yields showed that energy use of minimum and maximum paddy yield values were 1.94 and 1.68 MJ per kilogram of paddy rice, respectively, or approximately + 7.1 and − 6.6% when compared with the baseline paddy yields. Thus, the variation in paddy yield affected the energy use results only nominally.

Fig. 4 Particulate matter formation from rice cultivation

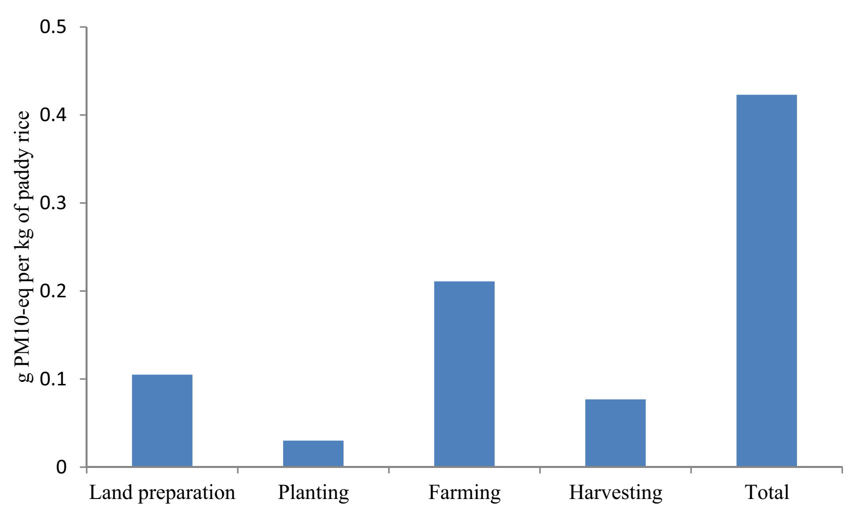


Table 6 Energy analysis and environmental impacts of rice straw managements (per tonne of rice straw, dry basis)

	Open burning			Soil incorporation			Electricity generation		
	GHG (kg CO_2-eq)	En (MJ)	PM10 (g PM10–eq)	GHG (kg CO_2-eq)	En (MJ)	PM10 (g PM10–eq)	GHG (kg CO_2-eq)	En (MJ)	PM10 (g PM10–eq)
Rice straw cultivation				7.47	21.05	1.97	7.47	21.05	1.97
Emissions from open burning	1714		12,700						
Emissions from incorporation practice				8.40	120	30.14			
Field emissions from rice straw incorporation				1111					
Rice straw baling							13.80	262	43.2
Transportation of rice straw baling							6.17	206.5	52.4
Electricity conversion processes							1312	− 2207	23,585
Total balance	1714		12,700	1127	141	32.11	1339	− 1718	23,683

Particulate matter formation

Particulate matter formation was evaluated from each stage of rice cultivation and reported as PM10-eq, as shown in Fig. 4. The total particulate matter emissions of rice cultivation were 0.42 g PM10-eq per kilogram of paddy rice. The majority of PM10 emissions in rice cultivation were from the farming stage resulting from many chemical fertilizers and pesticides use, contributing approximately 50%, followed by land preparation and harvesting stages with 26 and 19% respectively, which were influenced from diesel fuel use of agricultural machineries. The planting stage had the smallest contribution to PM10 emissions at approximately 7%.

Sensitivity analysis performed on variation of paddy yield values showed that the PM10 emissions for minimum and maximum paddy yield were 0.46 and 0.39 g PM10-eq per kilogram of paddy rice, respectively, or approximately + 7.8 and − 6.7% when compared with the baseline paddy yield.

Impacts of rice straw management practices

This study assumes that after harvesting, the rice straw was managed by open burning, soil incorporation, or electricity generation. The environmental impacts were allocated to rice straw by economic values of the co-products from rice cultivation stage for rice straw utilization, i.e., incorporation and electricity generation. As for open burning, the cultivation impacts were not allocated to rice straw. Table 6 shows the environmental impacts of rice straw management scenarios; they include GHG emissions, energy use, and PM10 emissions. The results revealed that open burning had the highest GHG emissions per tonne of rice straw at 1714 kg CO_2-eq. On the other hand, this scenario had much lower energy use when compared with other scenarios. Rice straw incorporation into soil as fertilizer had approximately 35% lower GHG emissions than open burning. The PM10 emissions of rice straw incorporation scenario were much lower than open burning at 32.11 g PM10-eq. Rice straw utilization for electricity generation had the highest PM10 emissions at 23,683 g PM10-eq per tonne of rice straw but then this scenario could reduce the GHG emissions by approximately 22% respectively, when compared with the current practice of open burning. Also this scenario could produce electricity at 2207 MJ, or 613 kWh, per tonne of rice straw, dry basis.

The net energy output of rice straw to electricity scenario was 1718 MJ per tonne of rice straw, dry basis. Therefore, the net electricity output was 477 kWh per tonne of rice straw and the net GHG emissions saving when compared with open burning was 0.79 kg CO_2-eq per kilowatt hour according to the similar rice straw-based power generation study in Thailand by Saramaythangkoor and Gheewala (2008) that reported the net GHG emissions saving of power generation from rice straw was 0.78 kg CO_2-eq per kilowatt hour. However, another similar study in Thailand by Silalertruksa and Gheewala (2013) found that the total GHG emissions of rice straw electricity were 348 kg CO_2-eq per tonne of rice straw which is approximately four times lower than this study. This may have been because their studies did not include the CO_2 emissions from rice straw combustion because they considered these as biogenic; they only included non-CO_2 GHG emissions in their calculations.

Conclusion

This study used the life cycle assessment (LCA) concept to evaluate the environmental impacts, i.e., greenhouse gas (GHG) emissions, energy use, and particulate matter formation (PM10), of rice cultivation and rice straw management practice in northern Thailand. The rice straw management scenarios consist of open burning, incorporation into soil, and utilization for biomass to electricity generation system, as well as to compare the environmental impacts of rice straw management scenarios. The LCA results of rice cultivation stage revealed that GHG emissions were 0.64 kg CO_2-eq per kilogram of paddy rice. The field emissions are the largest contributor to life cycle GHG emissions accounting approximately 70% of total life cycle GHG emissions of rice cultivation. The total energy use and the total PM10 emissions per kilogram of paddy rice were 1.80 MJ and 0.42 g PM10-eq, respectively. The results of rice straw management practice indicated that soil incorporation of rice straw or electricity generation from rice straw could reduce the environmental impacts when compared with rice straw open burning.

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