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Generating a positive energy balance from using rice straw for anaerobic digestion

V.H. Nguyen [a,*], S. Topno [a], C. Balingbing [a], V.C.N. Nguyen [b], M. Röder [c], J. Quilty [a], C. Jamieson [a], P. Thornley [c], M. Gummert [a]

[a] International Rice Research Institute, Philippines
[b] Can Tho University, Viet Nam
[c] University of Manchester, United Kingdom

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ABSTRACT

About 150 million metric tons of rice straw is produced in Southeast Asian countries every year. Several barriers impeding the collection of rice straw from the fields as well as the lack of knowledge on alternative uses of rice straw led to the practice of burning which causes air pollution and greenhouse gas emissions. To identify the benefits and uses of rice straw for energy generation is the main objective of this research. The study evaluated the energy balance of the rice straw supply chain and energy conversion through anaerobic digestion (AD).

The input energy was categorized either as direct and indirect energy. Direct energy included agricultural inputs, fuel consumption and manpower. Fuel consumption was measured directly from the vehicles and equipment used in the experiment while manpower was measured using the metabolic equivalent of task (MET) based on labor time per ton of straw. Indirect energy was calculated based on the energy for the manufacture, lubrication, and maintenance of machines and equipment.

The net energy of the rice straw supply chain for biogas generation through AD is 3,500 MJ per ton of straw. This rice straw management option can provide a 70% net output energy benefit. The research highlighted the potential of rice straw as a clean fuel source with a positive energy balance, helping to reduce greenhouse gas emissions compared with the existing practice of burning it in the field.

1. Introduction

There is a large surplus of rice straw in South and Southeast Asia (Gadde et al., 2009). Long term research at the International Rice Research Institute (IRRI) has shown that the rice straw can be removed from flooded rice fields without reducing the levels of soil organic matter (Bijay-Singh et al., 2008). However, as a common practice, much of this straw surplus is burned in the field as a waste product. Burning one tone of rice straw in the field causes the emission of greenhouse gases such as methane (CH_4), which is produced at a rate of 1.2–2.2 g per kg dry straw and 0.03–0.07 kg of N_2O (Andreae and Merlet, 2001; Yevich and Logan, 2003; McMeeking, 2009; Gadde et al., 2009). Gathering the rice straw and using it as energy feedstock is one possible solution to prevent air pollution caused by field burning (Siemers, 2011). However, rice straw is a low-density material at 70 kg m^{-3} which makes it bulky (Kargbo et al., 2015) and difficult to handle and transport to the storage place for energy conversion.

One technology option that is suitable for Southeast Asian countries is anaerobic digestion (AD) which produces gas that can be used for cooking, generating heat for drying, and electric power. Using rice straw for AD can produce from 60 to 180 l of methane per kg of dry rice straw (Lubken et al., 2010; Mussoline et al., 2013). However, the lack of knowledge on rice straw supply chains and utilization options mean that farmers are limited in their capacity to utilize this biomass for energy production, and thus they often burn rice straw in the field. For this reason, the current study was conducted to focus on the energy balance analysis of the supply chain from harvesting to storage of rice straw for use in AD. This research aims to contribute knowledge that will improve the sustainability of rice production systems.

* Corresponding author.
E-mail address: hung.nguyen@irri.org (V.H. Nguyen).

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2. Methodology

2.1. Scope of research

This research of energy balance analysis follows an attributional lifecycle (Walsh and Thornley, 2012) with a focus on rice straw from rice production to the end product of biogas generation from anaerobic digestion. Fig. 1 shows schematic framework of the energy balance analysis. Input energy accounted for direct energy from diesel consumption and manpower while indirect energy was calculated based on the energy requirements of machine manufacturing and maintenance. Output energy was quantified as the energy produced from biogas and digestate.

2.2. Data collection

2.2.1. Rice production and rice straw supply chain

This research was conducted in two locations: at the International Rice Research Institute (IRRI) located in the Philippines for the mechanized and manual operations from harvesting to storage, and in the Mekong Delta (MD) of Vietnam for the AD experiments in 2014. Data on average rice production in the Philippines is cited from research previously conducted at IRRI (Quilty et al., 2014). This data source was selected for the following reasons:

- it is recently published;
- it is coherent with the scope of the current study;
- the data from farmers' fields was collected in five major rice-growing municipalities;
- the data of long term continuous cropping experiment (LTCCE) at IRRI is a reliable source of data going back to 1962.

In-field burning of straw is still widely practiced in rice farming systems across the Philippines. However, no rice straw burning has been undertaken in the LTCCE at IRRI since it began in 1962. Table 1 shows the agricultural inputs and average fuel consumption for rice production in the LTCCE and in farmers' fields in the Philippines.

Quantification of energy requirements for combine harvesting was undertaken at IRRI. Harvesting rice results in two products which are paddy grain and rice straw. Input energy (IE) of these co-products was based on economic allocation as shown in Eqs. (1) and (2).

$$\textit{IE allocation of rice straw} = 100 Y_{rs} P_{rs} (Y_{pd} P_{pd} + Y_{rs} P_{rs})^{-1}\ (\%) \quad (1)$$

where Y_{rs} is yield of rice straw; P_{rs} is price of rice straw; Y_{pd} is yield of paddy; and P_{pd} is price of paddy.

$$\textit{IE allocation of paddy} = 100 - \textit{IE allocation of straw}\ (\%). \quad (2)$$

The rice straw:paddy ratio was measured in-situ at harvest by hand or combine harvesting. The price of paddy grain at harvest was assumed to be about PHP30,000 per ton (Rappler, 2015). The price of rice straw was assumed to be about PHP2,000 per ton based on information gathered from farmers in the Nueva Ecija, where rice straw is used for mushroom production.

The rice straw supply chain processes from harvesting to storage were assessed in two different scenarios. The first scenario involved manual harvesting, the use of a mechanical thresher (10 HP), manual collection, and transportation using a two-wheel tractor (10 HP). The second scenario involved mechanized operations using combine harvester (Crop Tiger Terra Track C210, 60 HP), mechanical baler (CLAAS R250 Roller), four-wheel tractor (John deer 6150, 150 HP) for transportation, and handling using a forklift (Nisan 20, 90 HP).

Computation of manual labor energy requirements for piling straw was assessed in the Mekong Delta, while the energy requirements of outdoor storage using a high density polyethylene (HDPE) canvas material were calculated at IRRI. Rice straw was stored for five months before being used in AD. Diesel consumption of the respective machines in this study was measured by the fuel consumption meter EASYFLOW NT3.

2.2.2. Experiment of AD with rice straw and pig dung

Prior to AD the rice straw was ensilaged in a 1 m^3 container for five days with digestate from previous AD operations. The ensilaged rice straw was then mixed with pig dung at a ratio of 1:1 based on organic dry matter (ODM) (Fig. 2). The pretreated rice straw was then fed into a digester, mixed with pig dung and water. The digester is made of HDPE with a volume of 6 m^3. Untreated rice straw at 18%–20% moisture content is fed into the digester at a rate of 4.7 kg per day. The biogas generated from the digester was collected in a reservoir also made of HDPE.

The amount of materials for making canvas for storage, container for ensilaging, digester, and gas reservoir was 0.22, 2.84, 32.2, and 9.19 kg HDPE per ton of rice straw, respectively. These data were calculated based on an assumption of a five-year working life.

The moisture content (MC) and dry matter (DM) of the samples were measured using the oven-drying method at 105 °C. The ODM was measured by analyzing organic content of the total dried weight of the samples (dry matter). Biogas parameters were measured using the EUIK and GC analyzers.

2.3. Methodology and software used for calculation and simulation

Calculation and simulation of the system was done based on the Cumulative Energy Demand method of the SIMAPRO software, version 8.0.5.13 (PRé, 2015). Conversion of agricultural inputs to energy was made by referring to the database on Agri-Footprint, Ecoinvent 3, and Industry Data 2.0. All these library and methods are available in SIMAPRO. The amount of energy embodied in input materials that was unavailable in SIMAPRO was cited from previous research. The diesel burned in machinery was 44.8 MJ L^{-1} (Durlinger et al., 2014; Bowers, 1992; Fluck, 1992), and manufacture and maintenance of the machines based on diesel consumption was 15.6 MJ L^{-1} (Bowers, 1992; Fluck, 1992; Dalgaard et al., 2001). Input energies embedded in fertilizers were 78, 17, and 14 MJ per kg of Nitrogen, Phosphorus, and Potassium; respectively (Dalgaard et al., 2001; Mudahar and Hignett, 1987; Kool et al., 2012); and these of pesticides are 356 and 358 MJ kg^{-1} per kg of herbicide and insecticide, respectively (Dalgaard et al., 2001; Mudahar and Hignett, 1987).

Human labor energy input, the energy expended by humans in the process of producing rice, was calculated based on the metabolic equivalent of task (Quilty et al., 2014; Ainsworth et al., 2011) with the assumption of an Asian human body weight of 54.4 kg (IAEA, 1998). Based on these calculations, the energy demand of operating a 4-wheel tractor or combine harvester was 0.44 MJ h^{-1}; operating a 2-wheel tractor was 0.98 MJ h^{-1}; and manual harvesting, threshing, or straw handling was 0.89 MJ h^{-1}.

The direct gross calorific value of the rice straw was categorized as high heating value (HHV) and low heating value (LHV). The HHV was determined by using bomb calorimeter Parr 6100. HHVs were converted to LHVs in MJ kg^{-1} using Eq. 3 (IPCC, 2006).

$$LHV = HHV - 0.212 * H - 0.0245 * M - 0.008 * Y [\text{MJ kg}^{-1}] \quad (3)$$

where, H, M, and Y are the percentages of hydrogen, moisture, and oxygen, respectively.

Outputs of AD, biogas, and digestate were considered for replacing sources of avoided products (in SIMAPRO). Output energy (OE) obtained from biogas (OE_{biogas}) was calculated as in Eq. (4).

$$OE_{biogas} = 1000 * ODM * BY * BE\ [\text{MJ Mg}^{-1} \textit{straw}] \quad (4)$$

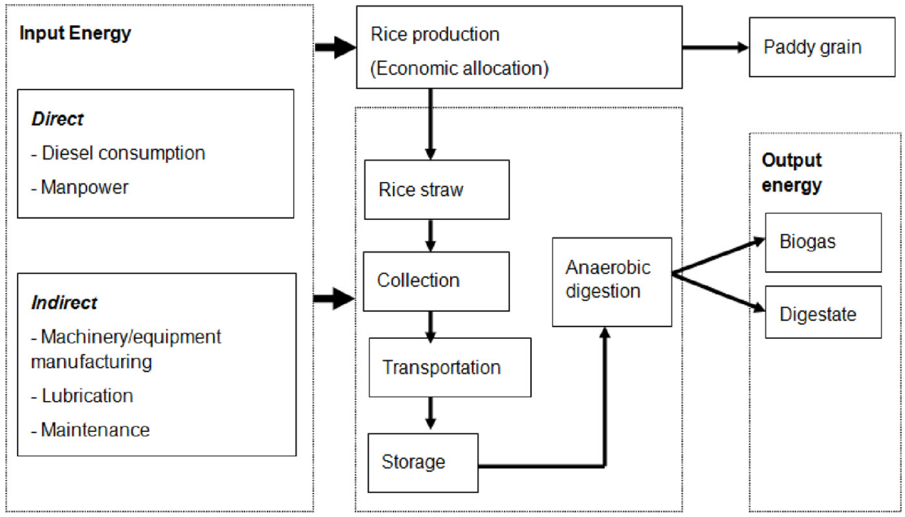

Fig. 1. Schematic framework for energy balance analysis.

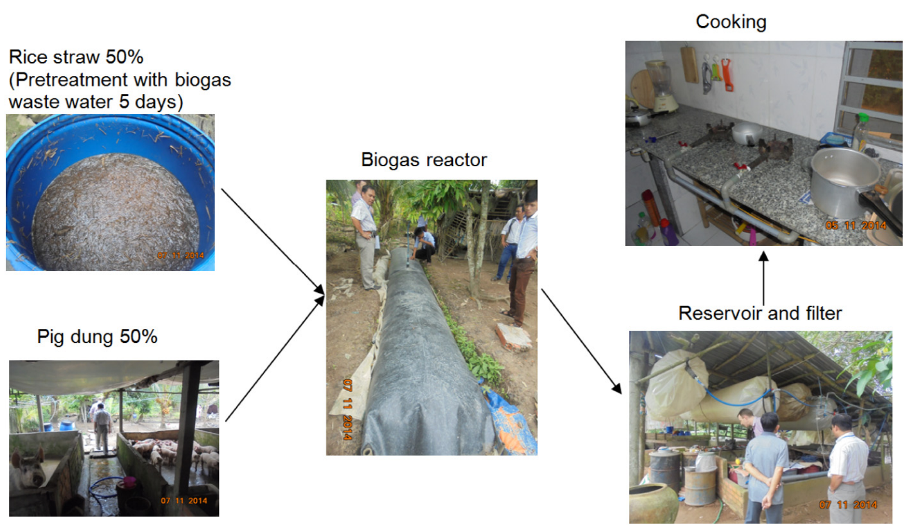

Fig. 2. Process of AD from rice straw in Can-Tho City of Vietnam.

Table 1
Agricultural inputs and fuel consumption of rice production in the Philippines.
Source: Adapted based on Quilty et al. (2014).

Parameters/items	IRRI field (long term experiment)		Philippines farmer's fields	
	Dry 2012	Wet 2012	Dry 2012	Wet 2012
Varieties	NSIC Rc222	NSIC Rc222	Rc18–38%, Rc222–33%, IR74–6%	Rc222–68%, Rc216–9%, Rc212–6%
Residue management	Removed	Removed	50% burnt	50% burnt
Grain yield (Mg ha −1)	6.9 (0.04)	5.7 (0.39)	4.8 (0.17)	4.0 (0.23)
Seeding rate (kg ha^{-1}) (transplanting)	20	20	60 (4.0)	61 (4.0)
Fertilizer (kg ha^{-1})				
N	195	90	100 (9.0)	87 (8.4)
P2O5	50	30	18 (2.3)	13 (2.3)
K2O	30	20	17 (2.3)	12 (2.3)
Herbicide	1.98	1.98	0.99	0.99
Insecticide	1.91	1.91	2.87	3.59
Diesel (L ha^{-1})	145	145	69	67
Draught animal (MJ ha^{-1})			320 (50)	340 (50)
Manual harvesting (MJ ha^{-1})	106.8	106.8	94.34 (8.0)	106.4 (17.3)
Total manual labor (MJ ha^{-1})	820	830	310 (20)	360 (30)

The standard deviation of the mean is displayed in parentheses.

where, ODM is the ratio between one kilogram organic dry matter and one kg rice straw, measured at 18% moisture content; BY is the biogas yield measured by liter per kg ODM (L kg^{-1}); and BE is biogas energy value equivalent to 0.02 MJ L^{-1} (Deublein and Steinhauser, 2008).

Approximately 20% of the digestate from AD was assumed to have been converted into organic fertilizer (Deublein, 2012). The nitrogen contents of the rice straw and pig dung, which were about 1% nitrogen in dry rice straw (Jenkins, 1998; Munder, 2013) and 18% DM in pig dung (4.5 kg nitrogen per ton) (Schmitt and Rehm,

Table 2
Measured fuel consumption of different machines during field operation and transportation.

Machines	Number of measurements	Operating capacity	Fuel consumption	
	N	Mg h^{-1}	L h^{-1}	L Mg^{-1}
Harvesting and collection				
Combine harvester	5	1.53	12.49	8.22
Tractor MF399 + Claas baler R250	5	4.19	17.55	4.19
Transporting rice straw (2 ∗ 4 kmround trip with empty return)				
2W tractor + trailer	3	0.40	0.60	1.5
Forklift for handling	3	10.07	1.30	0.13
4W Tractor + trailer	3	13.13	7.20	0.55

2002), were all assumed to have remained in the digestate after AD.

2.4. Statistical analysis method

The measurements were conducted during actual field activities such as moisture content, yield, and length of remaining rice straw after harvest, among others. The mean value and standard deviation of the data were calculated using Excel software. The data were also analyzed using Analysis of Variance (ANOVA) and Least Significant Difference (LSD) methods.

3. Results and discussion

3.1. Data of rice straw

The ratios of rice straw:paddy at the moisture content of 14% are 95% and 89% for manual harvesting and use of combine harvester, respectively. The measured HHV of rice straw in Vietnam and Philippines averaged at 14.2 and 15.3 MJ kg^{-1}, and the LHV of those rice straw at the moisture content of 18% was 13 and 13.7 MJ kg^{-1}, respectively.

3.2. Fuel consumption of machinery

In all field operations (i.e., harvesting, threshing, baling, transport, loading and unloading of baled straw), diesel was used as fuel. The effect of soil compaction during combine harvesting and baling was measured at 1375 ± 343 kPa. The volumetric water content of the soil during harvest was 59±4.4 L m^{-3}. The measured fuel consumptions translated into liters per ton of straw (L Mg^{-1}) are summarized in Table 2.

3.3. Input energy of manual labors

Table 3 shows the calculated labor energy for driving machines, such as tractors and combine harvester, as well as for other operations in preparing rice straw for AD. These data were obtained by measuring the time of each operation and manpower index.

3.4. Results of anaerobic digestion experiment with rice straw and pig dung

The AD experiment was conducted using a feedstock mixture of 50% rice straw and 50% pig dung based on ODM (AD 50–50). This was compared with 100% pig dung AD as shown in Table 4. Moisture content (wet basis) and ODM of rice straw were 18.6% and 79.8%, respectively; whereas ODM of pig dung were about 65% of dry mater. The results illustrate that AD 50–50 is better in producing biogas with lower hydrogen sulfide content and higher percentage of methane. Admixing high carbon content of rice straw with high nitrogen content of pig dung in AD 50–50 resulted in optimized C:N ratio of 24.2 and improved methane concentration in biogas. The methane content of biogas was likely improved because of the admixing with high carbon content rice straw and high nitrogen content of pig dung to produce an optimized C:N ratio of 24.2.

For 1 kg ODM of feedstock, the total biogas obtained from AD 50–50 was about 600 L whereas that from AD of 100% pig dung was 550 L. This illustration could lead to an assumption that about 300 L biogas was produced from 0.5 kg ODM of rice straw in the mix of 1 kg ODM feedstock for AD 50–50. The biogas yield then converted into energy value is 394 (±31.5) L kg^{-1} rice straw at the moisture content of 18.6%.

3.5. Energy balance analysis

The IE of supply chains was analyzed for eight scenarios of rice straw corresponding to farmers' fields (FRM) and from a long term experiment at IRRI fields (LTI) during the wet and dry seasons, with manual (Man) and mechanized (Mec) supply chains. The IE of the supply chain was accounted for by the rice straw from rice cultivation, harvesting, collection, transportation, and storage. The IE allocation of the rice straw from rice cultivation came from the energy from rice seed, fertilizer, pesticide, fuel consumption, and labor while the IE of collection, transportation, and storage came from fuel consumption, labor, and HDPE for making canvas for storage.

Adding to supply chain, the IE of AD was accounted for by the HDPE used for making containers for ensilaging, digesters, and reservoirs of biogas, as well as laborers. The OE was accounted for by the biogas and digestate base on the AD experimented results as above. The components of the IE and OE of the eight scenarios are shown in Table 5, with the IE indicated with a plus (+) sign and the OE with a minus (−) sign.

For one ton of rice straw collected and used for AD, the result of this study demonstrates that a total IE required ranged from 4367 to 4756 MJ, while the total OE of biogas and digestate generated from AD was approximately 8134 MJ. As the net energy gain from utilizing rice straw for AD bioenergy production is between 3378 and 3767 MJ t^{-1} and a positive net energy balance between 71% and 86%.

Fig. 3 show the energy balance network built in SIMAPRO for rice straw that was collected for AD from farmers' fields in the Philippines via mechanized supply chain. One ton of rice straw required a total IE (in + value) of 4714 MJ. The IE for AD included 3475 MJ for HDPE and 379 MJ for labor. The OE obtained is 8134 MJ comprised of 7880 MJ from biogas and 254 MJ recovered from digestate. The OE and IE resulted in a net energy gain of 3420 MJ for each ton of rice straw.

Energy balance network of the manual scenario was calculated in the same manner as for the mechanized supply chain; the total input energy of the manual scenario for one ton of rice straw was 4406 MJ. Of this total IE in the manual scenario, rice cultivation accounted for 440 MJ, in a total supply chain IE of 552 MJ. The IE of AD is the same for both scenarios. The net energy that resulted from the manual scenario is 3728 MJ per ton of rice straw.

Table 3
Energy used in human labor during rice straw preparation for AD.

Manual operation	IE per hour MJ h^{-1}	Operating capacity Mg h^{-1}	IE per ton straw MJ Mg^{-1}
Manual handling (collecting rice straw to the bund, loading and unloading)	0.89	0.19	4.78
Manual piling rice straw	0.89	0.14	6.41
Driving 2W tractor + trailer	0.98	0.40	2.45
Labor for threshing	0.89	0.60	1.48
Driving combine harvester	0.44	1.53	0.29
Driving tractor + baler R250	0.44	4.19	0.11
Driving forklift	0.44	10.07	0.04
Driving 4W tractor + trailer	0.44	13.13	0.03
Labor for storage	0.89	13.13	0.07

Table 4
Parameters of biogas from rice straw and pig dung.

Biogas	O_2 ref (%)	T-gas (°C)	T-air (°C)	CO_2 (%)	H_2S (ppm)	Biogas yield (L kg^{-1} ODM)	CH_4 (%)
AD 50–50 ($n = 3$)							
Average	5.00	31.67	30.80	44.60	48.00	600	54.93
STDEV	0.00	0.21	0.00	0.02	8.72	100	0.06
AD 100% pig dung ($n = 3$)							
Average	5.00	31.90	31.90	22.64	393.00	550	49.43
STDEV	0.00	0.35	0.00	11.61	119.51	30	0.23

Table 5
Comparison of net energy (MJ Mg^{-1} straw) for different rice straw scenarios.

Items/materials	FRM dry Man	FRM dry Mec	FRM wet Man	FRM wet Mec	LTI dry Man	LTI dry Mec	LTI wet Man	LTI wet Mec
Rice seeds	53.8	54.1	45.5	45.9	10.4	10.5	12.6	12.7
Fertilizers	246.7	248.5	176.8	178.1	282.5	284.5	162	163.2
Pesticides	40.8	41.1	46.7	47.0	23.8	24.0	28.8	29.0
Diesel	242.7	541.4	215.8	514.3	272.5	571.3	308.2	607.3
Labor	405.3	394.4	407.4	396.1	400.8	390.7	403.9	393.5
HDPE	3475	3475	3475	3475	3475	3475	3475	3475
Total IE	4464	4755	4367	4656	4465	4756	4390	4681
Biogas	−7880	−7880	−7880	−7880	−7880	−7880	−7880	−7880
Digestate	−254	−254	−254	−254	−254	−254	−254	−254
Total OE	−8134	−8134	−8134	−8134	−8134	−8134	−8134	−8134
Net energy	−3670	−3379	−3767	−3478	−3669	−3378	−3744	−3453
Net energy balance (%)	82	71	86	75	82	71	85	74

FRM: fields of farmers in the Philippines; LTI: long term experiment fields at IRRI, dry: dry season, wet: wet season, Man: manual supply chain, Mec: mechanized supply chain.

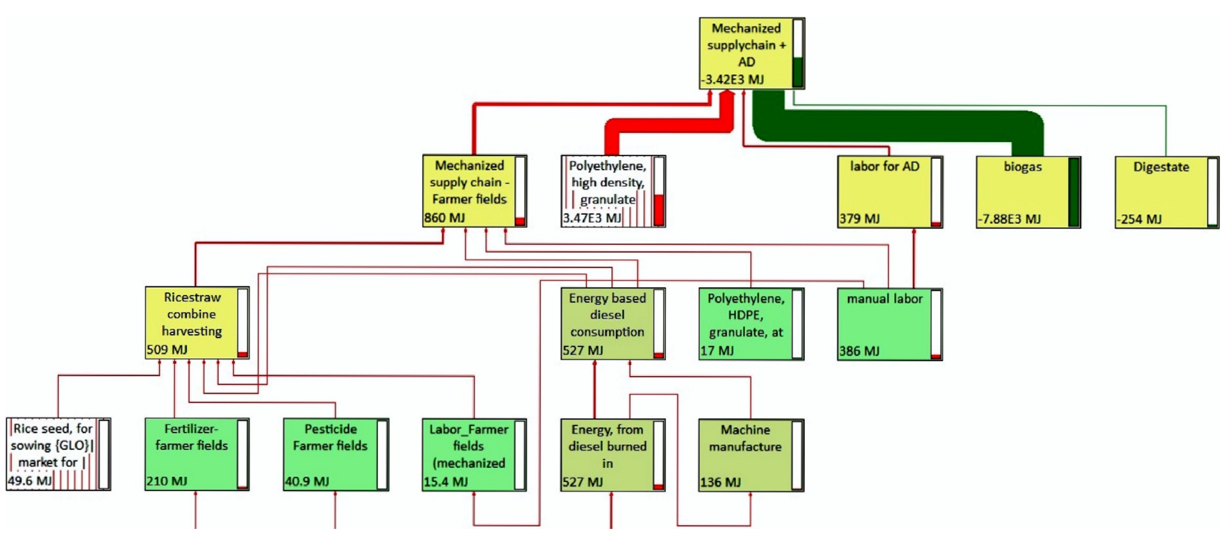

Fig. 3. Energy network of using rice straw for AD with mechanized supply chain.

3.6. Discussion of results

These results provide information on the net energy balance of using rice straw for AD which is a much better option for rice straw management rather than burning. The IE of rice straw at harvesting accounted for about 10% of the rice production. The IE of rice production in this research ranged from 14 to 18 MJ per ha depending on the method of harvesting (i.e., manual or combine harvesting). This IE is higher by 20% than that of the previous research conducted by Quilty et al. (2014) because the IE for machine manufacture and maintenance was considered in this research. The allocated IE of rice straw for manual and combine harvesting were 440 and 509 MJ per ton of straw, respectively.

The supply chain IE accounted about 550–860 MJ Mg^{-1} of rice straw. This resulted in a total IE including AD which was from 4367 to 4756 MJ Mg^{-1} straw. With an OE generation of 8134 MJ Mg^{-1} straw, these scenarios thus can produce a positive energy balance of about 70%–80% over the total IE.

On the other hand, if the IE of rice straw is calculated based on its low heat value of 13 MJ kg^{-1}, then the total IE including rice straw and AD operation is about 16, 000 MJ Mg^{-1} straw. In this case, with the OE of rice straw AD including biogas and digestate was just about 8000 MJ Mg^{-1} straw as show in Table 5 above, the efficiency of the system can be counted as 50%.

The transportation of rice straw from the field to the storage area consumed approximately 8 MJ Mg^{-1} km^{-1}. This result is in agreement with data for the similar agricultural transportation operations available from Ecoinvent 3 incorporated in SIMAPRO software.

The AD biogas yield in this research was about 400 L per kg rice straw at 18.6% MC (wet basis). When translated to methane yield, this is about 200 L of methane per kg of straw, which also agreed with findings of previous research (Mussoline et al., 2013; Dinuccio et al., 2010; Lei et al., 2010).

4. Conclusions

This study does demonstrate that the use of rice straw for AD is a sustainable solution in rice production systems. The total input energy for the rice production system scenarios in this study, including the rice straw supply chain supporting AD, ranged from 4367 to 4756 MJ Mg^{-1}. The rice straw supply chain from harvest to storage required an energy input of 500–900 MJ Mg^{-1}, accounting for 10%–20% of the total input energy for manual and mechanized systems, respectively. The total output energy obtained from biogas generation and digestate of AD was 8134 MJ Mg^{-1} of straw. The results of the energy balance calculations in this study give net energy output of 3400–3700 MJ Mg^{-1} of straw. This shows that the use of rice straw for biogas production can generate a positive net energy balance of between 70% and 80%. It should be noted that although the manual straw collection scenario resulted in a slightly higher net energy gain than the mechanized system, the mechanized option does have a lower labor requirement, which is an increasingly limited resource in many agricultural regions of the world. The results of this study clearly indicate that AD of rice straw is a technology that can increase energy security in rice producing regions.

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