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

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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.

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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).

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

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.

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

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).

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

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).

$$OE_{biogas} = 1000 * ODM * BY * BE\ [\mathrm{MJ\ Mg^{-1}}\mathit{straw}] \qquad (4)$$