



## Energy efficiency, greenhouse gas emissions, and cost of rice straw collection in the mekong river delta of vietnam



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### ABSTRACT

Collection is still a major challenge in the supply chain of rice straw to prepare feedstock for further use. Straw needs to be gathered from the field and compressed into bales to make it compact and easy to transport. With the introduction of combine harvesters, the collection of rice straw has become harder and more costly. This created negative impacts on other businesses that use rice straw. Mechanization of rice straw collection was introduced in Vietnam in 2013 and it has rapidly developed since. Most of the rice straw produced in the dry season in the Mekong River Delta (MD) of Vietnam is collected for mushroom and for livestock fodder production or for use as mulching materials. In order to quantify the performance of the mechanical operation of rice straw collection, this study conducted an analysis of energy efficiency, greenhouse gas emission (GHGE), and cost of rice straw collection in the MD for five collection machines that operated on the same field, the same rice variety, and the same harvest time under a demonstration in the MD. With rice straw yield of 4.72 t per ha, the collection machines operated at a capacity of 0.87–2.47 t per hour. This mechanized operation can reduce labor requirement by 90%. Specific weight of baled straw was from 73 to 104 kg per cubic meter, which is heavier by 50–100% than that of loose-form straw, at a moisture content of 12.4 ( $\pm 1.21\%$ ) in wet basis. Total energy consumption, ranging from 351 to 588 MJ per ton of straw collected, accounted for 10–17% of the total energy input using this collected straw for biogas production. Energy consumption from fossil fuels results in GHGE of 60–165 kg CO<sub>2</sub> equivalent per ton of collected straw. The cost of straw collection, which ranged from US\$12 to US\$18 per ton of straw in the MD, accounted for 10–20% of the total investment cost of biogas or mushroom production. This study illustrated the feasibility of the mechanization of rice straw collection for further processing. Despite the GHGE of this may cause through the consumption of fossil fuels, mechanized rice straw collection creates more benefits such as avoiding in-field burning, producing feedstock for further sustainable processing, and adding value to rice production.

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### 1. Introduction

Rice straw is a by-product of harvesting paddy. After traditional manual harvesting, rice straw is carried out from the field and saved for other uses. However, with farmers' wide adoption and use of combine harvesters that leave the rice straw spread out in the field, gathering them has become a more difficult and tedious task. This has resulted in the increase in the cost of gathering straw which, together with the heavy labor requirement during harvesting season, make manual collection of rice straw unfeasible.

In Vietnam, the total area planted to rice is about 7.5 million ha, with a total yield of 40 million tons (Mt). About 55% of the country's rice production occurs in the Mekong River Delta (MD) (Tran and Dinh, 2014). Correspondingly, about 13 million tons of rice straw from 60% of the rice straw produced in the MD are surplus. They are left to be burned in the field or considered as waste material while most of the remaining 40% is collected for mushroom production, livestock fodder production, or for use as mulching material. In the MD, about 90% of the paddy is harvested by combine harvesters (Nguyen et al., 2013) and the rice straw left spread out in the wet field becomes a main constraint in their efficient collection.

Because of this, farmers are left with no option but to burn the straw in the field. A case study conducted in 2004 in the cities of Can Tho and Tien Giang (two intensive rice production areas in MD)

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## Nomenclature and Units

EE	Energy efficiency
EC	Energy consumption
GHGE	Greenhouse gas emission
MD	Mekong river delta of vietnam
CO <sub>2</sub> -eq	Carbon dioxide equivalent
h	Hour
ha	Hectare
kg	Kilogram
L	Liter
m	Meter
% MC	Moisture content in wet basis
t	Ton
VND	Vietnamese dong

showed that 87% of the total rice straw was burned and the remaining had limited uses (Ngo, 2005). Open field burning of rice straw has become the key factor hampering sustainable management in intensive rice systems in Southeast Asia. Aside from causing pollution and reducing the opportunities for value adding, burning brings losses in nutrients such as 80% of nitrogen, 25% of phosphorus, 21% of potassium, and soil organic matter. This also kills beneficial soil insects and microorganisms (Mandal et al., 2004). In addition, rice straw burned in the field increases the emission of greenhouse gases (GHGs), such as methane (CH<sub>4</sub>), at a rate of 1.2–2.2 g per kg dry straw (Kadam et al., 2000; Yevich and Logan, 2003). Other researches, on the other hand, showed that partial removal of rice straw from the field does not significantly affect grain yield (Buresh et al., 2008; Bijay-Singh et al., 2008; Thuy et al.,

2008). Off-field rice straw could be used for non-energy purposes such as biochar, fertilizer, mushroom production, animal bedding, fodder, and the conversion of energy into fuel, heat, or electricity.

The mechanization of rice straw collection was introduced in Vietnam in 2013 and has rapidly developed since then. Now, farmers are using rice straw more productively. However, there is limited information on the techno-economic aspect of rice straw collection machines. This study conducted an analysis of energy consumption (EC), greenhouse gas emissions (GHGE), and cost of rice straw collection in the MD of Vietnam. It resulted in profiles of the researched factors (EC, GHGE, and cost) of this practice in the context of using off-field straw for further processing, such as biogas and mushroom production, considered within the research.

## 2. Materials and methods

### 2.1. Scope and function unit

The study was done with its in-situ measurements conducted during a demonstration of rice straw collection machines at the Cuu Long Rice Research Institute, Can Tho City, Vietnam in the dry season of 2016. Profiles of EC, GHGE, and cost of straw collection were identified in the context of using off-field straw for further processing. Fig. 1 shows the system boundary of this research. Rice straw is collected and transported to the side of the field by the collection machines. EC and cost accounted for (a) direct energy, which includes the fuel consumption of the collection and handling machines and the manpower for driving and handling; and (b) indirect energy obtained from the production and maintenance of the machines. GHGE was calculated indirectly based on EC.

The collection machines used in the research included: (1) a roller baler pulled by a tractor, which gathers the straw in a bale

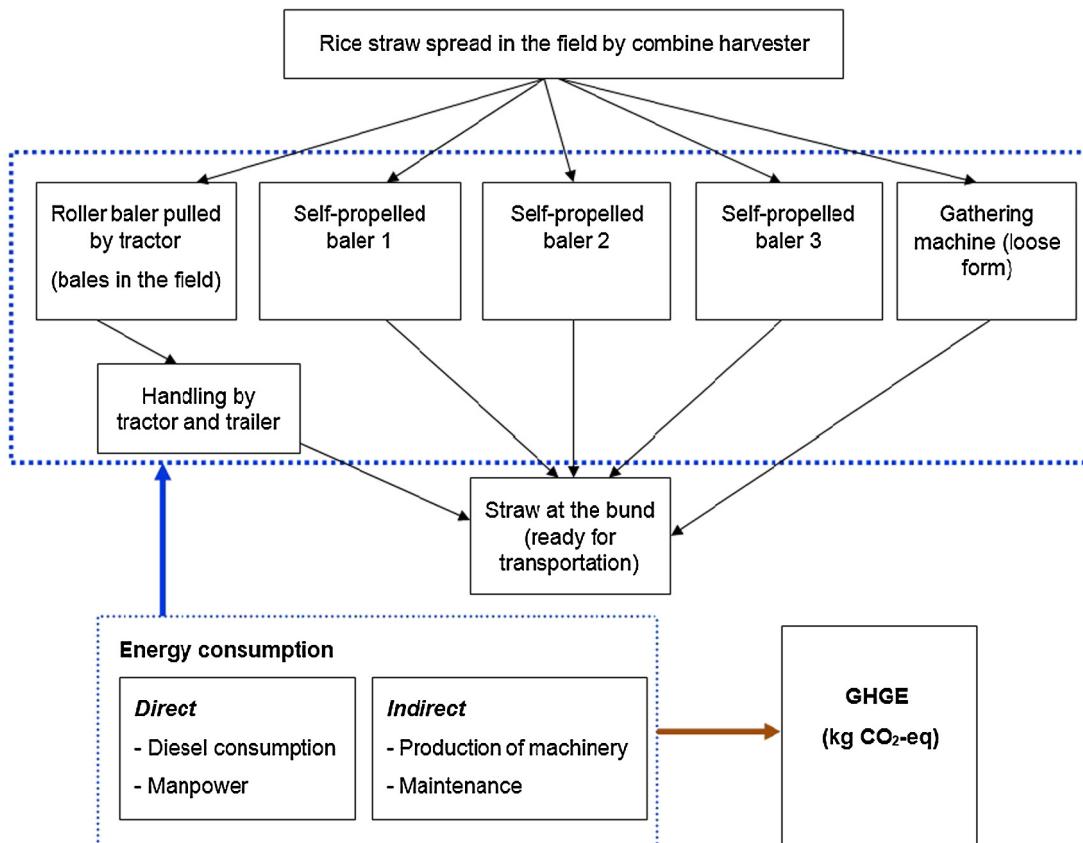


Fig. 1. System boundary of the research.



**Fig. 2.** (a) Roller baler pulled by a tractor. (b) Self-propelled balers. (c) Gathering machine (loose rice straw).

but leaves the bales in the field to be collected and transported to the side of the field in a separate operation ([Fig. 2a](#)); (2) three self-propelled balers, which take the rice straw to the side of the field ([Fig. 2b](#)); and (3) a self-propelled gathering machine, which collects rice straw in loose form without baling it ([Fig. 2c](#)).

## 2.2. Methodology of data collection and calculation

### 2.2.1. Experiment field and rice straw data

The study site is a 3.46 ha (309 m × 112 m) field located at 10° 07' 22.98" N and 105° 35' 12.06" E. The straw of rice variety OM4900 was left in the field four days after harvest using a combine harvester. Seven replications with the same number of sample

quadrats of 18 m<sup>2</sup> each was randomly selected in the experimental area to measure the cutting height (mm) of the rice straw stubbles that remained in the field, and the yield (Mg ha<sup>-1</sup>) of rice straw. The average result in each quadrat was calculated based on five replicated measurements. Rice straw moisture content (MC) was measured using the oven method (drying until only dry matter is left) based on the protocol of [ASAE \(1982\)](#). The average height of the remaining stubble was 137 (±40.6) mm. Rice straw yield was 4.7 (±0.90) t ha<sup>-1</sup> at an MC of 12.6 (±1.26)% in wet basis. The standard deviations of these parameters were high due to the lodging of the paddy before harvest. However, the field in this case was not used for comparative analysis or optimization of machines; it was just used to identify the profiles of EC, GHGE, and cost of mechanized collection in the context of using off-field straw for further processing to evaluate the techno-economic feasibility of this practice. The field was divided into five plots with 0.7 ha each. These five plots were completely randomized to examine the five corresponding collection machines.

### 2.2.2. Measurement of machine performances

The performance of the collection machines were evaluated based on their collection capacity, diesel consumption, specific weight of the rice straw bale, rice straw loss in the field, and the labor involved in all related operations. The collection capacity of the machines was calculated based on the length of collection time corresponding to their allotted area converted to tons of straw per hour (h t<sup>-1</sup>). The weight of straw in the working area was obtained based on the number of bales made and the average weight of each bale. However, for the machine that only gathers loose rice straw, the weight of straw was assumed the same as the average weight of straw gathered by the self-propelled balers based on our in-situ observations. The specific weight of the straw bale (kg m<sup>-3</sup>) was calculated based on the volume of the bale (except those that were collected by the gathering machine).

Rice straw loss in the field (%) was calculated using Equation (Eq. [\(1\)](#)).

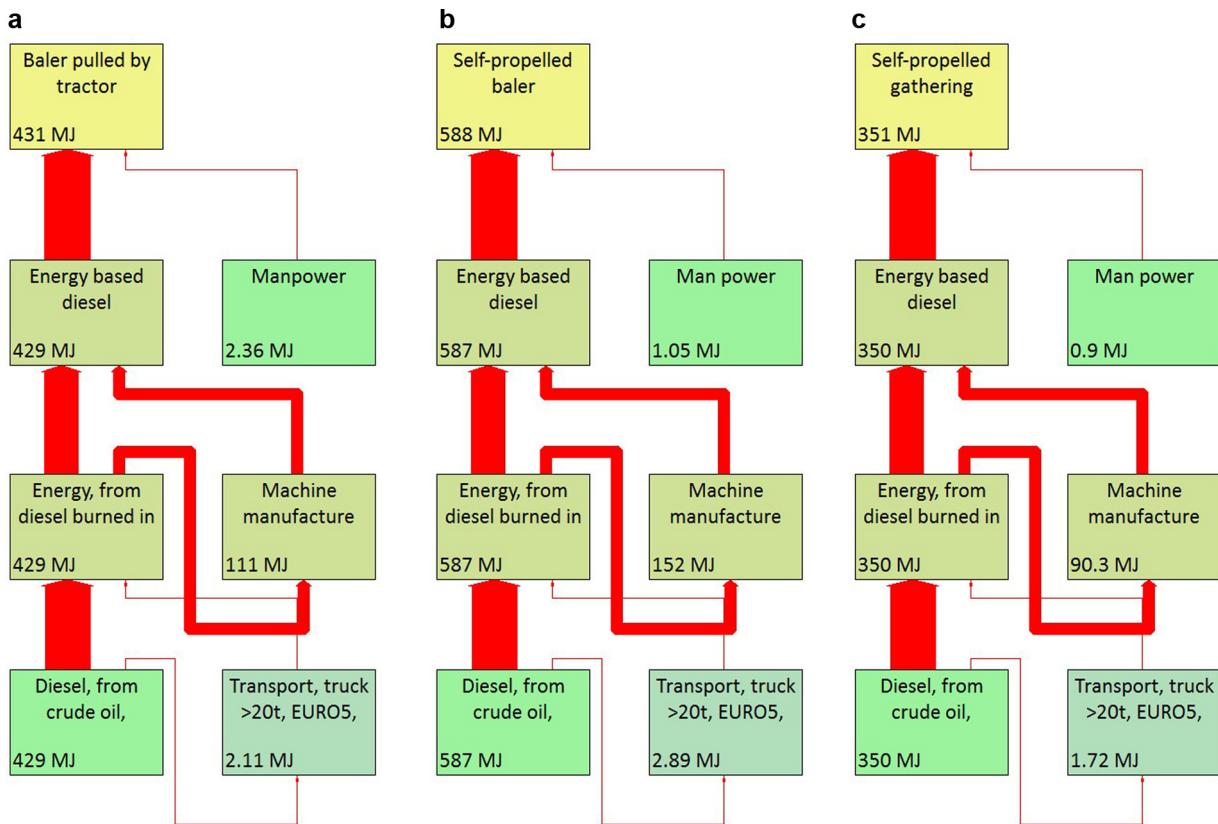
$$\text{Rice straw loss} = \frac{\text{Weight of available straw} - \text{weight of collected straw}}{\text{Weight of available straw}} \times 100\% \quad (1)$$

The weight of available straw per ha means the yield (t ha<sup>-1</sup>) of cut straw left in the field before being collected (i.e., not including the straw stubbles that remain in the field). The weight of collected straw was taken from the calculation for collection capacity. The measurement of the collected straw was done two hours after measuring the available rice straw, causing the rice straw to lose weight. To avoid this error, the weight of both collected and available rice straw were converted into the same moisture content.

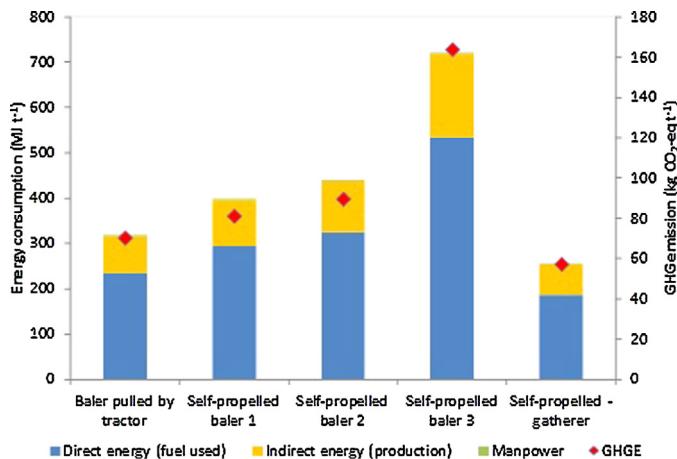
It was difficult to measure the exact diesel consumption of the machines because all five machines were made to work at the same time during the field demonstration. Hence, diesel consumption was calculated using Eq. [\(2\)](#) (adapted from [Oudshoorn et al., 2008](#)).

$$F = \frac{P.s.m}{\rho} \quad (2)$$

Where  $F$  is the fuel consumption in L t<sup>-1</sup>;  $P$  is the power delivered in kW, which is assumed as the full load of the machine based on its engine capacity;  $s$  is the specific diesel consumption in g(kWh)<sup>-1</sup>, which is selected as the maximum consumption ranging from 280 to 320 g(kWh)<sup>-1</sup> ([DLG, 2016](#));  $m$  is the engine load in%; and  $\rho$  is the specific weight of diesel, which is 0.832 kg l<sup>-1</sup> ([UFA, 2016](#)).



**Fig. 3.** (a) Energy consumption of rice straw collection using a roller baler pulled by tractor. (b) Energy consumption of rice straw collection using a self-propelled baler. (c) Energy consumption of rice straw collection using a gathering machine.



**Fig. 4.** Energy consumption and GHGE of rice straw collection.

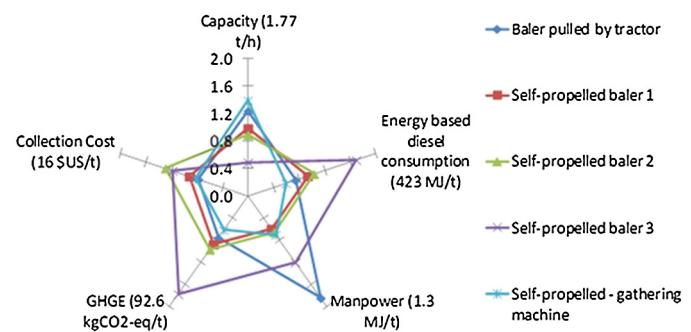
### 2.2.3. Energy calculation

EC was calculated based on Eq. (3).

$$EC = EC_{fuel} + EC_{production} + EC_{maintenance} + EC_{labor} [\text{MJ t}^{-1}] \quad (3)$$

Where  $EC_{fuel}$ ,  $EC_{production}$ , and  $EC_{maintenance}$  are the energies converted from fuel (diesel in this case) consumption, production, and maintenance of the machines for all related operations, including collection, baling, and handling of the rice straw to the side of the fields (Table 1).  $EC_{labor}$  is converted from the manpower used for all related operations.

Manpower EC was calculated based on the metabolic equivalent of the task (MET) as shown in Table 2. This is the ratio of the human metabolic rate when performing an activity to the metabolic



**Fig. 5.** Research parameters of rice straw collection (values in parentheses are average values).

rate at rest (Ainsworth et al., 2011). This was then converted to energy value as MJ per hour of work (Quilty et al., 2014), with the assumption of an Asian human body weight of 54.4 kg (IAEA, 1998).

### 2.2.4. GHGE calculation

GHGE was calculated based on fossil fuel consumption using Greenhouse Gas Protocol 1.01 (Ranganathan et al., 2016), which is available in the SIMAPRO software (PRé, 2015).

### 2.2.5. Calculation of collection cost

The cost of rice straw collection was calculated based on the depreciation, maintenance, interest, fuel consumption, and labor of all related operations, including gathering, baling, and handling of rice straw to the side of the fields.

**Table 1**

Energy in diesel for fuel consumption, manufacture, and maintenance of machines.

Items	Energy Value (MJ L <sup>-1</sup> )	Source
Diesel burned in machinery (calorific value + deliver)	44.8	a, b, c, d
Manufacture and maintenance-based diesel consumption	15.6	d, e, f

Source: a-Pimentel and Pimentel (2008); b-SIMAPRO (2015b); c-Bowers (1992); d-Richard (1992); e- Pimentel D. (1992); f-Dalgaard et al. (2001).

**Table 2**

Energy conversion for manual labor in related operations.

Activity	Met	MJ h <sup>-1</sup>
Driving tractor and baler	1.9	0.44
Manual handling	3.93	0.89

MET: metabolic equivalent of task, the ratio of human metabolic rate when performing an activity to the metabolic rate at rest.

### 2.3. Software and method of statistical analysis

Calculation and simulation of the system were conducted using SIMAPRO software, version 8.0.5.13 (PRé, 2015). Energy analysis was based on Cumulative Energy Demand 1.09 (Gallen, 2010) whereas CO<sub>2</sub> equivalent analysis was based on Greenhouse Gas Protocol 1.01 (Ranganathan et al., 2016). These methods and library are available in SIMAPRO.

The measurements were conducted during actual field activities. Rice straw data, such as cutting heights, yield, and moisture content were calculated based on randomly replicated samples. The mean value and standard deviation of the data were calculated using Microsoft Excel software.

## 3. Results

### 3.1. Performance of the collection machines

The performance of the collection machines differed greatly in the density of bales, collection capacity, rice straw loss in the field, and diesel consumption (Table 3). Except for loose straw obtained from the gathering machine, straw roller-bales collected by the other baler machines had almost the same length of 70 cm. This could be attributed to the machines having the same length of roller-chambers. The specific weight of the roller-bales ranged from 73 to 104 kg m<sup>-3</sup> at an MC of 12.4 ( $\pm 1.21\%$ ) (MC of rice straw was slightly reduced after baling). Collection capacity ranged from 0.87 to 2.47 t h<sup>-1</sup>. Rice straw loss in the field (which remained in the

field after collection) was very different and ranged from 18 to 43%. Diesel consumption ranged from 4.2 to 11.9 L t<sup>-1</sup>.

### 3.2. Energy consumption and greenhouse gas emissions

Total energy consumption consisted of fuel used for the production and maintenance of machines and manual labor used for driving tractors and balers and handling straw. EC networks of the collection machines ranged from 351 to 588 MJ t<sup>-1</sup>, with the main contributions from direct and indirect energy obtained based on diesel used (Fig. 3a–c). GHGE ranged from 60 to 165 kg CO<sub>2</sub>-eq per ton of collected straw, depending on the energy consumption of the machines (Fig. 4).

### 3.3. Cost of rice straw collection

The cost of collecting rice straw also varied widely among baler types (Table 4). For the baler pulled by a tractor, the depreciation and interest cost did not account for the cost of the tractor, but was calculated as rental cost. The collection cost already included the cost of handling straw bales to the side of the field, which ranged from VND 240,000 to 400,000 t<sup>-1</sup> or from US\$12 t<sup>-1</sup> to US\$18 t<sup>-1</sup>.

## 4. Discussion

Fig. 5 shows the range of the researched parameters corresponding to the five collection machines. The average capacity of straw collection was 1.77 ( $\pm 0.62$ ) t h<sup>-1</sup>. The highest capacity was obtained from the gathering machine, followed by the baler pulled by a tractor. This could be explained by the fact that the gathering machine only collects loose rice straw and can thus move continuously without needing to stop to unload bales like other balers do. The baler pulled by a tractor has a higher baling capacity because it leaves the bales in the field, whereas self-propelled balers do the added work of taking the bales to the side of the field. The self-propelled baler, having the lowest capacity of 0.87 t h<sup>-1</sup>, can cover about 10 rounds of labor (8 for gathering and 2 for handling). In addition to that,

**Table 3**

Performance parameters of the collection machines.

Baler type	Specific weight of roller-bale (kg m <sup>-3</sup> )	Collection capacity (t h <sup>-1</sup> )	Rice straw loss (%)	Diesel consumption (L t <sup>-1</sup> )	Notes
Baler pulled by tractor	93 (8.4)	2.20	21.4	2.61	Bales in the field
Self-propelled baler 1	73 (8.3)	1.75	17.7	6.57	Bales are collected to the side of the field
Self-propelled baler 2	104 (7.7)	1.58	21.9	7.26	
Self-propelled baler 3	75 (10.5)	0.87	42.6	11.92	
Gathering machine	NA	2.47	NA	4.18	Loose straw is collected to the side of the field

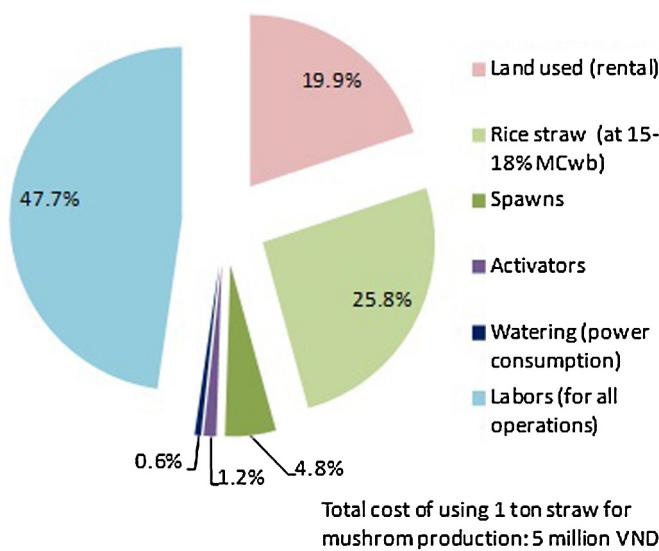
Value in parenthesis is standard deviation.

**Table 4**

Cost of rice straw collection (VND t<sup>-1</sup>).

Baler type	Depreciation + interest	Diesel consumption	Labor	Rope for baling	Total
Baler pulled by tractor	53,450*	30,038	76,500	76,923	236,911
Self-propelled baler 1	92,570	75,550	34,200	76,923	279,243
Self-propelled baler 2	165,520	83,483	69,000	76,923	394,926
Self-propelled baler 3	108,610	137,053	38,100	76,923	360,686
Self-propelled – gatherer	65,166	48,107	138,000		251,273

\* Depreciation cost does not include the cost of tractor.



**Fig. 6.** Cost percentage of the components in mushroom production using 1 ton of straw.

straw cannot be baled manually. Therefore, mechanized collection is necessary to not only solve the problem of labor shortage, but also to enable ease of transportation and reduced cost.

The energy consumption of self-propelled balers was higher than the other collection machines because they moved on rubber-chain wheels. For a better comparison of balers and the gathering machine on energy balance and cost, an assessment that includes subsequently compressing loose straw into bales should be done. In comparison with manual collection, the energy consumption of mechanized balers, which is mainly from fossil fuels, causes an adverse impact. However, assuming that rice straw is collected and used for biogas production, this range of energy consumption ( $317\text{--}721 \text{ MJ t}^{-1}$ ) only accounts for 10–17% of the total input energy of rice straw anaerobic digestion, which generated a net energy of  $3500 (\pm 160) \text{ MJ t}^{-1}$  of straw (Nguyen et al., 2016).

The fossil fuel consumption of mechanized collection resulted in GHGE of  $70\text{--}160 \text{ kg CO}_2\text{-eq}$  for each ton of straw collected. This almost equaled the emission from burning the same amount of rice straw in the field, which was calculated based on the data mentioned in the introduction. However, assuming that this collected straw is used for biogas production (Nguyen et al., 2016), the biogas generated can replace the use of fossil fuels and thus reduce  $87 (\pm 4.3) \text{ kg CO}_2\text{-eq}$  for one ton of straw.

Mechanized collection also saves labor and solves the problem of labor shortage. Labor for driving tractors or balers and handling rice straw contributes to only about 0.25% of the total EC for mechanized collection. This result is similar to results in previous studies (Olesen et al., 2004; Dalgaard et al., 2001).

The cost of collection varies among the machines and depends not only on the parameters shown in Fig. 5 but also on the investment and maintenance cost of the machines. This cost range from US\$12 to US\$18 per ton of straw. Similarly, assuming that the collected straw is for anaerobic digestion (Nguyen et al., 2016), the value of biogas generated ( $390 \text{ m}^3 \text{ t}^{-1}$  of straw) for about 160 Liters of kerosene is about US\$160. It means that straw collection cost only accounts for 8–13% of the output value of processing.

In the MD of Vietnam, one of the popular uses of rice straw is for mushroom production. An assessment for this practice was done recently to find the role of the collection cost in this production, which resulted in the cost components shown in Fig. 6. The rice straw cost, including collection and transportation (50 km),

accounted for 25.8% of the total investment cost; net profit of mushroom production using 1 ton of straw was US\$123 ( $\pm 14$ ).

## 5. Conclusions

Collection plays an important role in the rice straw supply chain to prepare feedstock for further uses. This study made a techno-economic and GHGE evaluation of mechanized straw collection and has resulted in the following findings:

- The capacity of the collection machines was 0.87–2.47 t per hour for operation in the rice field with a straw yield of 4.72 t per ha. This mechanized operation can reduce labor requirement by 90%. The specific weight of baled straw was  $73\text{--}104 \text{ kg m}^{-3}$  at a moisture content of  $12.4 (\pm 1.21)\%$  in wet basis, higher by 50–100% than that of loose rice straw.

- Total energy consumption required was from 351 to 588 MJ per ton of straw collected, which accounted for 10–17% of the total input energy of using the collected straw for biogas production. This energy consumption from mechanization caused GHGE of  $60\text{--}165 \text{ kg CO}_2$  equivalent per ton of collected straw.

- The cost of straw collection ranged from US\$12 to US\$18 per ton of straw in the MD, accounting for 10–20% of the total investment cost of biogas or mushroom production; net profits of mushroom production was US\$123 ( $\pm 14$ ) per ton of straw used.

This study illustrated the feasibility of the mechanization of rice straw collection. Despite fossil fuel consumption in mechanization resulting in GHGE, mechanized rice straw collection can help avoid in-field burning, produce feedstock for further sustainable processing, and add value to rice production.

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## References

- ASAE, 1982. Moisture measurement grain and seeds. In: ASAE Standard, 29th ed. St. Joseph, MI, USA, pp. 3521.
- Ainsworth, B.E., Haskell, W.L., Herrmann, S.D., Meckes, N., Bassett, D.R., Tudor-Locke, C., Greer, J.L., Vezina, J., Whitt-Glover, M.C., Leon, A.S., 2011. Compendium of physical activities: a second update of codes and MET values. *Med. Sci. Sports Exerc.* 43, 1575–1581.
- Bijay-Singh, S.Y.H., Johnson-Beebout, S.E., Yadavinder, S.Z., Buresh, R.J., 2008. Crop residue management for lowland rice-based cropping systems in Asia. *Adv. Agron.* 98, 117–199.
- Buresh, R.J., Ramesh, K.R., Chris, V.K., 2008. Nitrogen transformations in submerged soils. In: Nitrogen in Agricultural Systems, Agronomy Monograph 49. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Segev Rd., Madison, WI 53711, USA.
- DLG, 2016. PowerMix DLG test, <http://www.dlg.org/tractors.html> accessed 2016.
- Dalgaard, T., Halberg, N., Porter, J.R., 2001. A model for fossil energy use in Danish agriculture used to compare organic and conventional farming. *Agric., Ecosyst. Environ.* 87, 51–65.
- Gallen, S.T., 2010. Implementation of Life Cycle Impact Assessment Methods: Ecoinvent Report No. 3. Ecoinvent Center. [https://www.ecoinvent.org/files/201007\\_hischier\\_weidema\\_implementation\\_of\\_lcia\\_methods.pdf](https://www.ecoinvent.org/files/201007_hischier_weidema_implementation_of_lcia_methods.pdf).

- IAEA, 1998. International Atomic Energy Agency [http://www-pub.iaea.org/MTCD/publications/PDF/te\\_1005v2.prn.pdf](http://www-pub.iaea.org/MTCD/publications/PDF/te_1005v2.prn.pdf).
- Kadam, K.L., Forrest, L.H., Jacobson, W.A., 2000. Rice straw as a lignocellulosic resource: collection, processing, transportation, and environmental aspects. *Biomass Bioenergy* 18, 369–389.
- Mandal, K.G., Misra, A.K., Hati, K.M., Bandyopadhyay, K.K., Ghosh, P.K., Mohanty, M., 2004. Rice residue management options and effects on soil properties and crop productivity. *Food. Agric. Environ.* 2, 224–231.
- Ngo, T.T.T., 2005. An Environmental-Economic Assessment of Rice Straw Burning Practice in the Mekong Delta, Vietnam. Master Thesis. Can Tho University, Vietnam.
- Nguyen, V.H., Nguyen, L.H., Truong, Q.T., Phan, H.H., 2013. Drivers of Postharvest Development and Milestones of ADB-IRRI Rice Postharvest Project in Vietnam. <https://baa4a644-a-d6d9d6da-s-sites.googlegroups.com/a/irri.org/postharvest-unit/vietnam/Postharvest%20status-ADB-IRRI%20-VN%20Proj.pdf?attachauth=ANoY7crV1g6c6kWQKS6giAdnbPTNpZR43yi045zQTwd46nYEIldCVDNjwVQps02bGcnKNcM3hfGup1kkToulc7Y50vHE-ulwpiM9uAwul7jDMc6Q-h83dKipnXTpCgSX4jYsuYfx3wE5brzCuyqwAzzbSqvCqR6afkrRX8dAmxThqYlu5rcmzNSS55HshPFrUgumej20cbcRy6W3QInukz2agMcoyr2VN.WFPgzKbzzy81QsiUwMDZFTN.QqlfiyECwqWOdAS&attredirects=0>.
- Nguyen, V.H., Topno, S., Balingbing, C., Nguyen, V.C.N., Roder, M., Quilty, J., Jamieson, C., Thornley, P., Gummert, M., 2016. Generating a positive energy balance from using rice straw for anaerobic digestion. *Energy Reports* 2, 117–122.
- Olesen, J.E., Weiske, A., Asman, W.A.H., Weisbjerg, M.R., Djurhuus, J., Schelde, K., 2004. FarmGHG, A Model for Estimating Greenhouse Gas Emissions from Livestock Report Nr. 202, Plant Production. [http://agrsci.au.dk/institutter/institut\\_for\\_jordbruksproduktion\\_og\\_miljoe/xxmedarbejdere.old/jeo/farmghg\\_a\\_model\\_for](http://agrsci.au.dk/institutter/institut_for_jordbruksproduktion_og_miljoe/xxmedarbejdere.old/jeo/farmghg_a_model_for).
- Oudshoorn, F.W., Gemtos, F., Sorensen, C.G., 2008. Direct and Indirect Energy Audit in Arable Crop Production and Mitigation Possibilities. In Project Report: Integration of Farm Management Information Systems to Support Real-time Management Decisions and Compliance of Management Standards. No. 212117. [http://pure.au.dk/portal/files/34601282/FF\\_Deliverable\\_6.4\\_final.pdf](http://pure.au.dk/portal/files/34601282/FF_Deliverable_6.4_final.pdf).
- PRé, 2015. SimaPro Database Manual Methods Library. <http://www.pre-sustainability.com/download/DatabaseManualMethods.pdf>.
- Quilty, J.R., McKinley, J., Pedea, V.O., Buresh, R.J., Correa, T.J., Sandro, J.M., 2014. Energy efficiency of rice production in farmers' fields and intensively cropped research fields in the Philippines. *Field Crops Res.* 168, 8–18.
- Ranganathan, J., Corbier, L., Bhatia, P., Schmitz, S., Gage, P., Oren, K., 2016. Greenhouse Gas Protocol. World Business Council for Sustainable Development, [www.ghgprotocol.org/files/ghgp/public/ghg-protocol-revised.pdf](http://www.ghgprotocol.org/files/ghgp/public/ghg-protocol-revised.pdf) (accessed 2016).
- Thuy, N.H., Shan, Y., Bijay-Singh, S.Y.H., Wang, K., Cai, Z., Yadavinder, S.Z., Buresh, R.J., 2008. Nitrogen supply in rice-based cropping systems as affected by crop residue management. *Soil Sci. Soc. Am. J.* 72, 514–523.
- Tran, C.T., Dinh, T.B.L., 2014. Agricultural Production Policies in Vietnam. [http://ap.fftc.agnet.org/ap\\_db.php?id=275&print=1](http://ap.fftc.agnet.org/ap_db.php?id=275&print=1).
- UFA, 2016. Diesel Fuel Characteristics and Resources, <http://www.ufa.com/petroleum/resources/fuel/diesel.fuel.resources.aspx> (accessed 2016).
- Yevich, R., Logan, J.A., 2003. An assessment of biofuel use and burning of agricultural waste in the developing world. *Global Biogeochem. Cy.* 17 (4), 1095, <http://dx.doi.org/10.1029/2002gb001952>.