Life cycle assessment-based process analysis for fuel-grade bioethanol production using rice straw

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ABSTRACT: Rice straw is a major biomass residue from rice cultivation, which reaches to a world average of 740 million tonnes/year generation. Open burning of rice straw in paddy fields is the common practice, which could result in an average greenhouse gas emission of 92 kg of CO_2 eq/tonne of dry rice straw and other harmful airborne emissions. Existing studies indicate that bioethanol production from rice straw is more environmentally benign, compared to alternative options, such as gasification for combined heat and power generation and dimethyl-ether production. This study analyses the net energy indicators and carbon footprint of fuel-grade bioethanol production processes from rice straw comparing three dehydration techniques: 1. Extractive distillation, 2. Azeotropic distillation, and 3. Pressure swing distillation. Chemical process simulations using the Aspen Plus software were utilized to evaluate the bioethanol production process from rice straw, with a plant output capacity of 222 litres/hr of fuel-grade bioethanol (99.7 vol% ethanol). The results show that the most environmental benign dehydration technique is extractive distillation. The findings from this study can support decision making for future waste-to-biofuel plants using waste rice straw in the world.

INTRODUCTION

Fuel grade bioethanol can be blended with gasoline in different proportions to produce gasohol blends (E10, E20, and E85). These gasohol blends can be used to fuel vehicles without any engine modifications. When compared with edible feedstocks for bioethanol production, a non-edible lignocellulosic material like rice straw is an attractive option. The annual global rice straw production is about 740.95–1,111.42 million tonnes. However, from the total generation a small percentage of rice straw is subjected to value addition. The major percentile of rice straw is opened burned within the fields. Thus, rice straw can be introduced as an abundantly available lignocellulosic feedstock material for bioethanol production.

Life cycle assessment of bioethanol production using rice straw, figures out the sustainability of the process in energy and environmental perspectives. Several studies have been conducted in different countries to assess the environmental and energy analysis of bioethanol production using rice straw. Existing plant data in each country is used for most of the studies. A Life Cycle Assessment (LCA) study conducted in Thailand concludes that bioethanol production is the most environmentally-benign approach among other sustainable value addition approaches (Silalertruksa & Gheewala, 2013). Studies done in Japan and Thailand report that heat and electricity produced using lignin contained solid residues and biogas from waste recovery are sufficient (with a surplus) to cater the process energy requirement for bioethanol plants using rice straw (Delivand, Barz, & Pipatmanomai, 2012), (Saga, Imou, Yokoyama, & Minowa, 2010). The existing LCA studies report positive Net Energy Values (NEV) and Net Renewable Energy Values (NRnEV) have been reported for bioethanol from rice straw. Net Energy Ratio values, NER > 1 and Renewability factors, Rn > 1 have been reported for bioethanol production using rice straw (Rathnayake, Chaireongsirikul, Svangariyaskul, Lawtrakul, & Toochinda, 2018). These studies have also resulted with net GHG emission reductions through bioethanol production using rice straw.

There are varieties of dehydration techniques used to obtain fuel grade bioethanol production processes, such as extractive distillation, azeotropic distillation, pressure swing distillation, molecular sieving, pervaporation, etc. No published study reports the environmental effect of each bioethanol dehydration technique. Hence, this study is focused on LCA-based process analysis for three dehydration techniques for bioethanol production using rice straw, which could support future decision making for new bioethanol plants from waste rice straw.

METHODOLOGY

Process description

Life cycle of the fuel-grade bioethanol production process is designed based on ISO 14040/44 LCA framework. Average global rice straw composition (cellulose 36.7 wt%, hemicellulose 23.9 wt%, lignin 16.0 %, and ash and others) was considered. The net energy consumption, net material consumption, and net GHG emissions were analysed for each process scenario. Process simulations and energy calculations are performed based on the considerations as follows,

1. Functional unit: 1,000 L of 99.7 vol% bioethanol
2. The effect from infrastructure process is considered negligible at this scale of study (Silalertruksa & Gheewala, 2009).
3. Energy used in transportation and raw material manufacturing is totally fossil energy.
4. Wastewater from bioethanol producing stages are treated for anaerobic digestion (Moriizumi, Suksri, Hondo, & Wake, 2012).

$$Generated\ Methane\ Amount(kg) = wastewater\ volume$$

5. Recovered biogas and solid residues (after pre-treatment) are used to cogenerate process heat and electricity.
6. Surplus electricity generated is credited to average grid-mix electricity.

Energy calculations for bioethanol process

For process analysis, the whole process (Figure 1) is categorized into five process stages; 1. Drying and Baling Stage, 2. Transportation Stage, 3. Pre-treatment Stage, 4. Ethanol Conversion Stage, and 5. Ethanol Dehydration Stage. Diesel volume for feedstock transportation is calculated using equation (01).

$$Disel\ volume\ (L) = \frac{distance\ (km) \times material\ amount\ (tonne)}{truck\ fuel\ economy\ \left(\frac{km}{L}\right) \times truck\ capacity\ (tonne)} \quad (01)$$

The energy consumption for transportation of chemicals from foreign countries to the port, is calculated from the equation (02) (Rathnayake et al., 2018).

$$E_{nautical} = 6000\ (km) \times 0.08 \left(\frac{MJ}{tonne \cdot km}\right) \times material\ amount\ (tonne) \quad (02)$$

Required inventory data and energy calculations for the remaining process stages for pre-treatment, conversion, and dehydration stages are obtained using the process simulation technique.

Net energy analysis

The net energy indicators were calculated according to equations (04), (05), (06), and (07).

$$Net\ Energy\ Value\ (NEV) = total\ net\ energy\ outputs - total\ net\ energy\ inputs \quad (04)$$

$$Net\ Energy\ Ratio\ (NER) = \frac{total\ net\ energy\ outputs}{total\ net\ energy\ inputs} \quad (05)$$

$$Net\ Renewable\ Energy\ Value\ (NRnEV) = total\ net\ bioenergy\ output - total\ net\ fossil\ energy\ input \quad (06)$$

$$Renewability\ (Rn) = \frac{total\ net\ bioenergy\ outputs}{total\ net\ fossil\ energy\ inputs} \quad (07)$$

Net GHG emissions and carbon footprint

Emission factors in all sub-processes (Ecoinvent 3.0, 2018) were obtained to evaluate the net GHG emissions and carbon footprint in each process scenario.

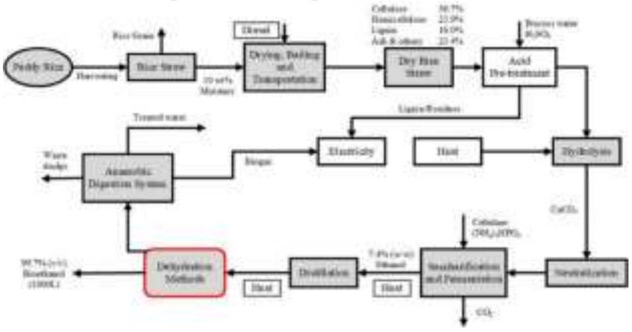

Figure 1. Cradle-to-gate bioethanol production process, using waste rice straw.

RESULTS AND DISCUSSION

Net energy analysis results

According to the stagewise energy results shown in Figure 2, for extractive distillation route, the dehydration stage consumes only about 12.41% of the total energy consumption, where the dehydration stage consumes the highest portion of total energy requirement for azeotropic distillation and pressure swing distillation routes. Thus, converting hydrous bioethanol to fuel grade anhydrous bioethanol is a more feasible option when extractive distillation is used as the dehydration technique.

Net energy indicator results illustrated in Figure 3 exhibit that extractive distillation is the most renewable and energy-wise sustainable bioethanol dehydration technique to produce fuel-grade bioethanol from rice straw. The same relationships could be observed for the carbon footprint of the three techniques, where extractive distillation route has the lowest carbon footprint of 8.28 tonnes of CO_2 eq/1,000 L bioethanol.

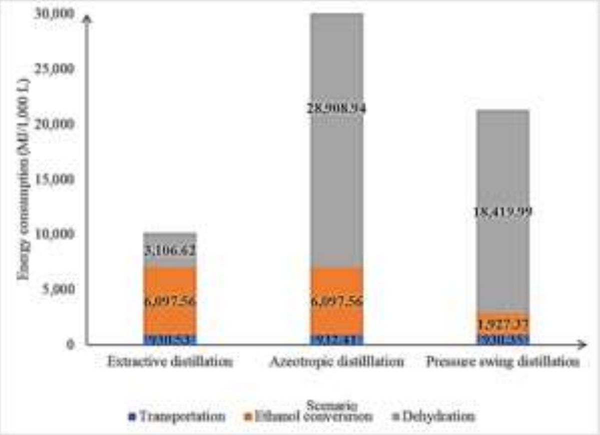

Figure 2. Stagewise energy consumption results

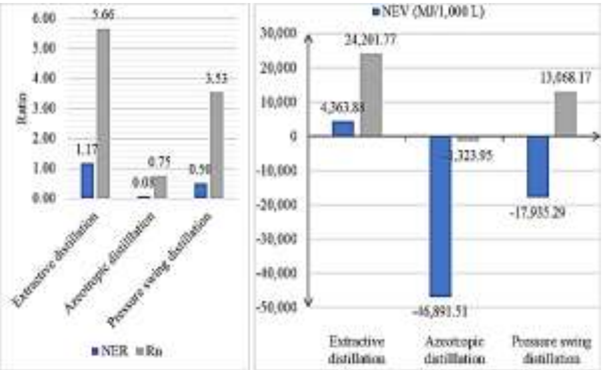

Figure 3. Net energy indicator results

CONCLUSION

This study extends a comparative analysis of net energy consumption and net GHG emissions on fuel-grade bioethanol production process from waste rice straw using extractive distillation, azeotropic distillation, and pressure swing distillation. Compared with the three dehydration techniques, extractive distillation comprises the most environmentally benign approach. Higher energy consumption in azeotropic distillation and pressure swing distillation cause them undesirable for fuel-grade bioethanol production using rice straw. The useful findings from this study would support decision making for future waste-to-biofuel plants using waste rice straw.

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