Techno-economic analysis of bioethanol production from rice straw by liquid-state fermentation

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Abstract. Renewable energy is the latest approach of the Malaysian government in an effort to find sustainable alternative energy sources and to fulfill the ever increasing energy demand. Being a country that thrives in the service and agricultural sector, bioethanol production from lignocellulosic biomass presents itself as a promising option. However, the lack of technical practicality and complexity in the operation system hinder it from being economically viable. Hence, this research acquired multiple case studies in order to provide an insight on the process involved and its implication on production as well as to obtain a cost analysis of bioethanol production. The energy input and cost of three main components of the bioethanol production which are the collection, logistics, and pretreatment of rice straw were evaluated extensively. The theoretical bioethanol yield and conversion efficiency obtained were 250 L/t and 60\% respectively. The findings concluded that bioethanol production from rice straw is currently not economically feasible in Malaysia’s market due to lack of efficiency in the pretreatment phase and overbearing logistics and pretreatment costs. This work could serve as a reference to future studies of biofuel commercialization in Malaysia.

1. Introduction
Biofuels among other renewable and sustainable energy resources offer a worthy solution to counter depleting conventional fuel sources as well as to put a halt to climate change. As a developing nation, Malaysia’s energy demand keeps increasing especially with the advancements in the industrial and transportation sector Malaysia [1]. One of Malaysia’s thriving economic sectors is the agricultural sector with palm oil and paddy being the most dominant [2, 3]. What both of these have in common is the abundance of waste agricultural residue generated from harvest. Research has shown that agricultural waste such as rice straw which is a crop residue that comes from paddy harvesting has a great potential to generate as biomass recourses for the generation of biofuels [4]. Its lignocellulosic biomass could be broken down into simple sugar via hydrolysis which is then fermented into the final product, bioethanol [5, 6].

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Rice straw can be found in abundance and currently has minimal practical uses which are as livestock feed or material for building [7]. However, despite the impressions that bioethanol production from rice straw is sustainable and environmentally benign, it has its technical limitations such as the difficulty and complexity in the operation system, low production yield and low biomass-to-product efficiency. Besides that, the produced fuels’s energy properties and production cost are yet to be determined before its viability and competitiveness in the current Malaysia’s economic market could be assessed. Hence, this work was dedicated to address this issue by reviewing Malaysia’s biomass potential and its current renewable energy alternatives in general. Detailed analysis on the process involved in the production of bioethanol from rice straw biomass through liquid state fermentation will allow the assessment of its technical and economical feasibility.

2. Methodology

2.1 Rice straw acquisition
The rice straw is collected from paddy fields in several states in Malaysia which were; Perlis, Penang, Kedah and Perak. The energy of the process is calculated according to Equation 1;

\[ E_{rsc} = E_{fc} \times F_{cc} \times A_{rsc} \]  

where \( E_{rsc} \) is the energy of rice straw collection (J), \( E_{fc} \) is the energy of fuel for collection (J/L), \( F_{cc} \) is the fuel consumed for collection (L/ha) and \( A_{rsc} \) is the area of rice straw collection (ha). As for the cost of rice straw collection, it is as expressed in Equation 2;

\[ C_{rsc} = (C_{fc} \times F_{cc} \times A_{rsc}) + (C_{dfe} \times R_{c}) \]  

where \( C_{rsc} \) is the cost of rice straw collection (RM), \( C_{fc} \) is the cost of fuel for collection (RM/L), \( C_{dfe} \) is the cost of driver fee for collection (RM/rate) and \( R_{c} \) is the rate for collection. The amount of bale that would be produced was calculated according to Equation 3;

\[ RSB = \frac{RST \times A_{rst}}{R_b} \]  

where \( RST \) is the total amount of rice straw produced (kg/ha), \( A_{rst} \) is the total plantation area (ha), \( RSB \) is the amount of rice straw bale (kg) and \( R_b \) is the bale size ratio (kg rice straw/kg bale).

2.2 Rice straw logistics
The logistics component of the production of bioethanol consists of transportation of the rice straw bale from the plantation area to either a collection center or directly to a processing plant. The energy involved was calculated according to Equation 4;

\[ E_{rst} = D_{t} \times E_{ft} \times F_{ft} \times N_{t} \]  

where \( E_{rst} \) is the energy of rice straw transportation (J), \( E_{ft} \) is the energy of fuel for transportation (J/L), \( F_{ft} \) is the fuel consumption of transportation (L/km), \( D_{t} \) is the distance of transportation (km) and \( N_{t} \) is the number of trips for transportation. The cost component is similar to the technical equation where energy is replaced with the cost of fuel shown in Equation 5;

\[ C_{rst} = (D_{t} \times C_{ft} \times F_{ft} \times N_{t}) + (C_{dft} \times R_{t}) \]  

where \( C_{rst} \) is the cost of rice straw transportation (RM), \( C_{ft} \) is the cost of fuel for transportation (RM/L), \( C_{dft} \) is the cost driver fee for transportation (RM/rate) and \( R_{t} \) is the rate for transportation.
2.3 Rice straw conversion
The rice straw conversion includes the hydrolysis and fermentation otherwise known collectively as the pretreatment process of the production. The summation of these adds up to give the amount of bioethanol that can be produced. For the energy involved, it is calculated based on Equation 6.

\[ E_{rsp} = M_{rs} \times \sum (E_{rs,pre} \times \eta_{conv}) \]  \hspace{1cm} (6)

where \( M_{rs} \) is the mass of rice straw that will undergo the converting process (kg) and is a product of \( RST \cdot A_{rst} \), \( E_{rsp} \) is the energy of rice straw pretreatment (J), \( E_{rs,pre} \) is the energy of rice straw pretreatment processes (J/kg) (hydrolysis and fermentation), and \( \eta_{conv} \) is the conversion efficiency.

The economic version of the pretreatment process then becomes the cost of each of the required components for the pretreatment to take place as shown in Equation 7.

\[ C_{rsp} = M_{rs} \times \sum (C_{rs,pre}) \]  \hspace{1cm} (7)

where \( C_{rs,p} \) is the cost of rice straw pretreatment (RM) and \( \sum C_{rs,pre} \) is the cost of all the pretreatment processes (RM/kg). Other pretreatment component such as the mechanical pretreatment will be included for processes that involves multiple types of pretreatment. The equation then becomes;

\[ C_{rsp} = M_{rs} \times [(\sum C_{rs,pre}) + C_{rs,pre M}] \]  \hspace{1cm} (8)

where \( C_{rs,pre M} \) is the cost of mechanical pretreatment process (RM/kg).

2.4 Bioethanol production
The bioethanol yield is calculated according to Equation 9;

\[ Y_{ethanol} = RST \times A_{rst} \times Y_{theoretical} \times \eta_h \times \eta_f \]  \hspace{1cm} (9)

where \( Y_{ethanol} \) is the bioethanol yield (L), \( Y_{theoretical} \) is the theoretical bioethanol yield from rice straw (L/kg), \( \eta_h \) is the hydrolysis efficiency and \( \eta_f \) is the fermentation efficiency.

3. Results and discussion
3.1 Bioethanol yield from rice straw
From an amount of roughly 1.3million rice straw produced annually, the potential bioethanol yield is calculated [8]. Thus, with pretreatment efficiency of 51%, hydrolysis of 90% and fermentation of 50%, the annual theoretical yield of bioethanol is 340 million liter.

3.2 Energy consumption in bioethanol production
The total energy input was calculated as 26.67 MJ/L bioethanol produced. Comparing this value to the amount of energy released from the combustion of ethanol which is 21.2 MJ/L, it gives overall deficit of 5.44 MJ/L of energy. This shows that ethanol with its lower energy content and high energy input would not be a viable a fuel source.

3.3 Life Cycle Cost Analysis (LCCA)
The LCCA of this study was conducted to evaluate the three components of bioethanol production; Rice straw collection, logistics, and pretreatment. As demonstrated in Table 1, the major cost of the process comes from logistics.
Table 1. Cost distribution of bioethanol production

| Process    | RM/bale | Weightage (%) |
|------------|---------|---------------|
| Collection | 20.44   | 23            |
| Logistics  | 48.79   | 23            |
| Production | 20.47   | 54            |

3.4 Rice straw collection and pretreatment
For rice straw collection, the labor contributes to majority of the cost (63%), followed by machinery (20%), fuel (9%), and twine (8%). Meanwhile, for rice straw pretreatment, the major cost comes from sulfuric acid (RM 0.48/L) and the total costs were RM 1.51/L (with acid recovery) and RM 7.85/L (without acid recovery).

4. Conclusion
It can be concluded that rice straw presents a great potential as a biomass for bioethanol production. The theoretical bioethanol yield and conversion efficiency obtained were 250 L/t and 60% respectively. Despite having low conversion efficiency, the yield could be improved by optimizing the pretreatment process. From the economical perspective, it was found that the bioethanol production form rice straw is for the moment not viable due to expensive logistics and pretreatment components.

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