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Global warming potential and energy analysis of second generation ethanol production from rice straw in India

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HIGHLIGHTS

- First LCA study of second generation ethanol based on DA and SE pretreatment technologies in India.
- Enzyme production is identified as the major GHG emissions and energy consumption process in ethanol production.
- SE is better than DA in terms of ethanol yield and GHG emissions reduction.
- Surplus electricity produced in the ethanol plant replaces coal based grid electricity and makes the process more greener.
- Cellulosic ethanol production in India is sustainable from GHG and energy savings perspective.

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ABSTRACT

The environmental sustainability of cellulosic ethanol production from rice straw in India is conducted using life cycle assessment (LCA). Greenhouse gas (GHG) emissions, net energy ratio (NER) and net energy balance (NEB) are studied for ethanol production system using two diverse pretreatment technologies, *i.e.* dilute acid (DA) and steam explosion (SE) followed by separate hydrolysis and fermentation. 1 ton of rice straw is the reference flow of study and 1 MJ transportation fuel is the functional unit while comparing the results with gasoline. The inventory data is collected based on several experiments conducted at our pilot plant and is a novel contribution to country specific LCA. Using DA and SE, the ethanol yields from the processing of 1 ton straw are 239 and 253 L and life cycle GHG emissions are 292 and 288 kg CO_2 eq./ton straw respectively. The results indicated that production of enzyme used in hydrolysis is the major contributor to GHG emissions in both DA (54%) and SE (57%) methods of ethanol production. The net energy input during the life cycle of ethanol is 1736 and 1377 MJ/ton straw in DA and SE respectively. The major GHG emissions and energy benefits are obtained using lignin produced in the plant to generate electricity resulting in displacement of the coal based electricity. With a higher xylose recovery in the SE, it gives larger amount of ethanol and also generates more surplus electricity. Enzyme production and its use are identified as GHG emission and energy consumption hotspot in the ethanol production process. While comparing the results with gasoline, DA and SE resulted in a reduction of 77 and 89% GHG emissions and NER of 2.3 and 2.7 respectively. The E5 blending would reduce GHG emissions by 4.3% (DA) and 4.8% (SE) whereas; E20 blend would lead to a reduction of 17.4% (DA) and 18.8% (SE) respectively. Sensitivity analysis indicates that with every 12.5% increase in the price of rice straw from the base case, there is a 2.3% increase in GHG emissions and vice versa. 1 FPU/g WIS increase during hydrolysis gives 2.9% increase in ethanol production, but at the same time there is an increase of 5% emissions from enzyme production. The results of the study conclude that cellulosic ethanol production technology in India is sustainable from GHG reduction and energy efficiency perspective.

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1. Introduction

The spike in global energy demands due to growing economies like of India and China poses an intimidating challenge to mitigate greenhouse gas (GHG) emissions [1]. Various countries across the globe have drawn their plan to reduce GHG emissions by switching

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over to ethanol, which is considered as an alternative to transportation fuel. Brazil is using sugarcane as a feedstock to produce ethanol and is leader in the world, whereas United States (US) programme is based on corn [2,3]. The European Union (EU) and US promotes biofuels with an intention to reduce carbon emissions in transportation sector. The main instruments in Europe are directives from European Commission which set specific target of 10% renewable energy use in transportation sector by 2020 and reducing 6% GHG emissions in transportation sector [4]. In the lines with the EU and the US, Indian government has also mandated use of 20% blends of ethanol across the country by 2017 [1,5].

Ethanol derived from food crops like corn and sugarcane, classified as first generation ethanol have been promoted over the past two decades, however, leading to intense debate on the food versus fuel [2]. Therefore, to meet the demand of fuel ethanol, there is a need to utilize the non food based materials such as lignocellulosic materials from agriculture and forestry for ethanol production. Rice straw, a by-product of rice is one of the most abundant lignocellulosic agricultural residues across the world. In 2014, the annual world rice production was 718 MMT, wherein, China (206 MMT) was the largest producer followed by India (152 MMT) [6]. The most common practice to manage the straw in India is to burn it in the fields so as to make the fields ready for the next crop [6]. The utilization of surplus rice straw for the ethanol production in India could therefore be highly beneficial for enhancing energy security, meeting increased fossil energy demand, reducing environmental pollution and improving rural economies [5].

The straw contains 35–40% of cellulose, 17–25% of hemicelluloses and 10–20% of lignin apart from significant amount of extractives and silica [7]. These polymeric carbohydrates (cellulose and hemicellulose) can be hydrolyzed to glucose, xylose, galactose, arabinose and mannose using chemicals, enzymes and are further converted to ethanol using *Saccharomyces cerevisiae* [7,8]. However, due to recalcitrant nature of biomass, extracting sugars from these residues poses challenges. Thus, pretreatment process is an essential step in any biochemical conversion process to hydrolyze structural carbohydrates into sugar monomers. The main aim of the pretreatment is to improve hexose and pentose sugar yields in downstream processing and remove or disrupt the protective layer of lignin from the biomass in order to make the polymeric carbohydrates more amenable to enzymes [9,10]. Above all, pretreatment process is an important step in the biomass conversion to ethanol process which determines the ethanol yield [11,12]. There is a wide range of pretreatments available for producing cellulosic ethanol and are broadly classify in four categories as given in Table 1.

In general, many of the cellulosic ethanol technology have not been developed to the extent which can meet the demands of replacing fossil fuels. Nevertheless, most of the pretreatment methods are still being under development and there is a limited knowledge on the impact of these technologies on GHG emissions and energy use [13]. This study aims to compare two most widely used pretreatment technologies of dilute acid (DA) and steam explosion (SE) using the data obtained from pilot scale in India and establish which of the process is most suitable for scale up.

Table 1
Pretreatment methodologies for conversion of biomass to ethanol [11,13].

Pretreatment types	Process/methods
Physical	Grinding, wet milling, dry milling
Physicochemical	Microwave/ionic liquids, steam explosion (SE)
	Catalyzed SE, ammonia fiber explosion (AFEX)
Chemical	Alkaline hydrolysis, dilute acid (DA)
	Organosolv, ozonolysis, ionic liquids
Biological	Fungal degradation

The GHG emission reduction potential of cellulosic ethanol is recognized in policies of transportation sector *i.e.* California's Low Carbon Fuel Standard (LCFS), the US Renewable Fuels Standard (RFS) and the EU Renewable Energy Directive (RED) [14,15]. US Environment Protection Agency (EPA) has classified advanced biofuels, which reduces the GHG emissions >60% as compared to gasoline. US EPA has also categorized each biofuel with distinct identification number and with GHG reduction potential. Therefore, cellulosic ethanol must reduce >60% GHG emissions with respect to gasoline [16]. Thus, it is not sufficient to produce biofuels, but the produced fuel must show the minimum legislated GHG reductions. In the US and the Europe, the financial incentives are extended only to those biofuels, which meet the GHG reduction criterion [16,17] and India along with other countries are most likely to follow the similar practice. Therefore, in order to establish the US EPA criteria is met, it is essential to carry out the life cycle assessment (LCA) of the biofuel production [18], which is a conceptual framework to assess the environmental and potential impacts associated with a product throughout its life cycle.

Numerous authors in different countries have worked on the environmental and energy analysis of lignocellulosic ethanol technologies. For instance; Wang et al. [3] evaluated well to wheel emissions for corn, sugarcane and switchgrass based ethanol in US. Sinistore et al. [19] studied the impact of regional differences on LCA of switchgrass ethanol by studying its production in Wisconsin and Michigan agricultural contexts. McKechnie et al. [20] explored the impacts of process technology development and regional factors on life cycle greenhouse gas emissions of corn stover ethanol in US. Prasad et al. [13] and Wang et al. [12] evaluated different pretreatment process for ethanol production from corn stover and wheat straw in UK. Zech et al. [14] conducted environmental and economic assessment of Inbicon lignocellulosic ethanol technology varying the feedstock, pentose-use, process energy, enzyme production and location parameters. Karlsson et al. [21] presented a comparative LCA of ethanol production from agriculture residue and forest waste based on two different methodology. Guo et al. [22] studied the environmental profile of bioethanol produced from current and potential future poplar feedstocks in the EU. LCA studies by authors of [23–26] considered GHG and energy analysis of ethanol produced from corn stover. Having assessed the current literature, it was found that rice straw still remains a limited explored feedstock for ethanol production from LCA perspective. Some efforts have been made in other Asian countries like Thailand [27] and Japan [28] on straw ethanol based on data from other publications and default value. To the best of our knowledge, no evaluation of life cycle GHG and energy balances for lignocellulosic ethanol production in India has been published to date. This data gap is mainly due to the lack of reliable and systematic statistical data on biomass to ethanol processing at an industrial scale. In fact, this is the first LCA of cellulosic ethanol, based on a reasonably good size pilot plant of DA and SE, established at Indian Oil Corporation Limited (IOCL), Research and Development Centre, Faridabad. The inventory data is collected from actual experiments conducted at these plants. The main objective of this study is to find out the sustainability of cellulosic ethanol based on two diverse pretreatment technologies and to provide the outcome to the policy makers for decision making. The study analyzes the GHG emissions and energy use at each stage of ethanol production with an aim to identify the main GHG emission and energy consumption hotspots. The LCA results of current study are further compared with previously published cellulosic ethanol studies and with the LCA of other rice straw utilization practices in India.

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