CHAPTER 5

LIFE CYCLE ASSESSMENT OF SECOND GENERATION ETHANOL FROM RICE STRAW IN INDIA

Rice straw is the most abundant and surplus biomass available in India. In most of the northern states farmers usually burn straw in the fields so as to make their fields ready for the successive crop and therefore, adversely affecting the environment. Based on the compositional analysis of straw, researchers have identified rice straw as a potential feedstock for ethanol production. This chapter discusses in detail the sustainability of cellulosic ethanol i.e. 2G ethanol using two diverse pretreatment technologies i.e. dilute acid (DA) and steam explosion (SE) followed by separate hydrolysis and fermentation. Greenhouse gas (GHG) emissions, net energy ratio (NER) and net energy balance (NEB) are the indicators studied. Sensitivity analysis is also conducted on the uncertain parameters during the life cycle.

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5.1 INTRODUCTION

India is an agro-economic country with 13.7% share of agriculture in gross domestic product (GDP) [256]. Large varieties of crops are produced in different regions of India. Among these crops, rice is the most staple food crop that is consumed in largest quantity by human population. Rice, *Oryza sativa* is the grain of the grass species and belongs to family Poaceae. It is grown in different states of India having tropical climate, 8°-25° N latitude and an altitude of 2,500 meter above sea level. The ideal geographical conditions for growth are: temperature range between 15-25°C, rainfall of 150-200 cm and clayey/loamy/alluvial soil. The plant requires high humidity and heat and for its favorable growth. Plain fertile land and slope are must for growing rice as plant requires standing water in the field in initial phase of growth, as shown in Figure 5.1.

In 2015, the annual world rice production was 718 MT, wherein, China (206 MT) was the largest producer followed by India (152 MMT) [256]. Consequently, rice straw is the most abundant agriculture residue produced, accounting to 23% of the total agricultural crop residue [151]. India is the world's largest country having large area grown under rice within wide range of agro ecological conditions. The production of rice straw depends on variety of rice, climatic conditions, fertilization level, farm size, irrigation facilities, soil type etc. Three major ecosystems in which rice is grown are rain fed upland (16%), rain fed lowland (42%) and irrigated lowland (42%) [257].

Figure 5.1 Rice plants growing in standing water at fields (Source: Internet Image)

In most states of India, farmers grow three crops in a year and the mode of harvesting is changing from manual to mechanical, which leaves the straw standing in the fields. To make field ready for the next crop farmers apply the illegal practice of burning the straw (Figure. 5.2) leading to harmful effects on the environment and soil nutrient loss [258]. This also creates an adverse impact on environment and ultimately leads to serious health issues. Therefore, burning of rice straw should be avoided and utilization of such a potential biomass should be promoted. Straw can be utilized for different purposes such as manure, paper industry, roofing material, fodder, electricity, ethanol, biogas etc. [259]

Figure 5.2 Farmers of India burning rice straw in the field (Source: Internet Image)

Among all these practices, use of rice straw for making ethanol is a promising technology for enhancing energy security, meeting increased fossil energy demand, reducing environmental pollution and improving rural economies [260]. Moreover, ethanol derived from food crops like corn and sugarcane categorized under first generation are now under intense debate of food versus fuel [261]. 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 most abundant lignocellulosic agricultural residues in most Asian countries. It has been identified as a potential feedstock for making ethanol as it contains 35–40% cellulose, 17–25% hemicelluloses and 10–20% lignin apart from significant amount of extractives and silica [262]. These polymeric carbohydrates (cellulose and hemicellulose) can be hydrolyzed to monomer sugars (glucose, xylose, galactose) by the action of chemicals, enzymes and further converted to ethanol using *Saccharomyces cerevisiae* [262, 263] . However, due to recalcitrant nature of biomass, extracting sugars from these residues poses challenges. Thus, pretreatment is an essential step in biochemical conversion pathway as it hydrolyzes structural carbohydrates into sugar monomers. During pretreatment, the protective layer of lignin from the biomass is broken down and this makes polymeric carbohydrates more accessible to enzymes [125, 264]. The main aim of pretreatment is to improve overall sugar recovery as ethanol yield is dependent on the effectiveness of pretreatment method [124, 133]. There is a wide range of pretreatment methods available for producing cellulosic ethanol and are broadly classified in four categories as given in Table 5.1.

Table 5.1 Pretreatment methodologies for conversion of biomass to ethanol [126, 133]

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

In general, many of the cellulosic ethanol technologies have not been developed to the extent which can substitute fossil fuels. Nevertheless, most of the technologies are under research and development phase, with limited knowledge on the impact of these technologies on GHG emissions and energy use [126]. 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 [265]. 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 [265, 266] 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 [267], which is a conceptual framework to assess the environmental and potential impacts associated with a product throughout its life cycle.

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 [171] and Japan [115] on straw ethanol based on data from other publications and default values. 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. Infact, 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.

5.2 AIM OF STUDY

The aim of study is to find out the sustainability of cellulosic ethanol based on two diverse pretreatment technologies of DA and SE. 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.

5.3. METHODOLOGY

In order to meet the objective of increasing ethanol demand, two pilot scale plants based on DA (Figure 5.3) and SE (Figure 5.4) were installed 5 years ago at IOCL. Moreover, Government of India is very serious to put up several commercial scale cellulosic ethanol plants very soon. In order to assess IOCL lignocellulosic ethanol technology, the characteristic features of pilot plant are studied in detail. The methodological approach to analyze GHG emission and energy use is explained afterwards based on an input-output LCA model.

Figure 5.3 Lignocellulosic pilot plant based on dilute acid pretreatment

Figure 5.4 Lignocellulosic pilot plant based on steam explosion pretreatment

5.3.1 CHARACTERISTICS OF THE IOCL 2G ETHANOL TECHNOLOGY

In India, the technology for biomass conversion to ethanol are under research and development phase and only few have been successful to establish the technology at pilot scale [147]. The technological feature of IOCL is shown in Figure 5.5. Biomass is initially milled, soaked in acid and then structure is broken with steam using two diverse pretreatment technologies of DA and SE. Both the pretreatment technologies have different set-up in two distinct plants and operate at different temperature and mechanism of solubilizing C5 sugar from the hemicellulose in liquid hydrolysate. After pretreatment, the solid obtained in the form of slurry, predominantly having C6 sugars are directly used for enzymatic hydrolysis to obtain monomeric sugars. The C6 and C5 monomers are then co-fermented using yeast strain to produce ethanol. The leftover lignin and holocellulose residues are burnt internally in co-generation plant to produce electricity. The energy requirement of plant is met up by internal bio-electricity, and surplus electricity is sold to the grid that displaces coal based electricity. The waste water generated during the process is anaerobically digested for production of biogas. The process conditions are optimized after conducting large set of experiments in pilot facility and these conditions would be transferred to the demonstration scale in near future.

5.3.2 GOAL AND SCOPE

Life cycle assessment (LCA) is conducted used for 2G ethanol and estimates the GHG emissions and their reduction potential as compared to the gasoline [268]. Based on ISO guidelines the impacts from cultivation of straw are not included in study as these are agriculture residues and not the dedicated energy crops. Biogenic CO_2 emissions from each stage of life cycle are assumed to be neutral as CO_2 produced during production is utilized by the plants in their next cultivation cycle. Some authors have studied direct and indirect land use changes [117, 269] while producing ethanol from biomass. However, rice straw is a residue and not a crop, therefore, land use changes are not accounted in the results of the current study. Allocation and system expansion are conducted to deal with multi-functionality.

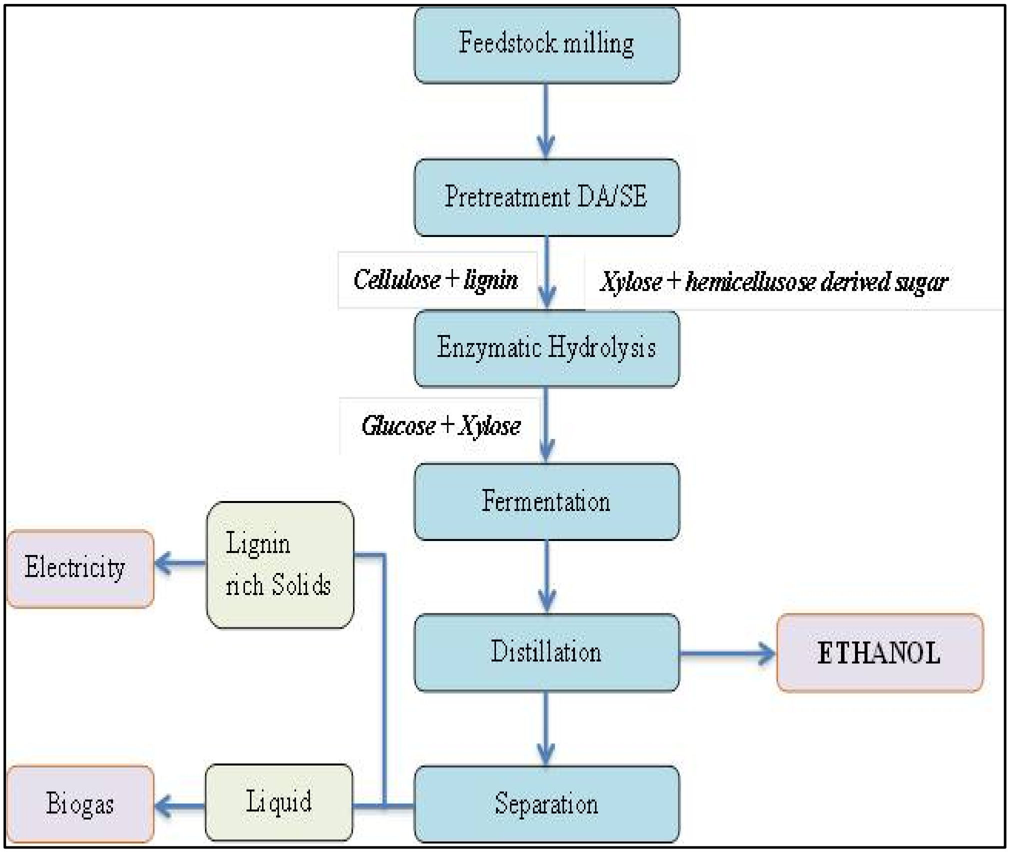


Figure 5.5 Cellulosic ethanol production technology of IOCL

5.3.2.1 System Boundary

The ethanol processing pilot plant is situated in Faridabad, 30 miles southeast of New Delhi, the national capital. The processing capacity of both the DA and SE plant is to 250 kg dry biomass/day. The system boundary shown in Figure 5.6 has the following unit processes: biomass collection, biomass transport, pretreatment, enzymatic hydrolysis, fermentation, distillation and dehydration, ethanol blending, distribution and end use. The ethanol produced from the processing of 1 ton straw is the reference flow of the study and while comparing the results with gasoline as a reference system, 1MJ of transportation fuel is chosen as the functional unit. In the near future, rice straw could be a more valuable by-product; therefore, sensitivity analysis is conducted by extending the system boundary and including agriculture phase in the analysis. The electricity use and surplus produced in the plant are represented as separate units in study so as to make results more clear and relevant.

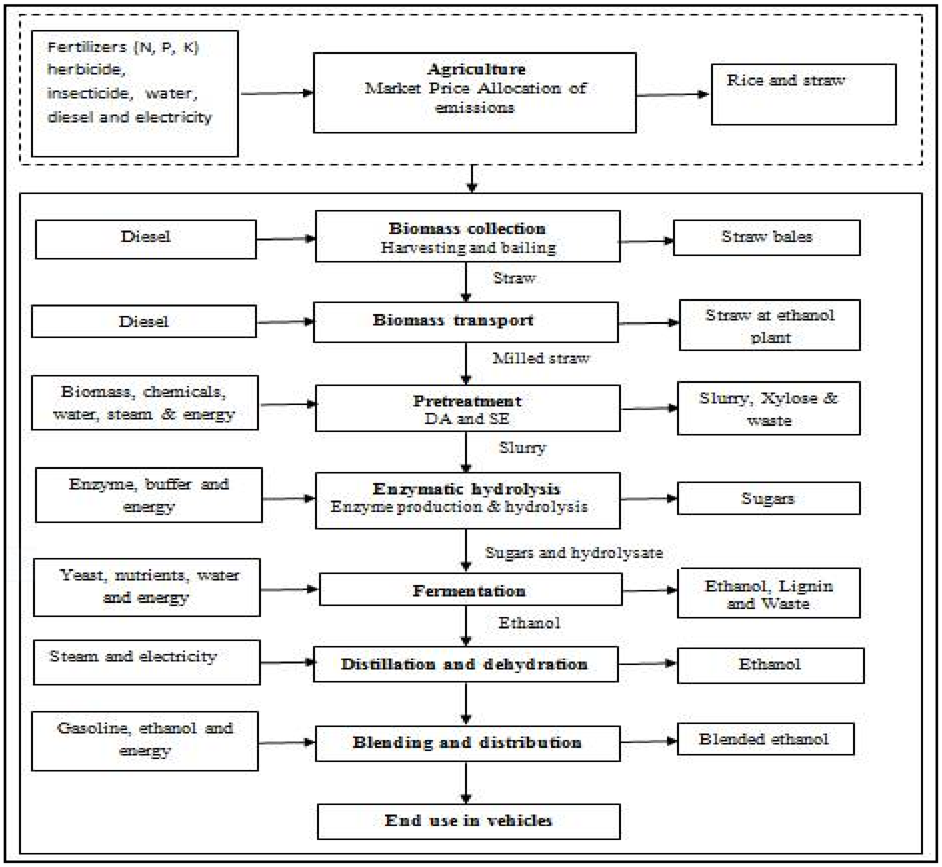


Figure 5.6 System boundary of 2G ethanol from rice straw

5.3.3 LIFE CYCLE INVENTORY (LCI) AND PROCESS DESCRIPTION

Being the first cellulosic ethanol LCA study in India, collection of data was a challenging task. Therefore, the data and facts about cellulosic ethanol are taken from three sources:

- Harvesting and collection: Various site specific studies and research papers [259, 270]
- Transportation and distances: Personal communication with industrial experts
- Biomass processing to ethanol: Experiments undertaken at the pilot plant and in the laboratories of the IOCL.
- Energy flow: Based on NREL reports [271]

Microsoft excel spreadsheet are used to register and organized the collected data for each unit process. The detail of each process is described in following paragraphs:

5.3.3.1 Biomass Collection

The harvesting of rice is mostly a mechanical process and is conducted by leaving the straw 15 cm above the ground so that the carbon content of soil remains unaffected. Straw is collected manually and bailed with the machines on the field. The average mass of bale is 20 kg. The average yield of rice obtained is 3.5 ton/ha and based on the straw to grain ratio (SGR) of 1.2 [259, 270] calculated straw production is 4.2 ton/ha.

5.3.3.2 Biomass Transport

The baled straw is transported from the field to the collection centre (average distance 10 km) by the tractor. The carrying capacity of tractor is 1.5 ton and diesel consumption is 4.5 km/L on loaded and 5.5 km/L on unloaded conditions. The rice straw from collection centre is then transferred to the plant (average distance 50 km) by truck. The carrying capacity of the truck is 10 ton and diesel consumption is 4km/L on loaded and 5 km/L on unloaded conditions.

5.3.3.3 Pretreatment

Upon reaching the ethanol plant, straw is debaled and reduced to a size of ~10 mm with the knife mill. The crushing capacity of the mill is 200 kg/hr with the power consumption of 5.5 kWh. The rice straw obtained after milling has moisture content between 6-10%, which is directly used for pre-soaking in acid solution before pretreatment. During pretreatment most of the hemicellulose is converted to xylose and a very little cellulose is also converted to glucose. The pretreatment technologies differ in terms of chemical and energy input and also on the recovery of sugars. Life cycle GHG emissions and process energy use are dependent on these parameters and therefore, impact the LCA results [126]. The two different pretreatment processes analyzed in this study are DA and SE and discussed in following paragraphs:

- **Dilute acid (DA):** The pilot plant consists of series of equipments such as loss in weight feed hopper, pug mill, shredder and horizontal reactor. The process begins with the impregnation of straw in 1% w/w sulfuric acid for 30 minutes at room temperature. The excess water from straw is removed using a pneumatic hydraulic press. The acid soaked rice straw together with steam is reacted at 162°C for 10 minutes at 5 bar pressure.
- **Steam explosion (SE):** The pilot plant comprises of high pressure reactor of 10 L made of stainless steel (SS) equipped with feeding device, cyclone separator, quick opening pneumatic butterfly valve, boiler and a noise absorber. Before starting the experiment, the digester is flushed 3-4 times with steam at 15 bar to quickly attain the desired operating temperature. The pretreatment is performed using 0.5% (w/w) sulfuric acid for 10 minutes at 190°C.

Table 5.2 Process parameters and recovery in ethanol production process

Pretreatment	**Dilute acid (DA)**	**Steam explosion (SE)**
Temperature (ºC)	162	190
Pressure (bar)	5	15
Acid concentration (%)	1	0.5
Residence time (min)	10	10
Glucose recovery (%)	95	95
Xylose recovery (%)	59	73
Enzymatic hydrolysis		
Temperature	50	50
WIS/ Total solids loading (%)	15/ ~20	15/~20
Residence time (hrs)	48	48
Saccharification yield (%)	74	72
Fermentation		
Temperature (°C)	32	32
Pressure (bar)	1	1
Residence time (days)	2	2
Glucose to ethanol (%)	90	90
Xylose to ethanol (%)	80	80

The slurry obtained after pretreatment process is neutralized using sodium hydroxide to a pH of 5.0 for saccharification. The process parameters and sugar conversion efficiency of pretreatment, hydrolysis and fermentation is given in Table 5.2.

5.3.3.4 Enzymatic Hydrolysis

In this process, cellulose is hydrolyzed to glucose and residual hemicellulose to xylose with the help of cellulases. The neutralized solid received from pretreatment is directed to enzymatic hydrolysis with a solid loading of 20% and the enzyme dose of 10 FPU/g of water insoluble solids (WIS). The process includes emissions and energy use during the production of enzyme which is taken at par with the enzyme produced by a major commercial enzyme producer on the basis of equivalent activity.

5.3.3.5 Fermentation

The fermentation reaction is conducted by C5 and C6 sugars fermenting strains that are provided as a gift by NREL, USA. In the summation of impacts, the biogenic emissions from fermentation and lignin burning are assumed to be sequestered from the environment by photosynthesis during agriculture phase. Hence, CO_2 emissions produced in this unit process are not accounted into calculations.

5.3.3.6 Distillation and Dehydration

The fermented mixture is distilled in a distillation column to obtain anhydrous ethanol, which is further purified by pressure swing adsorption (P.S.A) using molecular sieves in purification columns to obtain fuel grade ethanol. In this technology, ethanol solution is vaporized and sent through a bed of molecular sieves at high pressure and on reducing the pressure; the ethanol is desorbed from the sieves and recovered. After distillation, the solids comprising of lignin is used to generate electricity at the plant and surplus electricity is exported. The liquid is treated anaerobically to produce biogas and is used in heating process of the plant.

5.3.3.7 Blending and Distribution

Ethanol is transported from the conversion plant to blending depots. After blending fuel is then distributed to the retail outlets. The transportation distance from ethanol plant to fuel station is 100 km and carrying capacity of the truck is 20 KL.

Table 5.3 Life cycle inventory for biomass to ethanol conversion process using DA and SE pretreatment technologies

Input	**Unit**	**DA**	**SE**
Biomass	kg	1000	1000
Chemicals			
$H_2SO_4{}^*$	kg	109	83
$NaOH^*$	kg	10	5
$(NH_4)_2PO_4{}^*$	kg	2.6	2.7
MgSO4[*]	kg	0.1	0.1
Yeast[*]	kg	1.2	1.3
Antifoam[*]	kg	0.4	0.5
Enzymes[*]	kg	29	30
Steam[a]	kg	1512	1176
Diesel[b]	L	25	25
Electricity[c]	kWh	136	146
Cooling water[d]	KL	119	101
Process water[d]	KL	21	24
Output			
Ethanol*	L	239	253
Surplus electricity[e]	kWh	256	303
Emissions			
GHG emissions	kg CO_2eq.	288	292
Avoided GHG emissions	kg CO_2eq.	-208	-246

[*] Calculated values from the experiments conducted at the pilot plant and laboratory at Faridabad

[a] The emissions and energy use in steam generation are included in overall electricity consumed in the process [264, 271], [b] Includes diesel required in harvesting, collection, bailing and transport of straw from field to ethanol plant,

[c] Electricity data adopted from NREL reports [264, 271]. Electricity consumed in ethanol production is produced from burning of lignin in the plant and surplus electricity is sold to the grid, [d][264], [e] Surplus electricity produced in DA and SE is 1.07 [271] and 1.20 kWh/L [9] respectively.

5.3.3.8 End use

The blended ethanol is used in transportation sector for gasoline spark plug engines. Based on the above process parameters, an input-output model is developed for the study and is given in Table 5.3.

5.3.4 ALLOCATION AND SYSTEM EXPANSION

During cellulosic ethanol production, multiple products are formed, such as grains from agriculture phase and in downstream processing along with the ethanol, lignin and biogas are produced. There are different allocation approaches such as mass, energy and economic to allocate emissions between product and byproduct [103]. Therefore, in the sensitivity analysis, emissions from agriculture phase are distributed between rice and straw based on economic allocation, one of the most suitable approach to handle agriculture residues [171]. An allocation factor of 0.13 is obtained for straw based on average economic price of rice 25000 Rs/ton (~367US$/ton) and 3000 Rs/ton (~44 US$/ton) for straw. System expansion is applied while allocating emissions between ethanol and surplus electricity produced in the plant. The surplus electricity produced from lignin is sold to the grid that replaces coal based electricity.

5.3.5 ANALYSIS OF GHG EMISSIONS AND ENERGY USE

The various emission and energy factors given in Table 5.4 are used to calculate the GHG emission and energy use during ethanol production chain. Most of the emission and energy factors given in Table 5.4 are specifically derived to Indian conditions; however, due to unavailability of factors at certain levels, they are adopted from reported literature of other countries. While using these factors, adjustments in calculations and assumptions have been considered, so, as the overall results remain unaffected.

5.3.5.1 Global Warming Potential (GWP)

GWP is a quantified measure of the globally averaged relative radiative forcing impacts of a particular greenhouse gases over a 100 year time horizon. The IMPACT 2002+ assessment method gives GHG emissions in units of equivalent released CO_2. The GHG impacts from CH_4 and N_2O are normalized to CO_2 eq. using a multiplier of 25 and 298 that reflects their GWP respectively [272].

5.3.5.2 GHG Emissions Reduction

The GHG emission reductions are calculated based on formula given in Eq. 5.1 [71, 72]. The emissions for 1MJ energy from gasoline and ethanol respectively are used in the given formula

$$\%\mathbf{GHG\ reduction} = \frac{\mathbf{GHG\ emissions_{gasoline}} - \mathbf{GHG\ emissions_{ethanol}}}{\mathbf{GHG\ emissions_{gasoline}}} * \mathbf{100}\% \qquad (\boldsymbol{Eq.5.1})$$

Table 5.4 GHG emission and energy factors for input used in LCI

Input	**GHG emission factor ($kgCO_2$eq./kg)**	**Reference**	**Energy factor (MJ/kg)**	**Reference**
H_2SO_4	0.2	[273]	3.6	[273]
NaOH	1.2	[242]	16.0	[274]
Enzymes	5.5	[275]	24.0	[142]
$(NH_4)_2PO_4$	2.8	[273]	7.8	[275]
KH_2PO_4	1.4	[273]	7.9	[275]
$MgSO_4.7H_2O$	0.6	[273]	3.6	[275]
Yeast	3.2	[276]	0.8	[276]
Antifoam	1.3	[275]	24	[275]
Diesel	3.6	[277]	38.6	[277]
Electricity*	0.8	[278]	3.6	[71]

* GHG emission factor is $kgCO_2$eq. /kWh and energy factor is MJ/kWh.

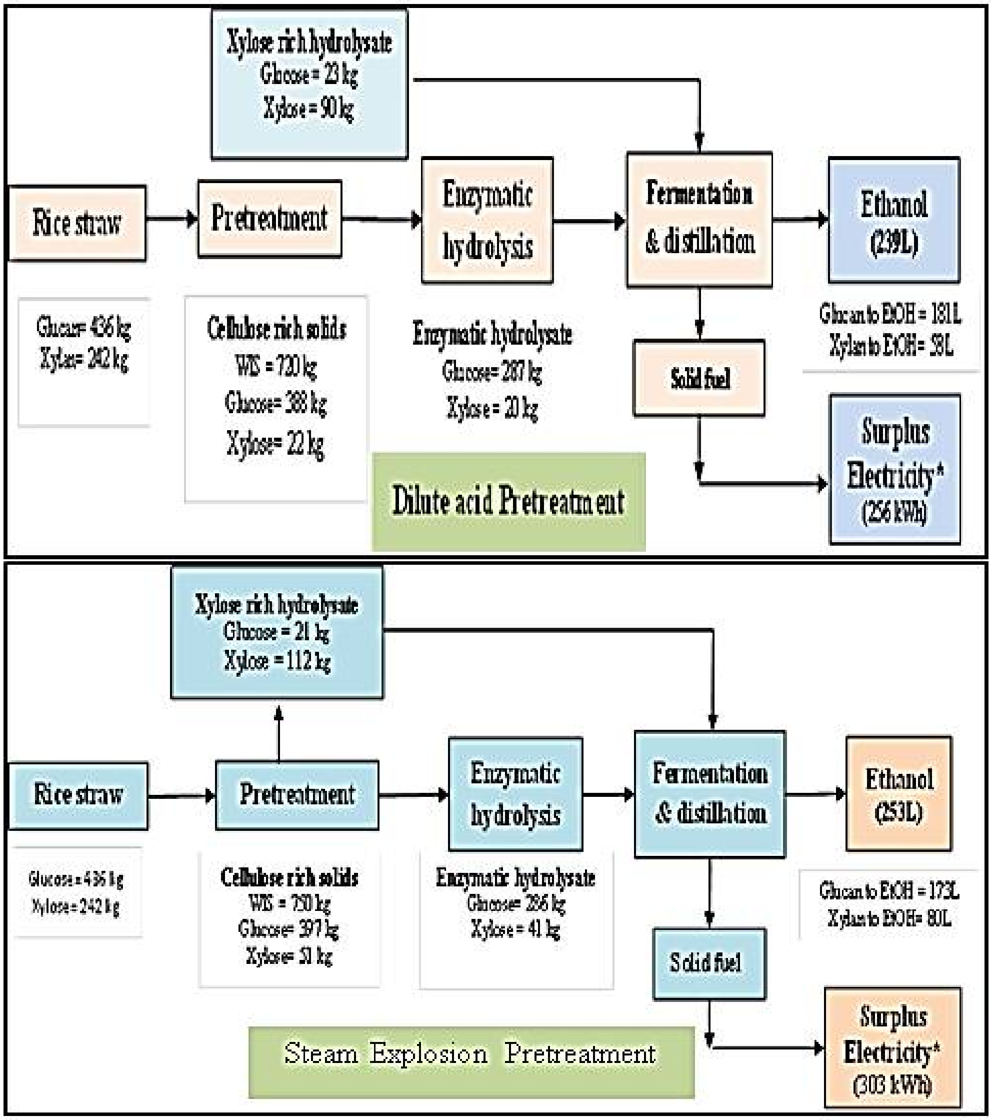
5.3.5.3 Net Energy Ratio (NER) and Net Energy Balance (NEB)

The NER and NEB are the most widely used indicators to estimate the renewability of ethanol [83, 125, 147]. The system is considered renewable only if NER>1 and NEB is positive. The following formulae are used to calculate NER and NEB [72].

NER= Total Output Energy /Total Input Energy
NEB= Total Output Energy -Total Input Energy

5.4 RESULTS AND DISCUSSION

Cherubini and Stromman [83] described that LCA studies of bioenergy systems that are at an early stage of development includes green house gas (GHG) emissions and energy use as impact categories. In this study the results are based on processing of 1 ton rice straw to ethanol via enzymatic hydrolysis and fermentation. While comparing results with gasoline as a reference system 1MJ transportation fuel is chosen as the functional unit. The detailed mass balance of both the pretreatment process is given in Figure 5.7.



* Electricity consumed in ethanol production is produced from burning of lignin in the plant and surplus electricity is sold to the grid. The energy use data is adopted from published literature and NREL report [264, 271]

Figure 5.7 Mass balance of ethanol production using two different pretreatment technologies

5.4.1 GHG EMISSIONS

1 ton of rice straw using DA and SE yields 239 and 253 L ethanol respectively. The amount of GHG emitted using DA and SE pretreatment technologies for processing 1 ton straw to ethanol are analyzed and shown in Figure 5.8 and 5.9 respectively. The stagewise GHG emission in DA and SE respectively follow the trend: enzymatic hydrolysis (54, 57%) > biomass collection (22%) > pretreatment (10, 7%) > biomass transport (6%) > fermentation (2.3%) > electricity use (1.7, 2.1%) > ethanol end use (2.0%) > blending and distribution (0.5%). In case of DA, of the total 292 kg CO_2 eq. GHG emissions, the emissions from enzyme production (159 kg CO_2 eq. / ton rice straw) accounts for 54% of total emissions. Similarly, in SE of the total 288 kg CO_2 eq./ton rice straw enzyme production (165 kg CO_2 eq.) accounts for 57% of total GHG emissions. The difference in GHG emissions among DA and SE pretreatment is due to variation in input used in the form of chemicals in pretreatment and enzyme in enzymatic hydrolysis.

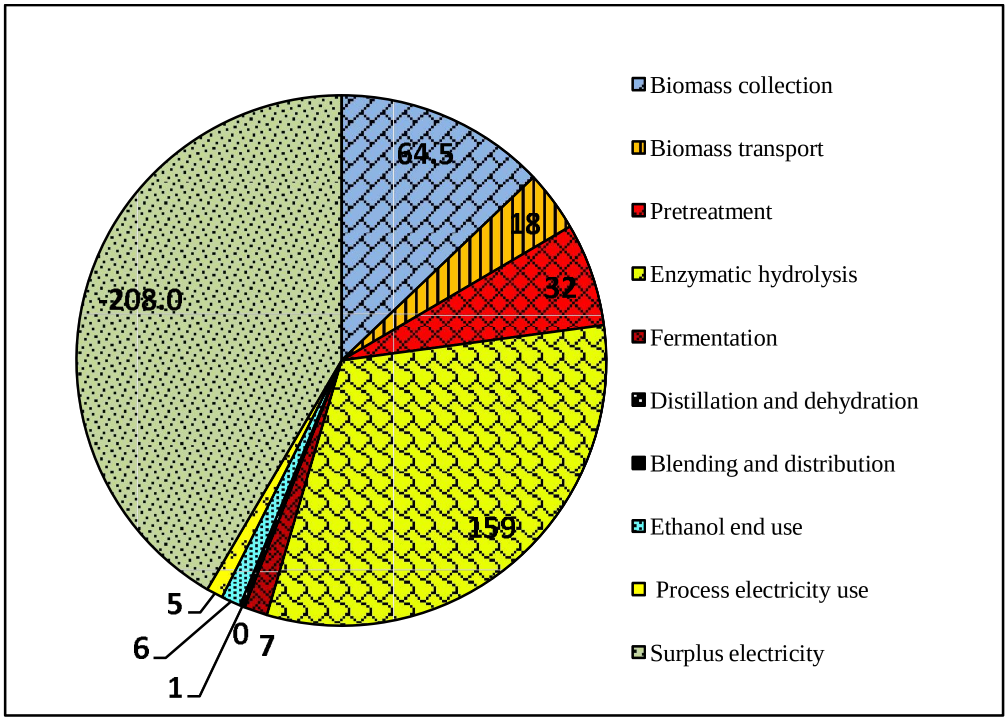


Figure 5.8 GHG emissions (kgCO_2eq.) from 1 ton processing of rice straw using dilute acid (DA) pretreatment

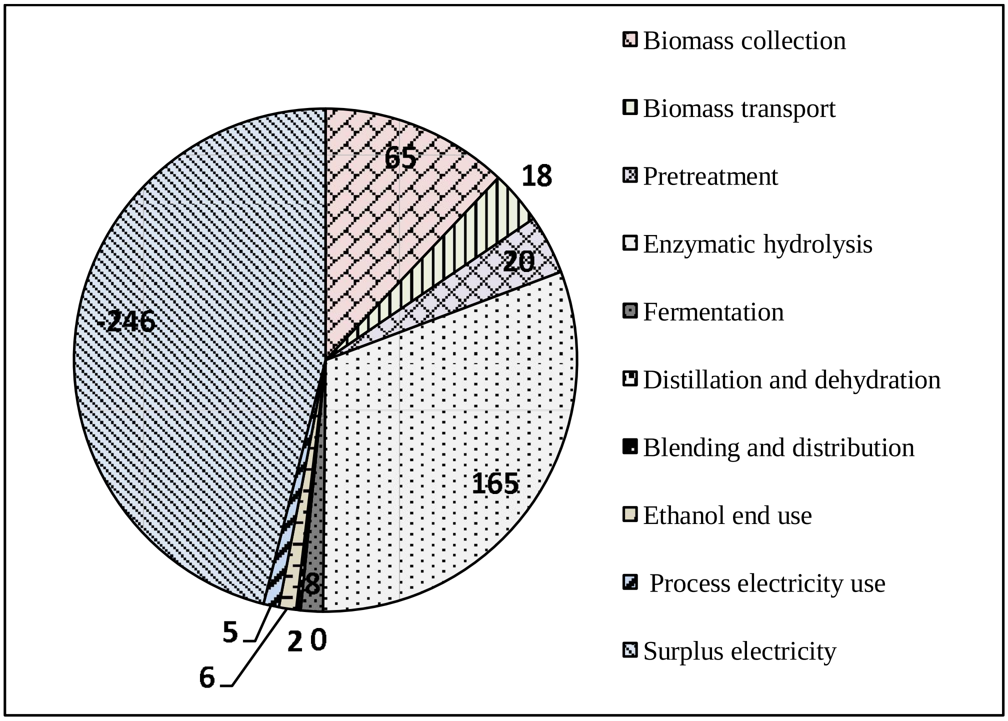


Figure 5.9 GHG emissions (kgCO_2eq.) from 1 ton processing of rice straw using steam explosion (SE) pretreatment

The electricity used in the ethanol production process is produced from lignin which is biogenic in nature. Hence, emissions from electricity are insignificant which could have otherwise contributed to a much higher extent, if coal based electricity is used. SE performs better than DA due to higher sugar recovery pretreatment, therefore, gives a higher ethanol yield. The results of study are in accordance with authors of [124] [86], where enzyme production contributed highest to the GHG emissions. In ethanol life cycle GHG emissions are avoided by burning all the solids recovered in the form of lignin and anaerobic digestion of waste water to produce biogas. The electricity generated from the co-products substitute the coal based electricity and resulted in the credit of 208 kgCO_2eq. and 246 kgCO_2eq. emissions respectively in DA and SE. The net GHG emissions from DA and SE are 84 and 42 kgCO_2 eq./ton straw respectively and the responsible factors for better performance of SE are higher xylose recovery. In a comparative LCA study evaluating the impact of different pretreatment technologies using wheat straw [124] and grass straw [125] for ethanol production, SE is proven to be the better pretreatment method for GHG emission reductions.

5.4.2 GHG EMISSIONS VIS-À-VIS GASOLINE

The cradle to grave life cycle GHG emissions of E100 using DA and SE are 20 and 8 $gCO_2eq.MJ^{-1}$ respectively, corresponding to 77 and 89% GHG emission reductions as compared to the gasoline. This GHG performance exceeds the present criteria of minimum 60% GHG emissions reduction criteria defined by the US EPA [265]. Current Indian biofuel programme implies only 5% blending (E5) and has ambitious plan of 20% (E20) in gasoline. The current study predicts GHG savings of 4.3 and 4.7% in E5 and 17.4 and 18.8% in E20 blends (Figure 5.10) using DA and SE respectively.

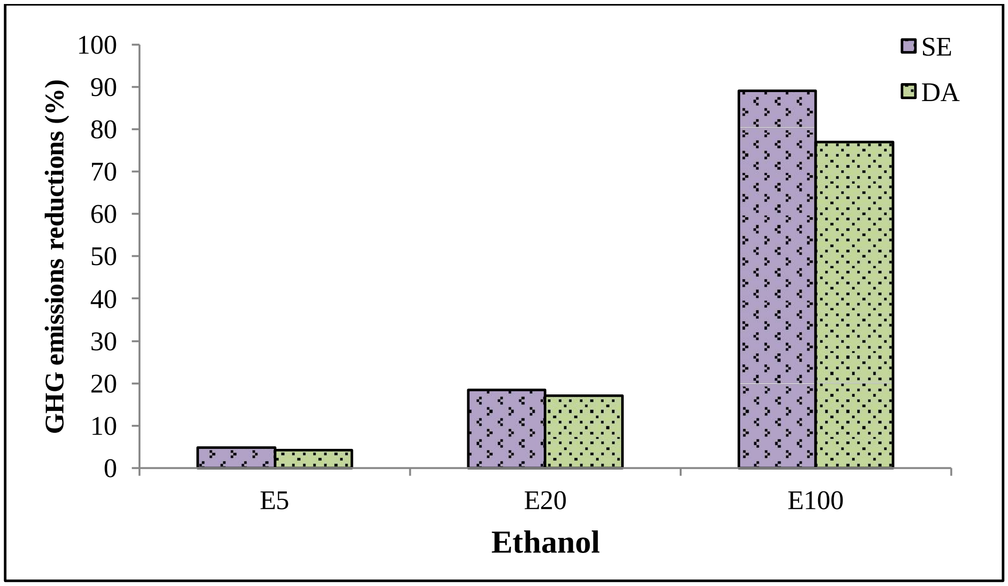


Figure 5.10 GHG emission reductions of ethanol blends and pure ethanol with respect to gasoline obtained from SE and DA process

Most of the GHG emissions in ethanol life cycle are during production stage and very few are from fuel use. However, opposite is the case with gasoline where 85% of life cycle GHG emissions come from the fuel use in the vehicles and rest during production and distribution. The major advantage of producing lignocellulosic ethanol is the displacement of coal based electricity by the surplus electricity produced from the residual lignin. The results of current study would have a significant impact on Indian biofuel programme, as 20% blending mandate would reduce approximately 18% GHG emissions with respect to gasoline in transportation sector. Therefore, Government of India should promote industries in setting up larger scale lignocellulosic ethanol plant so as to reach the ethanol demand of country and reduce the GHG emissions.

5.4.3 LIFE CYCLE ENERGY USE

Energy use during the ethanol production process is calculated as the fossil energy consumed during various field activities and conversion processes. The energy consumption in DA and SE is 2660 and 2471 MJ/ton dry rice straw. The stage wise energy consumption for DA and SE respectively follow the trend: Pretreatment (37, 30%) > enzymatic hydrolysis (26, 29%) > electricity consumption (18, 21%) > biomass transport (10%), biomass collection (6%) > fermentation (1.5%) and blending and distribution (0.5%). Energy is consumed in the form of chemicals, diesel, enzyme and electricity in different unit processes as shown in Figure 5.11.

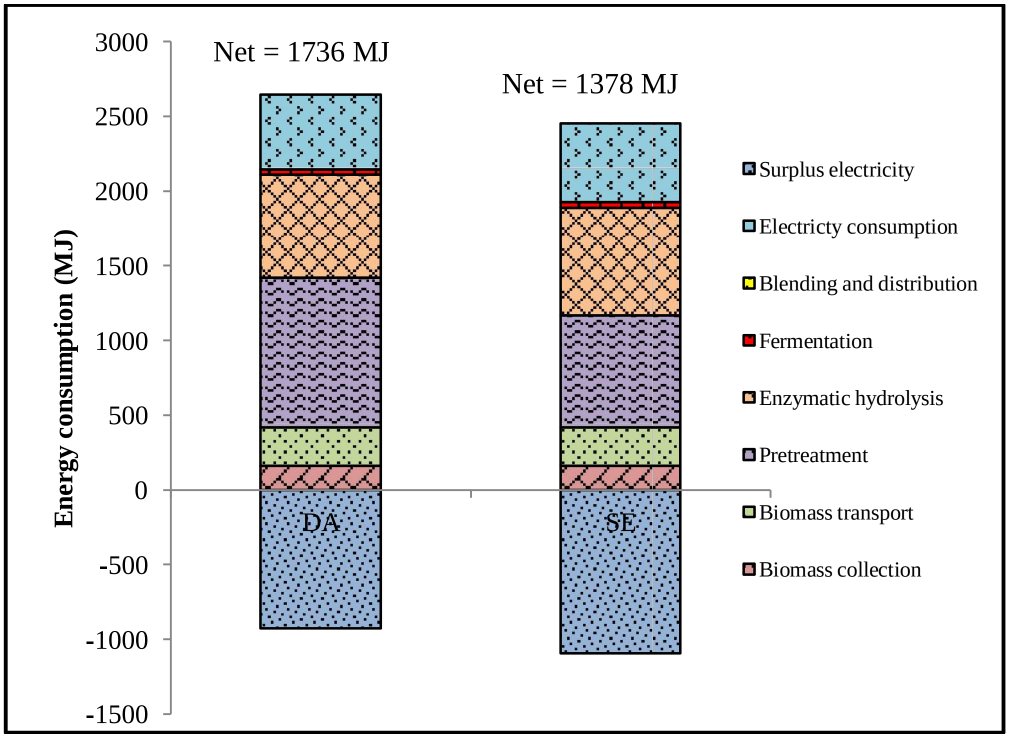


Figure 5.11 Life cycle fossil energy use in ethanol production using DA and SE pretreatment

The chemicals use in pretreatment such as sulphuric acid, sodium hydroxide and production of cellulase enzyme are major energy consuming factors in the process. The steam and electricity used in the process is generated from the lignin. The surplus electricity produced in DA and SE methods is 924 and 1093 MJ/ton rice straw respectively. This surplus energy is supplied to the grid to replace the coal based electricity. Due to lower requirements of chemical and higher production of electricity, the net energy use is lower in SE (1378 MJ/ton rice straw) compared to DA (1736 MJ/ton rice straw). In case of grass straw to ethanol using SE process [264], the overall energy use results in benefits of 0.15 MJ/MJ ethanol and is almost equal to the current study (0.19 MJ/MJ ethanol). The reason for such a gain in energy is lower energy input and higher generation of co-product energy during ethanol production.

5.4.4 NET ENERGY RATIO (NER) AND NET ENERGY BALANCE (NEB)

The NER and NEB is calculated for 1L ethanol, a most convenient way to represent and compare the results with other literature studies. NER value >1.0 or positive value of NEB indicate the renewability of fuel because fossil energy used in production is lower than the output energy delivered by fuel. The NER for ethanol using DA and SE pretreatment method is 2.3 and 2.7 respectively (Table 5.5). These values fit in the range of NER (1.7-4.5) reported in literature [115, 125, 279]. The reported values in literature showed a range and key issues responsible are difference in type of biomass use, conversion technologies, system boundary, input data, end-use technologies and allocation method.

Table 5.5 Comparison of ethanol NER and NEB with gasoline

	DA	**SE**	**Gasoline [277]**
Net energy ratio	2.3	2.7	0.84
Net energy balance (MJ/L)	14.9	16.3	-7.8

The NEB for DA and SE is 14.9 and 16.3 MJ/L respectively and these values are comparable to NEB values (10.8- 23 MJ/L), published in the literature [115, 134, 280, 281]. In this study, NER and NEB values are positive for both the pretreatment processes indicating energy benefits in the production of ethanol in India. Significant energy benefits are seen while comparing the results with NER (0.8) and NEB of gasoline (-7.8) for gasoline

[125][41]. The factors responsible for higher NER and NEB of ethanol in comparison to gasoline is lower fossil energy requirement during production process and at the same time having benefits from the co-generation of electricity in the plant.

5.5 SENSITIVITY ANALYSIS

Uncertainty is inherent element of LCA, which requires cautious examination before interpretation of results [282]. In the LCA studies of biofuel, the results vary due to choices of system boundary, co-product accounting methods and comparison with reference system [83]. Furthermore, lignocellulosic bioethanol technology is in development phase and cannot be considered to be static and uniform. The variations in technology while reaching up to the commercial scale would likely to be a major contributor to the uncertainty of life-cycle environmental impacts [50]. By analyzing a range of key parameters, sensitivity analysis helps to avoid drawing false conclusions regarding LCA of any process or product [200]. Sensitivity analysis is performed with respect to economic allocation factor and enzyme technology (by varying enzyme loading in enzymatic hydrolysis process) [52].

5.5.1 INCLUDING AGRICULTURE PROCESS IN THE SYSTEM BOUNDARY

In general, rice straw is a byproduct of cultivation of rice and is considered as a waste. Under such consideration, straw has no economic value and therefore, environmental emissions of agriculture are attributed only to the grain. However, a scenario is studied in the sensitivity analysis where system boundary is extended to include agriculture phase of rice. This is the possible scenario in the future, if we are utilizing rice straw for a commercial use; it has to be procured from the market and hence imparts certain economic value. The emissions of agriculture phase are attributed between grain and straw based on economic allocation. While including agriculture process in the system boundary and conducting economic allocation between rice and straw, there is a reduction in GHG emissions from 77% (base case) to 65% in case of DA and from 89% (base case) to 77%, in reference to gasoline. The price of straw might vary to a great extent and this would affect the GHG emissions allocated to the straw. The effect of straw price on overall emissions is studied by varying the price from 2000 to 4000 INR/ton. GHG emission reduction is plotted as a function of straw price in INR/ton. When the price of straw changes from 3000 to 4000 INR/ton there is an increase in allocation factor for straw from 0.13-0.16, which is responsible for an increase in GHG emissions. With every ±12.5% change in price of rice straw from the base case, there is ±2.3% change in GHG emissions. There is no doubt that the development of ethanol industry at larger scale would strengthen the bio economy of country. But at the same higher price would contribute more in emissions. Therefore, price of straw should be decided based on environment and economic perspectives.

5.5.2 ENZYME DOSAGE

One of the important determinants of GHG emissions in LCA of bioethanol is the enzyme dosage [52]. 10 FPU/gm WIS is the base case enzyme dose in both pretreatment methods. Overall, ethanol yield increase with an increase in enzyme dose of 1 FPU/g WIS but at the same time there is an increase in GHG emissions as well. Comparing from the base case, increase in 1FPU lead to overall 5% increase in GHG emissions and thus decrease in GHG savings with respect to gasoline. Although, 1 FPU/gm WIS increase gives 2.9% increase in ethanol production, but at the same time there is an increase of 5% emissions from enzyme production and vice versa. An increase in enzyme dose is responsible for higher environmental burden irrespective of the ethanol yield. Since, we are currently using purchased enzymes and that add cost to the ethanol, therefore, the dosage need to be minimized so as to lower the impacts from enzymes. A lot of efforts are going at the Centre to improve the pretreatment process for enhancing hydrolysis yield and lowering the dosage of enzyme. This includes an additional soaking of biomass in alkali prior to acid so as to remove the extractives and lignin partly. Moreover, enzyme companies are doing rigorous research on reformulating enzyme and develop cocktail of enzymes to reduce enzyme inhibition. For example, enzyme companies have reformulated the cellulase enzyme to achieve the considerable enzyme efficiency [86]. In large scale plants, on-site enzyme production could further reduce the emissions [86].

5.6 COMPARISON WITH LITERATURE STUDIES

There are many studies reported on LCA of cellulosic ethanol in various countries and the conclusions drawn from these studies are given in Table 5.6. The reason for disparity in the results is due to different feedstock, their cultivation, harvesting, design of system boundaries, methodologies, assumptions, emission factors, use of co-product and most importantly the allocation method. However, a generalized statement that can be concluded is that cellulosic ethanol in comparison to fossil fuels can give GHG emission reductions of 55-90 % and NER >1 and hence, establishing the sustainability of fuel ethanol. Moreover, from the Table 5.6, it can also be seen that how LCA results are affected with the difference in biomass, technologies and inclusion/exclusion of co-products in ethanol production. Few studies are published on the sustainability assessment of rice straw ethanol in South Asian countries. Therefore, a detailed comparative assessment with these published studies would highlight the novelty of current study and stressing the need and importance of conducting country specific LCA study.

A similar kind of case specific LCA in Thailand [171] evaluated GHG emissions and energy use during ethanol life cycle. The system boundary included cultivation of rice, harvesting, bailing and transport followed by dilute acid pretreatment, enzymatic hydrolysis and co-fermentation, as practiced by NREL. The reference flow was processing 1 ton rice straw to ethanol and technical data was adopted from NREL reports. In Thailand, 1 ton straw yielded 260 L ethanol and 341 kgCO_2eq. emissions/ton straw. Out of 341 kgCO_2eq. emissions, 301 kgCO_2eq. are attributed from cultivation phase and only 29 kgCO_2eq. from processing of straw. When this study is compared to our current study, out of total 292 kgCO_2eq. emissions, processing of biomass to ethanol is responsible for 209 kgCO_2eq. emissions. The reason for such a huge difference is attributed to the lower usage of enzyme dose in Thailand (9.3 kg/ton straw) with respect to Indian case (29 kg/ton straw). The process parameters and inputs in processing of biomass to ethanol therefore, play a crucial in overall GHG emissions. Moreover, Thailand study includes cultivation phase of straw, therefore, total GHG emissions from processing 1 ton straw in Thailand are on higher side.

Another study was conducted on energy analysis of ethanol production from rice straw in Japan [115]. The management practices include cultivation of rice, transportation and biochemical conversion to ethanol utilizing internal lignin and unreacted holocellulose to meet the process steam and heat requirements. For one hectare, the total energy use was about 82.8 GJ and rice yield is 8.2 ton (high yield variety of rice). Inspite of high yield, the net energy ratio reported in this study was 1.17. While comparing the NER of current study with that of Japan, it is identified that although technologies for production of ethanol are similar in both the countries but the two major differences seen are: (1) In Japan, authors have included the cultivation phase of rice which consumes huge amount of energy in form of fertilizers and diesel. (2) The amount of lignin in case of Japan only meets the process requirements and no surplus electricity is available. Therefore, credits obtained from selling surplus electricity are zero.

Table 5.6 GHG emissions ($gCO_2eq.MJ^{-1}$ ethanol) and NER of cellulosic ethanol from different feedstocks

Country	Feedstock	Pretreatment	GHG emission	NER	Remark	Ref.
India	Rice straw	DA	20	2.3	Includes credits of surplus electricity	This study
		SE	8	2.3		
USA	Corn	DA	76	1.61	Include DGS credit	[279]
	Sugarcane		45	4.32	Energy based allocation	[279]
	Corn Stover		23	4.77	Includes electricity credit	[279]
	Switch grass		29	5.44	Includes electricity credit	[279]
	Miscanthus		22	6.01	Includes electricity credit + LuC (land use change)	[279]
	Grass straw		42	1.1	Includes electricity credits	[125]
	Sorghum		47		Electricity produced from lignin is utilized within plant	[281]
Europe	Spruce	SE	14	1.16	Energy allocation b/w ethanol and solid fuel	[283]
	Wheat straw		16			[269]
Japan	Rice straw	LHW, Alkaline	9	1.51	Lignin is used to generate electricity	[115]
Thailand	Rice straw	DA	33	NA	Includes avoided emissions from open burning and grid electricity substitution	[171]

5.7 CONCLUSION

Utilization of rice straw for ethanol not only provides the solution for its management in the field, but also reduces pollution by avoiding burning, provides cleaner source of renewable fuel and enhances the socio-economic status of rural people. The findings of this study would help the policy makers in the biofuels sector of India for making meaningful and more informed decision. Further research on improving and modifying the pretreatment process is undergoing at the Centre, so as to have a minimum requirement of chemicals, higher sugar recovery and reduction in the enzyme dosage for the process. LCA of this modified pretreatment process would be the upcoming study.