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Life Cycle Assessment of Second Generation Bioethanol from Sorghum and Pearl Millet Feedstocks

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Abstract

Fossil fuels depletion has attracted increasing attention to blending bio-fuels worldwide. India's energy demand is expected to grow at an annual rate of 4-5 times over the next couple of decades. With self-sufficiency levels in crude oil becoming a distant dream, there is growing interest to look out for alternative fuels and the biofuels are an important option for policy makers in India. In this context, this paper reviews the experiences in India in the last two decades with respect to bio-fuels cultivation and its impact on land use, environment and impact on the livelihoods of rural communities. The objective of this paper is to assess the performance of Sorghum and Pearl millet feed stocks for biofuel production in India using a Life Cycle Analysis (LCA) approach. Baseline study was conducted during the year 2013 in the Madhya Pradesh state of India covering five districts and 333 sample farmers to understand the farmers perception about the various issues related to the production of biofuels using Indian staple food crops Sorghum and Pearl millet. Empirical data from the multi-locational trials conducted during the years 2014-15 and 2015-16 in farmers' fields was used to conduct the LCA analysis. Sorghum and Pearl millet feed-stocks which are rain fed crops are considered for bioethanol production with different pre-treatment methods. Net Energy Ratio (NER), Net Energy Balance (NEB), Net Carbon Balance (NCB) and % Carbon reduction were some of the key parameters used for analysis and the results are evaluated based on the environmental impacts through the Life Cycle Assessment at 5% blending. Findings reveal that, dilute alkali pre-treatment process is most energy intensive due to consumption of alkali consumption. Whereas dilute acid pre-treatment has higher conversion efficiency than the other pre-treatment processes which is due to higher glucan and xylan conversion efficiencies. The study concludes that Sorghum feedstock is more energy intensive than Pearl millet feedstock due to higher water requirement and yield.

Key words: Biofuels, Energy and Life Cycle Analysis

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1. Introduction

Depletion of fossil fuels at an alarming rate has attracted increasing attention to blending bio-fuels worldwide. India's energy demand is growing at an annual rate of 4.2% with highest demand growth of +129% in 2017(BP, 2017). Depletion of fossil fuels at an alarming rate coupled with ever-growing challenges due to anthropogenic induced climate change has attracted increasing attention to blending biofuels worldwide. India's energy demand is also observing an uptick over the last few decades and is projected to become the largest single source of global oil demand growth after 2020(International Energy Agency, 2015). Of the total primary energy supplied to Indian economy in 2013, 75% was from commercial fuels and 25 % from non-commercial fuels. Of the total commercial energy, Coal constitutes-44%, followed by Oil (23 %), Natural Gas (6 %), and Carbon-free hydro, nuclear, and other new renewable resources (3%) (International Energy Agency, 2015). Despite coal being the country's major resource endowment, the major source of India's energy insecurity stems from the heavy and growing dependence on oil imports, prices of which are often very volatile. With self-sufficiency levels in crude oil becoming a distant dream, there is growing interest to look out for alternative fuels and the biofuels are an important option for policy makers in India (Reddy *et al*, 2015).

National Biofuel policy promoted blending 20% bio-ethanol and bio-diesel by 2017 and gave thrust for the development of second generation biofuels and other new feedstocks for production of bio-fuels fuels (Ministry of New & Renewable Energy, 2009). Attempts are being made to identify new feedstocks for ethanol production. These include the use of straw from food crops such as paddy, wheat sorghum and pearl millet. The straw contains 35-40% of cellulose, 17-25% of hemicellulose and 10-20% of lignin apart from significant amount of extractives and silica. The cellulose and hemicellulose can be hydrolysed to glucose, xylose using chemicals and enzymes. These hydrolysed sugars can be further converted into ethanol upon fermentation using yeast. Ethanol produced upon denaturing, can be used as a blending fuel for Internal Combustion Engines.

It is against this background an Indo-US Bilateral JCERDC (Joint Clean Energy Research and Development Centre) project for Development of Sustainable Advanced Ligno-cellulosic Biofuels Systems was initiated in the USA and India with multiple consortium partners in each country.

The objective of this paper is to assess the performance of Sorghum and Pearl millet feed stocks for bioethanol production in India using a Life Cycle Assessment (LCA) approach.

1.1 Life Cycle Assessment Methodology

Cradle to grave approach of Life Cycle Assessment designed excel based model was used to assess the renewability potential of the bioethanol feedstocks. This model was designed based on the ISO 14040-Life Cycle Assessment standard(International Organisation of Standards, 2006)to design the system boundaries for a functional unit of 1 Tonne per Day (TPD) of dry biomass feedstock plant. These system boundaries included feedstock farming, transportation of feedstock, ethanol production, ethanol transportation, ethanol blending and fuel combustion. Along with baseline survey data (of 2013) collected for feedstock with 333 farmers covering five districts of Madhya Pradesh state of India, empirical data from the 66 multi-locational trials of Sorghum and Pearl millet conducted during the years 2014-15 and 2015-16 in farmers' fields was used to conduct the LCA analysis. Data from secondary sources was used to conduct the analysis.

Life Cycle Assessment as per the ISO-14040 has multiple steps. They are i) to define the goal and scope of the work ii) inventory analysis iii) impact assessment which demands clear distinction and definition of all the unit processes and their impact separately iv) interpretation phase which validates the study and provides concluding remarks for the product under study.

1.2 Approach

To carry out a LCA for Sorghum and Pearl millet stalks as feedstock and identifying their viability for biofuel production. As per the LCA methodology, it is important to design a system boundary. The first step to any process design is to develop a set of process flow diagrams (PFDs). Figure 1contains the PFDs used for this study. A typical ethanol production requires separate saccharification of pentose and hexose sugars. In this study, simultaneous saccharification and co-fermentation is considered. Farming data was collected from data sources: Centre for Economic and Social Studies (CESS) and agro-India. High Biomass Variety (HBV) was considered for this study and the data on these hybrids were taken from International Crops Research Institute for the Semi-AridTropics (ICRISAT). In the present model analysis was carried out for both rain fed and irrigated crops. Lignocellulosic feedstock considered in this study are a high biomass variety crops which yield high fodder and are grown specifically for meeting bioethanol blending target. This feedstock gives fodder which is considered as an additional market value gained and hence it is important to analyse its life cycle inventory from the farming stage for a better comparison and allocation. Certain inventory input values were either calculated for Madhya Pradesh region or collected from secondary data sources. The model considers mass and energy balances associated within the processes.

1.3 Process Overview

Processes included in this study and their significance is explained in this section;

- Farming: The feedstock is cultivated, harvested and dried in this process.
- Feedstock handling and storage: The feedstock is handled and stored at the farm and transported using a tractor or truck
- Size reduction: Size reduction is through a knife mill
- Pre-treatment: This process is carried out to separate lignin from the cellulose and hemicellulose.
- Simultaneous Saccharification and co-fermentation: Hydrolysis and fermentation is carried out to convert the glucose and xylose to ethanol.
- Distillation: Steam distillation is employed to purify ethanol
- Product purification: the product ethanol is purified using a second distillation column to refine the ethanol and then the ethanol is denatured
- Product storage: Ethanol produced is directly shipped to the nearest blending stations instead of storing
- Waste water treatment: water is treated and the lignin is separated from the waste water.
- Lignin Combustion: Lignin combustion to produce process steam and excess steam to produce electricity.
- Ethanol transportation to the blending station
- Ethanol blending at the blending station
- Ethanol blended fuel combustion

The process overview is indicated in the Process flow diagram shown in Figure 1.

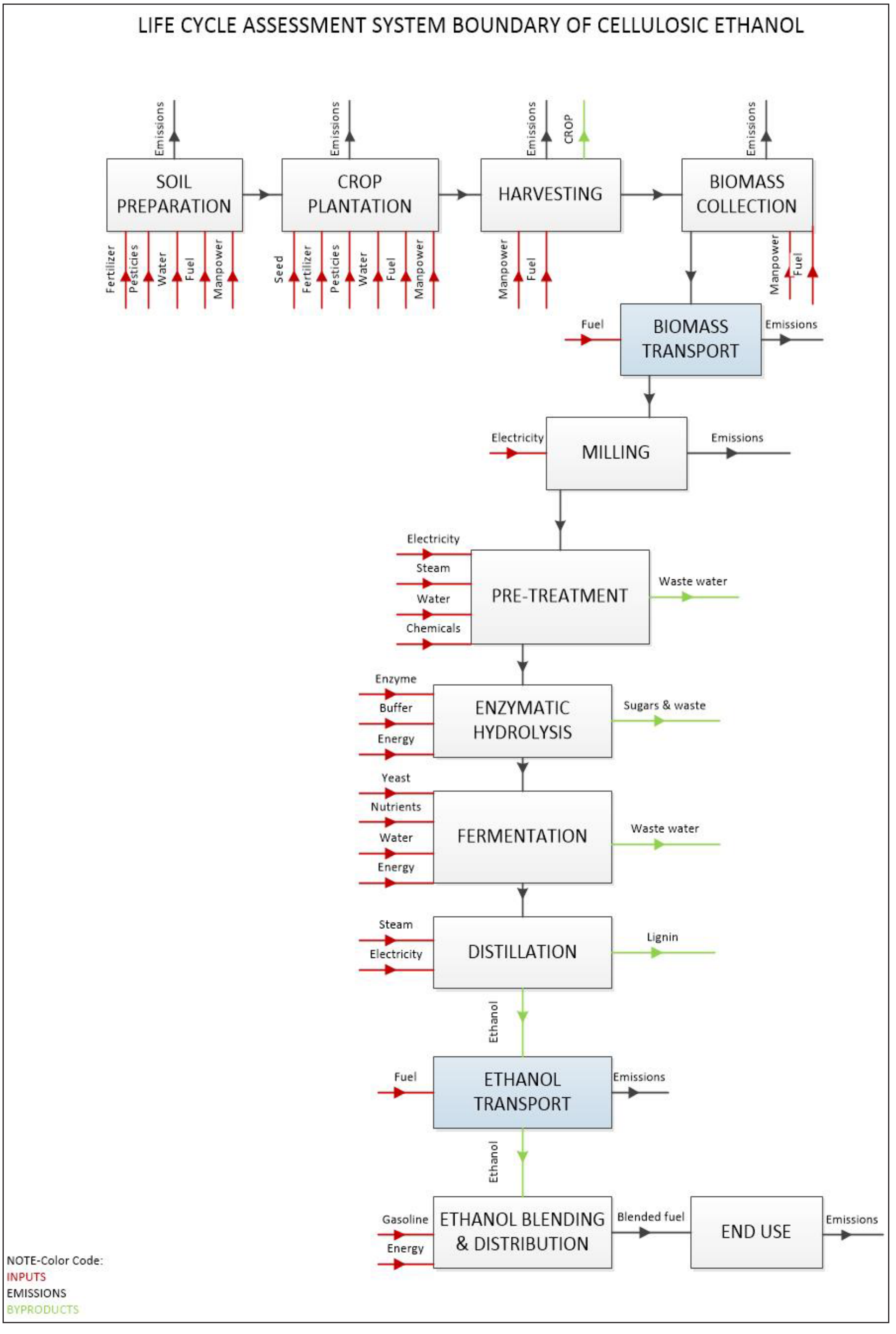
2. Life Cycle Assessment System

Life Cycle Assessment is an analysis to assess the impacts associated in all the stages of the product formation from the raw materials.

2.1 Farming and transportation of the feedstock

Farming includes soil preparation, sowing, cultivation and harvesting. Soil preparation involves ploughing and levelling which can also be mechanised. Water will be provided for the crop based on the irrigation requirement and number of irrigations. Crop duration is 120 days and on attaining maturity the crop is harvested by cutting down the stem and allowing the remaining plant to fertilise the soil.

Figure 1: System Boundary



Basis: As per ISO standards, Functional Unit=1 Tonne per Day (TPD) of dry biomass feedstock

2.1.1 Land requirement

Land required for growing feedstock for a plant capacity of one Tonne per day (TPD). It is calculated based on the dry biomass yield(Stakeholder, 2015)

Equation 1

$$Land\ requirement(hectare) = \frac{Plant\ Capacity\ (TPD)}{Dry\ biomass\ yield\ (\frac{Tonne}{hectare})}$$

Table 1: Feedstock or Biomass yield and land requirement

Feedstock	Dry fodder yield (kg/acre)	Land requirement (ha)
Sorghum stalk	4000	0.10
Pearl millet Stalk	2000	0.20

2.1.2 Water requirement

Sorghum and Pearl millet are usually rain fed crops. To estimate the impact caused if the crop was irrigated, water requirement becomes an important parameter. Water requirement for crops are given in terms of depth of irrigation and number of irrigations. Average values for kharif and rabi crops are considered for irrigation depths(Gangaiah, 2012). The crop is irrigated at the flower primordial initiation and flowering stages i.e 70-80 days after cultivation.

Equation 2: water requirement

$$Water\ requirement\ (kL) = water\ depth(mm) \times Area(ha) \times No\ of\ irrigations$$

Table 2: Water requirement

Feedstock	Water depth (mm)	One irrigation water requirementa (kl/hectare)	No of irrigations	Water requirement (kl)
Sorghum stalk	550	5500	1-2	550
Pearl millet Stalk	300	3000	1-2	300

a Depth of water (mm) requirement is converted to mm3/ha

2.1.3 Chemicals required

Chemical inventory was based on the empirical data collected by CESS from farmers of Madhya pradesh state (see table 3). Fertiliser and pesticide usage for sorghum and pearl millet crops was based on farmer's survey in Madhya Pradesh.

Table 3: Fertilizer /pesticides requirement for Sorghum and Pearl millet crops

Feedstock	Urea (kg/acre)	Di-ammonium phosphate (DAP) (kg/acre)	Potash (kg/acre)	Complex (kg/acre)	Herbicides (L/acre)	Pesticides (L/acre)
Sorghum stalk	71.3	60.1	41.3	117.8	1.0	1.5
Pearl millet Stalk	45.2	20.0	6.0	0.0	1.0	1.5

Area converted from bigha to acre. 1 acre=2.49 bigha(Easy Calculations.com, 2017)

2.1.4 Diesel requirement

Land preparation is a one crop time activity where the ploughing is done well in early showers. It is done using a cart or a tractor.By a stake holder interaction with a farmer, diesel requirement for land preparation is 4-7 litres per acre.

2.1.5 Electricity requirement

3 HP electric pump for irrigation is used in case of water drawn from bore well. In case of rain fed crops, electricity requirement become nil in case of irrigation purpose. This pump has a Total Dynamic Head (TDH) of 20-22 m(Pumpkart, 2017)

Equation 3: Electricity requirement

$$Electricity\ requirement(kWh) = water\ requirement\ \left(\frac{L}{ha}\right) \times power\ consumption\ \left(\frac{kWh}{L}\right) \times \text{Area (ha)}$$

Equation 4: Power of an electric pump

$$Power\ consumption\ of\ a\ pump = \frac{2.725 \times TDH}{\eta}$$

Where η=0.65

1 Mega litre of water to lift to 1 metre of height uses 2.725 kilowatt-hours (kWh) of electricity(Foley, 2015)

Table 4: Power consumption for irrigation

Feedstock	Power consumption (kWh)
Sorghum	52.71
Pearl millet	57.47

2.1.6 Seed requirement

Based on the literature, seed requirements are 10 kg/ha and 7 kg/ha for Sorghum and Pearl millet respectively (TNAU Agritech portal, 2017; Agropedia, 2017)

Table 5: Seed requirement for feedstock

Feedstock	Seed requirement (kg)
Sorghum	1.01
Pearl millet	1.42

2.1.7 Labour requirement

Labour requirement in Madhya Pradesh is 36.13 and 45.08 Man-days/ha for Sorghum and Pearl millet feedstock respectively (Jaiswal, 2009; Deshmukh, 2010). Assumption of 8 working hours is considered per day.

Table 6: Labour requirement for farming

Feedstock	Labour requirement (Man-hour)
Sorghum	29.2
Pearl millet	73.0

2.1.8 Transportation of feedstock

Certain underlying assumption for making this feedstock viable and to avoid the risk due to expensive transportation, farm to plant distance is 50 km as suggested by the experts. Transportation of the feedstock is usually be by a 40 HP tractor from farm to the plant. Through farmer's survey, an average carrying capacity of a 40 HP tractor is 5 ton which consumes 4 km/L of diesel in loaded condition and 7 km/L in unloaded condition. The feedstock can be collected and transported once in five days to divide the transportation inventory.

Equation 5: Fuel consumption for transportation

$$Fuel\ consumed = (Cp \times distance)/(Ct \times mileage)$$

Where Cp is the capacity of the plant (TPD)
Ct is the capacity of the vehicle (Tonnes)
Distance in km
Mileage in km/l

2.2 Ethanol production

Dry biomass feedstock is fed to a knife mill where the straw is debaled and size reduced to 10 mm. The crushing capacity of a knife mill is 360 kg/h with the power consumption of 10.53 kWh/Tonne(Bitra, 2009). The crushed biomass feedstock is sent to the pre-treatment reactor through a level ground conveyor of 100 TPH capacity (power capacity of 3.75 hp) connecting 300 ft. distance(Engineering Tool Box, 2017).

Composition of dry Sorghum and Pearl millet stalk is in Table 7.

Table 7: Feedstock composition

Component	Sorghum stalk (%)	Pearl millet stalk (%)
Cellulose	35.9	41.0
Hemicellulose	26.0	20.9
Lignin	7.5	18.3
Ash	0.7	6.0
Moisture	15.0	10.0
Others	14.9	3.9

Production of cellulosic ethanol via biological conversion consists of three critical steps:

- Pre-treatment of biomass
- Hydrolysis of sugar polymers to sugar monomers and
- Fermentation of sugar monomers to ethanol

2.2.1 Pre-treatment

Recalcitrant and heterogeneous structure of the biomass poses a fundamental challenge to depolymerisation of cellulose during enzymatic hydrolysis process. Enzyme accessibility is restricted by the lignin and hemicellulose which makes enzyme irreversibly bind to lignin thus slowing down the process(Kumar, 2011). Pre-treatment methods are aimed at enhancing the susceptibility of lingo-cellulosic biomass to enzymes thereby degrading the hemicellulose and lignin. Cellulose in the form of glucan and hemicellulose in the form of xylans and converted to pentose and hexose sugars in this model for the ethanol production. Pre-treatment of both Sorghum and Pearl millet feedstocks are explained in this section.

The following are the major pre-treatment techniques used in agro-based feed stocks:

- Dilute acid
- Steam explosion
- Hot water
- Dilute alkali
- Alkali hydrogen peroxide

a. Dilute Acid (DA)

The biomass consisting of cellulose, hemicellulose and lignin is treated with 1 % w/w sulphuric acid at180°C and 11 bar in a reactor for 15 min. Sulphuric acid acts as a catalyst. High and low pressure steam is fed into the reactor for maintaining the water in liquid stage. At this stage, some of the cellulose is hydrolysed to glucose. A fraction of lignin is converted to soluble lignin. However, most of the hemicellulose gets hydrolysed in this process(Kumar, 2011).

b. Steam Explosion

Biomass is heated at high pressure of 15 bar at temperature of180°C for 15 min and is flashed into a tank where the rapid expansion of steam causes rupture of the biomass structure. This process is highly effective on feedstock with large particle sizes thereby reducing the energy requirement for size reduction(Kumar, 2011).

c. Hot water

In an auto catalysed hot water pre-treatment process, acetic acid released from hemicellulose and self-ionisation of water at elevated temperatures act as dilute acid for breaking the cellulose and hemicellulose sugars. Thus feedstock undergoes hydrolysis(Kumar, 2011).

d. Dilute alkali

In this process, alkali swells the cellulose thereby increasing the surface area promoting the separation of carbohydrates from lignin. This treatment, also removes acetyl groups of hemicellulose resulting in higher lignin removal during dilute alkali pre-treatment compared to other pre-treatments(Kumar, 2011).

e. Alkali hydrogen peroxide

It is an advanced method developed by Indian Institute of Chemical Technology (IICT)-Hyderabad and Indian Institute of Technology (IIT)-Delhi as a Work Package-2. This process is effective for higher digestibility and prevents the formation of inhibitors.1 % (w/w) of alkali and hydrogen peroxide is added to the biomass feedstock at 550C and atmospheric pressure for 4 hours. This pre-treatment method eliminates the formation of furfural and Hydroxymethyfurfural (HMF) which inhibits the hydrolysis.

Reaction conditions of all the pre-treatment processes carried out in this study are in indicated Table 8.

Table 8: Pre-treatment conditions

Conditions	Units	Dilute Acid	Steam Explosion	Hot water	Dilute alkali	Alkali hydrogen peroxide
Temperature	°C	180	180	180	180	55
Pressure	Bar	11	11	11	11	1.0135
Residence time	Min	15	15	15	15	240
Solid loading	%	20	30	20	20	20
Acid/Alkali loading	% w/w	1	0	0	1	1

Under above reaction conditions, following reaction stoichiometry is attained.

$$Glucan + 0.111\ H2O \rightarrow 1.111\ Glucose$$

$$Xylans + 0.136\ H2O \rightarrow 1.\ 136\ Glucose$$

$$Lignin \rightarrow Soluble\ Lignin$$

$$Xylose \rightarrow 0.64\ Furfural + 0.36\ H_2O$$

$$Glucose \rightarrow 0.7\ HMF + 0.3\ H_2O$$

Where, Hydroxymethylfurfural (HMF) and furfural are fermentation inhibitors.A summary of the pre-treatment reaction conversion is mentioned in the Table 9(Kumar, 2011).

Table 9: Pre-treatment conversion

	Dilute Acid (%)	Steam Explosion (%)	Hot water (%)	Dilute alkali (%)	Alkaline hydrogen peroxide (%)
Cellulose to Glucose	13.04	5.00	0.43	0.29	50.00
Xylan to xylose	60.26	70.00	70.00	0.72	22.50
Lignin to soluble lignin	5.00	5.00	5.00	25.00	15.00
Xylose to furfural	5.00	15.00	2.50	0.01	0.00
Glucose to HMF	5.00	15.00	2.50	0.01	0.00

2.2.2 Simultaneous Saccharification and Co-fermentation

The pre-treated biomass was hydrolysed using the enzymes cellulase and hemicellulasefor cellulose and hemicellulose respectively. The enzyme loading of 15 Filter Paper Unit per gram (FPU/g) of cellulose was considered for dilute acid, steam explosion, dilute alkali and hot water treatment. Cellulose and hemicellulose hydrolysis can be done by Simultaneous Saccharification andCo-Fermentation (SSCoF) reactor which is proven successful in a pilot scale study(Kim, 2012; K.Réczey, 2004; Pothiraj, 2015).

Glucose is hydrolysed by Saccharomyces Cerevisiae. Zymomonasmobilis is an organism tested for co-fermentation of glucose and xylose(Thapelo Mokomele, 2005).

Reaction conditions, conversions and inventories are considered by work done by Deepak Kumar(Kumar, 2011)

Table 10: Reaction conditions

Parameters	Units	Dilute Acid	Steam Explosion	Hot water	Dilute alkali	Alkali hydrogen peroxide
Temperature	oC	35	35	35	35	55
Enzyme loading	FPU/g cellulose	15	15	15	15	15 FPU/g biomass
Time	Days	5	5	5	5	0.25

Under the above reaction conditions, following reaction stoichiometry is attained.

$$Glucan + 0.111\ H2O \rightarrow 1.111\ Glucose$$

$$Xylans + 0.136\ H2O \rightarrow 1.\ 136\ Glucose$$

$$Glucose \rightarrow 0.489\ CO_2 + 0.511\ Ethanol$$

$$Xylose \rightarrow 0.489\ CO_2 + 0.511\ Ethanol$$

Based on the stoichiometric balances, following conversions of ethanol under different pre-treatment conditions is shown in Table 11 and their inventory is in Table 13 and Table 14 for Sorghum and Pearl millet stalks respectively.

Table 11: Conversion of ethanol from feedstock

Conversion	Dilute Acid Treatment (%)	Steam Explosion (%)	Hot water (%)	Dilute alkali (%)	Alkaline hydrogen peroxide (%)
Cellulose to Glucose	79.0	70.0	78.5	84.8	67.5
Xylan to xylose	80.0	80.0	80.0	80.0	64.1
Glucose to ethanol	95.0	95.0	95.0	95.0	80.0
Glucose to CO2	95.0	95.0	95.0	95.0	80.0
Xylose to ethanol	70.0	70.0	70.0	70.0	80.0
Xylose to CO2	70.0	70.0	70.0	70.0	80.0

Table 12: Ethanol yield from different pre-treatment and feedstocks

Ethanol yield	Dilute Acid Treatment (%)	Steam Explosion (%)	Hot water (%)	Dilute alkali (%)	Alkaline hydrogen peroxide (%)
Sorghum Stalk	25.26	22.90	25.00	24.88	24.89
Pearl millet Stalk	25.62	27.86	25.26	25.55	25.89

Ethanol yield is calculated as output ethanol(kg) to that of the input dry biomass feedstock (kg)

The Life Cycle inventories are shown below. Chilled water, cooling water are used to dissipate heat during all the post heating process operations.Chemically treated water is used in processes for feedstock processing, dilutions and cleaning operations. DAP is used as a nutrient source for Z.Mobilis growth(Davis, 2013).

Table 13: Life Cycle Inventory for Sorghum stalk-ethanol production

Inventory	Dilute Acid	Steam explosion	Hot water	Dilute alkali	Alkaline hydrogen peroxide
Electricity*	179.29	168.35	164.80	164.00	175.47
Steam	1892.17	1169.76	1904.67	1835.54	1836.0
Steam (High pressure)	134.47	179.96	133.10	132.46	132.5
Cooling water	160159.29	116523.16	180642.23	157850.48	157886.5
Chilled water	233.72	258.33	266.21	264.92	265.0
Chemically Treated water	28417.84	28718.62	28278.43	28081.93	28088.3
Water	1920.99	1257.71	1901.50	1892.31	1892.7
Sulphuric acid	65.95	0.00	0.00	15.45	15.5
Ca Hydroxide	32.02	0.00	0.00	0.00	0.00
DAP	0.32	0.29	0.32	0.32	0.32
Cellulase	83.88	87.66	95.71	95.25	95.27
Yeast	0.96	1.16	0.95	0.95	0.97
Sodium hydroxide	0.00	0.00	0.00	49.52	49.53
Gasoline	2.56	2.32	2.54	2.52	2.52
Hydrogen peroxide	0.00	0.00	0.00	0.00	49.53

All units in kg

* Units in kWh

2.2.3 Distillation and steam production

Followed by SSCoF process, the slurry is stored in a beer well for 4 hours to allow settling. Ethanol is distilled using two distillation columns D1 and D2. The ethanol vapours from the first column are enriched in the second distillation column. In the process of enriching, an azeotrope of ethanol and water is formed in the distillation column D1 is separated using a molecular sieve to produce anhydrous ethanol which upon denaturing is ready for blending with gasoline.

The bottom effluent from the first distillation D1 column has lignin and non-fermentables. The bottom effluent is passed through pneumapress that further separates solids and liquids. Lignin rich solids are combusted in Fluidised Bed Combustor (FBC) for steam generation. Liquid rich stream containing water is evaporated, the evaporated condensate is recycled as process recycle water and the concentrate is sent to FBC for combustion.

Table 14: Life Cycle Inventory for Pearl millet stalk-ethanol production

Inventory	Dilute Acid	Steam explosion	Hot water	Dilute alkali	Alkaline hydrogen peroxide
Electricity	181.86	204.79	166.49	168.40	182.07
Steam	1919.30	1422.96	1924.19	1884.83	1909.9
Steam (High pressure)	136.40	218.92	134.47	136.02	137.8
Cooling water	162455.52	141745.27	182494.03	162089.01	164246.2
Chilled water	237.07	314.25	268.94	272.04	275.7
Chemically Treated water	28825.27	34934.93	28568.32	28835.97	29219.7
Water	1948.53	1529.95	1920.99	1943.12	1969.0
Sulphuric acid	66.90	0.00	0.00	15.87	16.1
Ca Hydroxide	32.48	0.00	0.00	0.00	0.00
DAP	0.32	0.35	0.32	0.32	0.33
Cellulase	85.09	106.63	96.69	97.80	99.11
Yeast	0.97	1.41	0.96	0.97	0.33
Sodium hydroxide	0.00	0.00	0.00	50.85	51.52
Gasoline	2.60	2.82	2.56	2.59	2.63
Hydrogen peroxide	0.00	0.00	0.00	0.00	51.52
Ethanol produced	324.76	353.09	320.16	323.85	103.75

All units in kg

* Units in kWh

Steam produced from lignin fraction is more than steam requirement of the plant. The excess steam is utilised for power generation which can be sold to the grid. The underlying assumption is that 1 kilo litre of ethanol gives 15.6 m3 of spent wash; 1 m3 of spent wash gives 35 m3 of biogas; 1 m3 of biogas gives 2.5 kWh of electricity and the same is calculated for different pre-treatments for Sorghum and Pearl millet feedstocks in Table 15 and Table 16 respectively.

Table 15: Ethanol production and byproduct from Sorghum feedstock

Product	Dilute Acid	Steam explosion	Hot water	Dilute alkali	Alkaline hydrogen peroxide
Ethanol (L)	320.16	290.26	316.92	315.39	315.46
Electricity (kWh)	437.03	396.21	432.59	430.50	430.60

Table 16: Ethanol production and byproduct from Pearl millet feedstock

Product	Dilute Acid	Steam explosion	Hot water	Dilute alkali	Alkaline hydrogen peroxide
Ethanol (L)	324.76	353.09	320.16	323.85	328.16
Electricity (kWh)	443.29	481.97	437.03	442.06	447.94

2.3 Ethanol Transportation

Bioethanol transportation from plant to blending station is by diesel driven tankers of 40 HP. The distance from the plant to the blending and distribution station is 100 km. Truck capacity is 18000 litres with loaded and unloaded mileage of 6 and 7 km/l(Soam, 2015; Hi-Tech Services, 2017).

2.4 Blending

Blending of E5, E10 or E15 can be carried out in the model. However, 5% blending of ethanol with gasoline by volume is considered under this report.

2.5 Combustion

Combustion of the ethanol blended fuel in comparison to pure gasoline in an IC engine is considered in this study.

3. Results

The results are evaluated based on the environmental impacts through the Life Cycle Assessment at 5% blending. Net Energy Ratio (NER), Net Energy Balance (NEB), Net Carbon Balance (NCB) and % Carbon reduction are essential in analysing LCA. These parameters are calculated as below.

3.1 Net Energy Ratio

It is the ratio of energy returned on energy invested. A fuel under study is considered renewable only if the NER is greater than one(Confederation of Indian Industry, 2010)

$$Net\ Energy\ Ratio = \frac{Energy\ Output\ from\ ethanol\ production}{Energy\ Input\ for\ ethanol\ production}$$

3.2 Net Energy Balance

It is the difference between the output energy to that of the input energy(Confederation of Indian Industry, 2010)

$$Net\ Energy\ Balance = Energy\ Output - Energy\ Input$$

3.3 Net Energy Balance per kilo litre of bioethanol

It is the net energy output per kilo litre of bioethanol produced(Confederation of Indian Industry, 2010)

$$Net\ Energy\ Balance\ per\ kilo\ litre\ of\ bioethanol\left(\frac{GJ}{kl}\right) = \frac{Net\ Energy\ Balance}{Quantity\ of\ ethanol}$$

3.4 Net Carbon Balance

It is the difference between the output and input carbon emissions(Confederation of Indian Industry, 2010)

$$Net\ Carbon\ Balance = Output\ Carbon\ emissions - Input\ Carbon\ Emissions$$

3.5 Net Carbon Balance per kilo litre of bioethanol

It is the net carbon emission output per kilo litre of bioethanol produced(Confederation of Indian Industry, 2010)

$$Net\ Carbon\ Balance\ per\ kilo\ litre\ of\ bioethanol\left(\frac{tCO2e}{kl}\right) = \frac{Net\ Carbon\ Balance}{Quantity\ of\ ethanol}$$

3.6 % Carbon emission reduction

It is the net quantity of Greenhouse Gas emissions avoided by using biofuel when compared to the use of fossil fuel(Confederation of Indian Industry, 2010)

$$Percent\ carbon\ reduction = \left(\frac{(1 - \frac{Total\ Carbon\ Input}{Quantity\ of\ Ethanol\ produced}}{Emission\ factor\ of\ petrol}\right)\%$$

NER, NEB, NCB without allocation for Sorghum and Pearl millet feedstocks are estimated and presented in Table 17, Table 18, Table 18Table 19 and Table 20respectively

Table 17: Energy renewability indicators of Sorghum feedstock-ethanol

Pre-treatment	Net Energy Ratio		Net Energy Balance (GJPY)		Net Energy Balance per kL of ethanol (GJ/kL)	
	Rain fed	Irrigated	Rain fed	Irrigated	Rain fed	Irrigated
Dilute Acid	2.629	2.492	1853.5	1790.9	17.5	17.0
Steam Explosion	2.332	2.213	1549.1	1486.5	16.2	15.5
Hot water	2.421	2.303	1738.1	1675.5	16.6	16.0
Dilute Alkali	1.908	1.834	1402.6	1340.0	13.5	12.9
Alkaline hydrogen peroxide	1.855	1.785	1358.9	1296.3	13.1	12.5

Table 18: Energy renewability indicators of Pearl millet feedstock-ethanol

Pre-treatment	Net Energy Ratio		Net Energy Balance (GJPY)		Net Energy Balance per kL of ethanol (GJ/kL)	
	Rain fed	Irrigated	Rain fed	Irrigated	Rain fed	Irrigated
Dilute Acid	2.469	2.339	1805.4	1737.1	16.8	16.2
Steam Explosion	2.374	1841.3	1909.6	1841.3	16.4	15.8
Hot water	2.279	2.167	1679.1	1610.9	15.9	15.2
Dilute Alkali	1.829	1.757	1371.7	1303.5	12.8	12.2
Alkaline hydrogen peroxide	1.788	1.720	1351.8	1283.5	12.5	11.9

Table 19: Environmental impact of Sorghum feedstock-ethanol

Pre-treatment	Net Carbon Balance(tCO2e/year)		Net Carbon Balance per kL of bioethanol(tCO2e/kL)		% Carbon reduction	
	Rain fed	Irrigated	Rain fed	Irrigated	Rain fed	Irrigated
Dilute Acid	-80.62	-98.41	-0.76	-0.94	-42.45	-49.80
Steam Explosion	-98.88	-117.66	-1.03	-1.23	-53.57	-61.68
Hot water	-90.07	-108.86	-0.86	-1.04	-46.51	-53.93
Dilute Alkali	-111.09	-129.88	-1.07	-1.25	-55.03	-62.48
Alkaline hydrogen peroxide	-129.71	-148.49	-1.25	-1.43	-62.40	-69.86

Table 20: Environmental impact of Pearl millet feedstock-ethanol

Pre-treatment	Net Carbon Balance(tCO2e/year)		Net Carbon Balance per kL of bioethanol(tCO2e/kL)		% Carbon reduction	
	Rain fed	Irrigated	Rain fed	Irrigated	Rain fed	Irrigated
Dilute Acid	-103.15	-123.63	-0.96	-1.17	-50.69	-58.59
Steam Explosion	-102.28	-122.76	-0.88	-1.05	-47.19	-54.45
Hot water	-133.15	-133.63	-1.05	-1.26	-55.17	-63.18
Dilute Alkali	-133.00	-153.48	-1.24	-1.44	-62.34	-70.26
Alkaline hydrogen peroxide	-151.24	-171.72	-1.40	-1.59	-68.63	-76.44

Sorghum and Pearl millet feedstock is a rain fed crop and hence rain fed Sorghum feedstock is considered for bioethanol production with dilute acid pre-treatment in inferring the study as follows

- The net energy ratio of bioethanol production from Sorghum stalk by dilute acid pre-treatment is 2.629, which implies that the total energy output for the production of bioethanol is 2.629 times that of the input energy consumed during its production.
- The net energy balance of 1853.5 GJPY is the delivered energy after subtracting the energy required for the production of ethanol.
- 17.5 GJ/kL of ethanol is the net energy balance per kL of ethanol produced implying that the extra energy delivered per kL of ethanol produced.
- The net carbon balance per kilo litre bioethanol is -0.76 tCO2e which means that for every kilo litre of bioethanol 0.76 tCO2e of emissions would be reduced.
- The % carbon emission reduction by using bioethanol with respect to the use of petrol is -42.45% thus signifying that bioethanol is a carbon negative fuel. This inference has occurred due to the fact that the energy consumed in the farming and chemicals have played a significant role in increasing the carbon emissions. These emissions can be reduced significantly by reducing the inventory like water and acid/alkali used.

Rain fed Pearl millet feedstock for bioethanol production with dilute acid pre-treatment infers the following

- The net energy ratio of bioethanol production from Sorghum stalk by dilute acid pre-treatment is 2.47, which implies that the total energy output for the production of bioethanol is 2.47 times that of the input energy consumed during its production.

- The net energy balance of 1805.4 GJPY is the delivered energy after subtracting the energy required for the production of ethanol.
- 16.8 GJ/kL of ethanol is the net energy balance per kL of ethanol produced implying that the extra energy delivered per kL of ethanol produced.
- The net carbon balance per kilo litre bioethanol is -0.96 tCO2e which means that for every kilo litre of bioethanol 0.96 tCO2e of emissions would be reduced.
- The % carbon emission reduction by using bioethanol with respect to the use of petrol is -50.69% thus signifying that bioethanol is a carbon negative fuel. This inference has occurred due to the fact that the energy consumed in the farming and chemicals have played a significant role in increasing the carbon emissions. Pearl millet feedstock would be more promising if the inventory was reduced either in the form of chemical consumption or water consumption.

The above inferences indicate that Pearl millet feedstock is less energy intensive than Sorghum feedstock in terms of NER and NEB. The technology needs further modification aiming at reducing the chemical consumption and thereby reducing the overall emissions.

3.7 Comparative Analysis of second generation biofuels to first generation biofuel

A comparison of the Net Energy Ratio of first generation molasses feedstock with second generation rice straw is in Table 21(Confederation of Indian Industry, 2010)

Table 21: Comparison of first generation and second generation feedstocks

Feedstock	Net Energy Ratio	% Carbon reduction
Molasses	4.57	75%
Rice straw	3.32	68%
Sorghum straw	2.629	-42.45%
Pearl millet Straw	2.469	-50.69%

As seen in the Table 21first generation molasses and second generation rice straw have higher per cent carbon reduction potential in comparison to current study. The LCA system boundary designed is subjected to the individual study and hence not comparative. The energy invested in the life cycle assessment is a boundary set by the assessor and is not a standard tool to compare the renewability of one feedstock with respect to another.

3.8 Allocation Approach

Allocation approach is given to the life cycle assessment in order to decide the exact impact of these inventories in the environment. For instance, if stalk is utilised instead of the grain which is the major output of a crop, major burden is allocated to the major produce in terms of the grain nutrient equivalent or energy equivalent. The burden in the form of allocation is distributed in the Table 22.

Table 22: Mass, Energy and market price allocation

Process	Without allocation (%)	Mass allocation (%)	Energy allocation (%)	Market price allocation (%)
Farming	100	70	70	18
Transportation	100	100	100	100
Production of ethanol	100	85	85	90
Transportation	100	100	100	100
Blending	100	100	100	100

In the farming stage, the bioethanol feedstock yield accounts to 70% of the total plantation and costs 18% of the price invested in cultivating the crops. Ethanol production considered at the standalone distillery, all of the process utilities are accounted (85% allocation) as a major constituent and the rest 15% offered for lignin and biogas as by-products not allocated in the mass and energy allocations. All the other stages of ethanol production do not have any by-products which deliver a market value for distributing the burden and reducing the overall burden of this process.

Incorporating the allocation, the results in the NER vary to a certain extent and the same are explained for Sorghum and Pearl millet stalk with dilute acid treatment as in Table 23and Table 24.

Table 23: Allocation for dilute acid treated Sorghum stalk ethanol production

Process	Without allocation	Mass allocation	Energy allocation	Market price allocation
Farming	545.24	381.7	381.7	98.1
Transportation	10.01	10.01	10.01	10.0
Production of ethanol	642.40	546.04	546.04	578.2
Transportation	1.64	1.64	1.64	1.6
Blending	1.31	1.31	1.31	1.3
Total Energy	1200.61	940.68	940.68	689.3
NER	2.49	3.18	3.18	4.3

All units except NER are in GJPY

Table 24: Allocation for dilute acid treated Pearl millet stalk ethanol production

Process	Without allocation	Mass allocation	Energy allocation	Market price allocation
Farming	632.71	442.9	442.9	113.9
Transportation	10.01	10.01	10.01	10.0
Production of ethanol	651.59	553.85	553.85	586.4
Transportation	1.67	1.67	1.67	1.7
Blending	1.33	1.33	1.33	1.3
Total Energy	1297.30	1009.75	1009.75	713.3
NER	2.34	3.01	3.01	4.3

All units except NER are in GJPY

4. Conclusion

The findings from the LCA study are indicated as below:

- Farming: Although Sorghum and Pearl Millet are rain fed crops, farming contributes to near 30% of the energy input in the ethanol production cycle. Highest contributors of GHG emissions are pesticides and fertilizers. Reduction in the use of pesticides and fertilizers has good impact on the energy savings.

- Pearl millet stalk is more energy intensive in the aspect of energy requirement in the form of manpower requirements. Reducing the manpower requirement with alternative machinery can make the process less energy intensive.

- Rainfed feedstocks reduced the energy consumption by 10% in comparison to irrigated crops.

- Sorghum feedstock is more energy intensive than Pearl millet feedstock due to low grain and fodder yield.

- Biomass Transportation is less energy intensive step as the biomass is dried and then sent to the ethanol plant. Also, it does not create a threat in diversion the resources for ethanol production feedstock transportation.

- Pre-treatment: Ethanol production from second generation biomass in terms of pre-treatment processes is very energy intensive because, the biomass is separately pre-treated. Dilute acid pre-treatment has higher conversion efficiency than the other pre-treatment processes. This is due to higher glucan and xylan conversion efficiencies. Dilute acid treatment is commercially used, however there is always an imbalance created by huge amounts of impurities like furfural and HMF thereby creating a need for an alternative. Other pre-treatment processes like hot water treatment and steam explosion consume a lot of water for the processing. Also, dilute alkali treatment has huge energy impact on the overall NER due to high energy coefficients of alkali. Modified alkali hydrogen peroxide process is promising as this reduces the overall burden of energy and emission impacts.

- Simultaneous Saccharification and co-fermentation considered in this study in the absence of primary experimentally data. However, the water, chemical inventories can be intensified on experimental values. Also, the type of enzyme used can be modified as the process requirement. Enzyme has high energy impact and this can be reduced by trade-offs through reduction in water and chemical requirements.

- The overall process is carbon negative with high NER, indicating that the process can be modified to reduce the impact and shifting it to carbon positive.

- Alkali hydrogen peroxide process is more promising with comparative yields. Reduction of process water by 70-80% can reduce the environmental impact significantly.

- Second generation ethanol production can be combined with first generation ethanol plants/distilleries to reduce the energy consumption in the distillation column. In first generation ethanol production, the energy used for cultivation and farming are not accounted as ethanol produced from the by-products. Whereas, in second generation, the additional burden comes at the farming stage which can be negotiated in the ethanol production stage by intensifying the process inventories by better enzymes, advanced processes.

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Conversion factors

1 bigha = 0.4005 acre

1 hectare = 2.47 acre

1 Tonne= 1000 kg

1 mm3 = 10-6 litre

Abbreviation:

kL :kilolitre

TPD : Tonne per Day

SSCoF : Simultaneous Saccharification & Co-fermentation

DAP : Di-ammonium Phosphate

TDH : Total Displacement Head

FPU : Filter Paper Unit

GJPY :Giga Joules per year

Energy values

1 Litre of Diesel contains 38.4 Mega Joules (MJ) of energy (Energy density)

1 kilowatt-hour (kWh) of electricity is equivalent to3.6 Mega Joules (MJ) of energy

Annexure:

Table 25: Energy coefficients and carbon footprints of inventories

Inventory	Units	Energy coefficient	Units	Carbon Footprint
Ethanol	MJ/L	23.4	kg CO2 eq/L	1.21
Lignin	MJ/kg	25		
Biogas	MJ/m3	18.84	kg CO2 eq/m3	0.016
Diesel	MJ/L	36.4	kg CO2 eq/litre	2.79
Gasoline	MJ/L	35	kg CO2 eq/L	2.32
Urea MJ/kg	46.9	kg CO2 eq/kg	6.92	
Diammonium Phosphate	MJ/kg	6.79	kg CO2 eq/kg	1.66
Potash	MJ/kg	6	kg CO2 eq/kg	1.47
Complex	MJ/kg	7.59	kg CO2 eq/kg	10.71
Herbicides	MJ/L	238	kg CO2 eq/kg	10.73
Pesticide	MJ/L	101.2	kg CO2 eq/kg	10.97
Man-hour	MJ/Man-hr	1.96	kg CO2 eq/Man-hour	0.196
Electricity	MJ/kWh	3.6	kg CO2/kWh	1.08
Sulphuric acid	MJ/kg	5.22	kg CO2 eq/kg	0.21
Sodium hydroxide	MJ/kg	19.87	kg CO2 eq/kg	1.19
Enzyme	MJ/kg	21.9	kg CO2 eq/kg	5.5
Lime MJ/kg	0.1	kg CO2 eq/kg	0.975	
Water	MJ/L	0.00102	kg CO2/litre	3.00E-05
Steam (Low pressure)	MJ/kg	2.6	kg CO2 eq/kg	0.24
Steam (High pressure)	MJ/kg	2.802	kg CO2 eq/kg	0.61
Yeast MJ/kg	13	kg CO2 eq/L of ethanol	0.96	
Hydrogen peroxide	MJ/kg	2.7	kg CO2 eq/kg	1.14
Machinery	MJ/hr	62.71	kg CO2 eq/MJ	4.45

Ethanol, biogas, diesel(Ocean Washington edu, 2005; Winnipeg edu, 2012); Urea, DAP, Potash(Fertiliser europe, 2008; Kool, 2012); steam (Winnipeg edu, 2012); water (Winnipeg edu, 2012), labour (Ziaei, 2015);enzyme (Olofsson, 2017; Agostinho, 2015); yeast(Dunn, 2012; Hertrampf, 2010)