CHAPTER 6

LIFE CYCLE ASSESSMENT AND LIFE CYCLE COSTING OF CONVENTIONAL AND MODIFIED PRETREATMENT METHOD FOR FUEL ETHANOL PRODUCTION FROM RICE STRAW IN INDIA

IOCL has developed a modified pretreatment method in order to reduce the enzyme dosage during ethanol production. This method uses soaking of biomass in varying alkali concentration prior to pretreatment. The environmental and economic impact of this modified pretreatment in comparison with conventional pretreatment is analyzed in detail in this chapter.

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6.1 INTRODUCTION

The global fuel ethanol production has increased remarkably over last a decade and many countries have recognized their potential to increase consumption of biofuels [71]. Therefore, policies are being made in several countries which promote the production and use of biofuels, e.g. Renewable Energy Directive (RED) in the EU has directed the use of 20% renewable energy use in transportation by 2020 [284]. Renewable Fuel Standard (RFS) in 2007 in US mandated a minimum production of 9.0 billion gallons of ethanol to be blended in the gasoline and required this mandate to be increased to 36 billion gallons per year by 2022 [265]. In line with the European Union (EU) and the United States (US), India in 2009 mandated 5% ethanol blending and set an ambitious target to reach 20% by 2017 [71].

In India, 21% of the total straw is left unused and is burnt in the fields. Straw consists of the cellulose (36-40%), hemicellulose (15-20%) and aromatic polymer lignin (20-23%) apart from extractives and ash [262]. To utilize the straw for ethanol production, a pre-treatment is a prerequisite as the first step to break biomass cell wall making cellulose amenable to enzymes. In second step, the pre-treated solids are exposed to cellulase enzymes releasing primarily monomeric sugars. Finally, the released sugars are fermented to ethanol using yeast. Among these three steps, pretreatment has been identified as one of the most crucial process for the ethanol production [147].

Biomass pretreatment for different feedstock has been investigated before by many authors and most of the processes have only been tested at laboratory/pilot scale. Indian Oil Corporation Limited (IOCL), Faridabad has 250 kg/day dilute acid (DA) pilot plant of lignocellulosic ethanol [149]. A huge set of experiments varying feedstock, acid concentration, reaction time and temperature have been performed. The key results from optimized conditions revealed that DA method results in the formation of inhibitory compounds and pseudo lignin along with burden of unnecessary materials like ash, extractive, lignin or their condensed products. Hence, reduces the conversion efficiency of cellulose to monomeric sugars and results in input of higher enzyme dose to achieve the desired hydrolysis efficiency. Life cycle assessment (LCA) results based on these pilot scale experiments data showed

that ethanol resulted in reduction of 76% GHG emissions as compared to gasoline [149]. However, LCA results revealed that the enzyme production is the GHG emission hotspot in ethanol production. Therefore, in order to address the above mentioned issues, there is a need to improve the pretreatment process in a way that: reduces the enzyme doses, gives higher ethanol yield, lower the emissions and consequently could reduce the ethanol cost.

This study analyzes the series of extraction process including water and varying alkali concentrations followed by DA pretreatment, enzymatic hydrolysis and fermentation to produce ethanol. In extraction process, significant amount of unwanted materials are removed, comprising of extractives, partly lignin and ash. This new process termed as modified pretreatment (MP), which is a strategy to reduce the enzyme dosage and have higher yield of sugars. In line with this, further step is to assess the sustainability of the process from an environment and economic perspective.

LCA and LCC are the most common tools used to evaluate environmental and production cost for second generation ethanol [51] [285]. However, there are no LCA and LCC studies reported on any improved methods/strategies for ethanol production from rice straw. The MP process is a novel approach developed by IOCL and this study is an extended step to analyze the environmental and economic impacts of this process. LCA and LCC results would give real insight on emissions and economic benefits by comparing different MP scenarios with CP. The results of current study would be used for selecting an optimum scenario for scale up of technology to a demonstration level.

6.2 AIM OF STUDY

The aim of study is to conduct LCA and life cycle costing (LCC) of MP process and compared with conventional pretreatment (CP) method of ethanol production from rice straw.

6.3 METHODOLOGY

LCA is used to assess the potential effects of CP and MP method for ethanol production. LCC is a technique to assess the procurement and production cost of any product and service over the life cycle. In procurement lowest fixed cost of purchase, installation, maintenance, operation and disposal are considered. LCC is a methodology used to optimize the cost of ethanol by identifying and quantifying all of the essential costs involved during the life.

6.3.1 EXPERIMENTAL DESIGN OF THE IOCL ETHANOL TECHNOLOGY

The ethanol plant modeled in this study is situated in IOCL, R&D Centre, Faridabad, with capacity of processing 250 kg of biomass/day. The utilization of rice straw as a feedstock to produce cellulosic ethanol using DA has been previously studied and it has been found that earlier DA pretreatment method had some limitations that can be overcome by the MP method developed by the Centre [149] [286]. The advanced technological feature of IOCL using MP is shown in Figure 6.1.

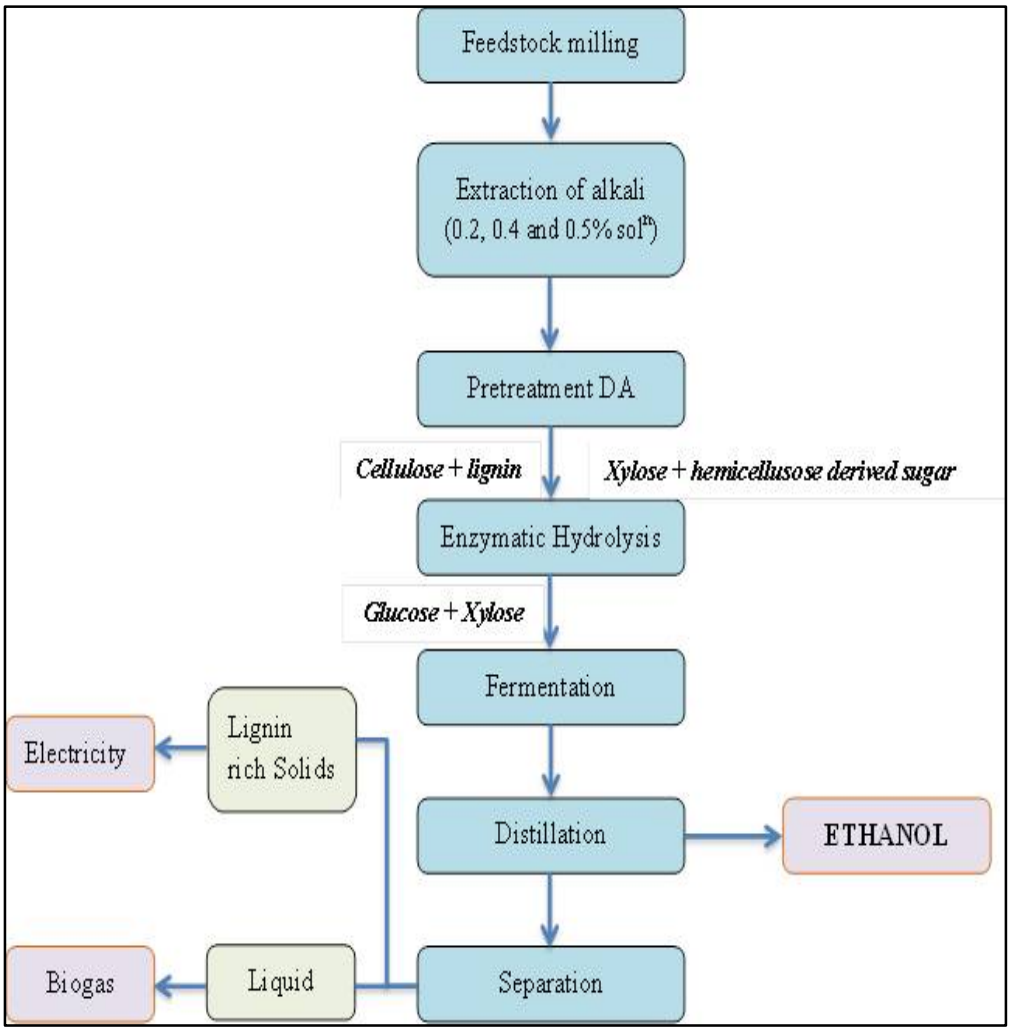

Figure 6.1 IOCL advanced pretreatment technology for ethanol production

The untreated rice straw with a moisture content of approximately 10% is initially milled to ~5mm size, soaked in water and 0.2, 0.4 and 0.5% alkali solution separately for 1 hr at 60°C. In case of alkali, the straw is washed 2-3 times after soaking so as to remove the alkali. The straw is then soaked in 1-1.1% (w/w) sulfuric acid for 30 minutes at room temperature followed by hydraulic pressing. Pressed straw with a solid content of ~60% is directed to pretreatment reactor at 162°C for 10 minutes and 5 bar pressure. These conditions were optimized after conducting wide range of experiments varying temperature and time. The pretreated slurry is collected in the flash tank, neutralized with caustic and is subjected directly to enzymatic hydrolysis without any separation or washing. The enzyme is purchased from M/s

Novozymes, Denmark and used at 8 FPU/g WIS for 48 hr. Glucose (C6) and xylose (C5) monomers are then co-fermented using yeast strain at 30°C to produce ethanol. The leftover lignin and other holocellulose residue are burnt internally in co-generation plant to produce electricity. The energy requirement of plant is met 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 the production of biogas.

6.3.1.1 Scenarios Description

In this study, five scenarios are studied as given in Table 6.1, covering CP and range of MP that includes an additional extraction step prior to pretreatment. MP scenarios include biomass soaking in water (MP1), 0.2% (MP2), 0.4% (MP3) and 0.5% (MP4) aqueous alkali, followed by DA pretreatment, enzymatic hydrolysis and fermentation. The chemical composition of untreated and pretreated rice straw obtained in each scenario was analyzed using NREL protocol [286] and given in Table 6.2.

Table 6.1 Details of pretreatment scenarios

Pretreatment	Scenarios	Alkali conc. (%)	Acid conc. (%)	pH of alkali soaking solution
Conventional	CP	0	1.0	NA
Modified	MP1*	0	1.0	NA
	MP2	0.2	1.0	11
	MP3	0.4	1.1	13
	MP4	0.5	1.1	13

* MP1 includes pre-soaking of biomass in water at 60ºC

6.3.2 GOAL AND SCOPE

The goal of study is to compare LCA and LCC of MP with CP method of ethanol production. Processing of 1ton straw is the reference flow and 1L of ethanol is the functional unit of study. The detailed system boundary with different unit processes is shown in Figure 6.2. The aim of study is to analyze the impact of MP for producing ethanol; therefore, use phase of the ethanol is excluded from current study. The impact categories studied are global warming potential (GWP), acidification potential (AP), eutrophication potential (EP) and photo chemical oxidation creation potential (POCP). As per the practice of LCA, emissions from capital and infrastructure are not included in study. Land use changes are not accounted in the current study as the land has not been diverted for the rice straw production rather already available surplus straw is utilized for ethanol production. Biogenic CO_2 emissions are not included in results as the amount of CO_2 released would be utilized by the plants in next cultivation cycle.

Table 6.2 Chemical composition of untreated and pretreated rice straw using conventional and modified method

Components	Untreated	CP	MP1	MP2	MP3	MP4
Glucan	37.8	52.69	56.9	59.0	66.3	70.6
Xylan	18.3	3.59	8.8	7.0	6.4	4.2
Arabinan	3.4	0.32	0.0	0.0	0.0	0.0
Lignin	12.9	26.99	24.3	22.0	20	21.1
Ash	6.3	16.42	10.5	12.9	8.0	4.8
Acetic acid	2	0.00	0.0	0.0	0.0	0.0
Extractives	19.8	0.00	0.0	0.0	0.0	0.0

6.3.3 LIFE CYCLE INVENTORY (LCI) AND PROCESS DESCRIPTION

The collection of inventory data is the most crucial step while performing LCA. The system boundary consists of following unit process: feedstock acquisition (S1), ethanol production (S2) and transport (S3). Feedstock acquisition (S1) includes collection of straw manually, bailing in the field and transport to ethanol plant. At this stage, the rice cultivation and harvesting is not included within the system boundary as straw is a by-product

of rice cultivation and is considered as waste. The inventory data of S1 and S3 is given in Table 6.3

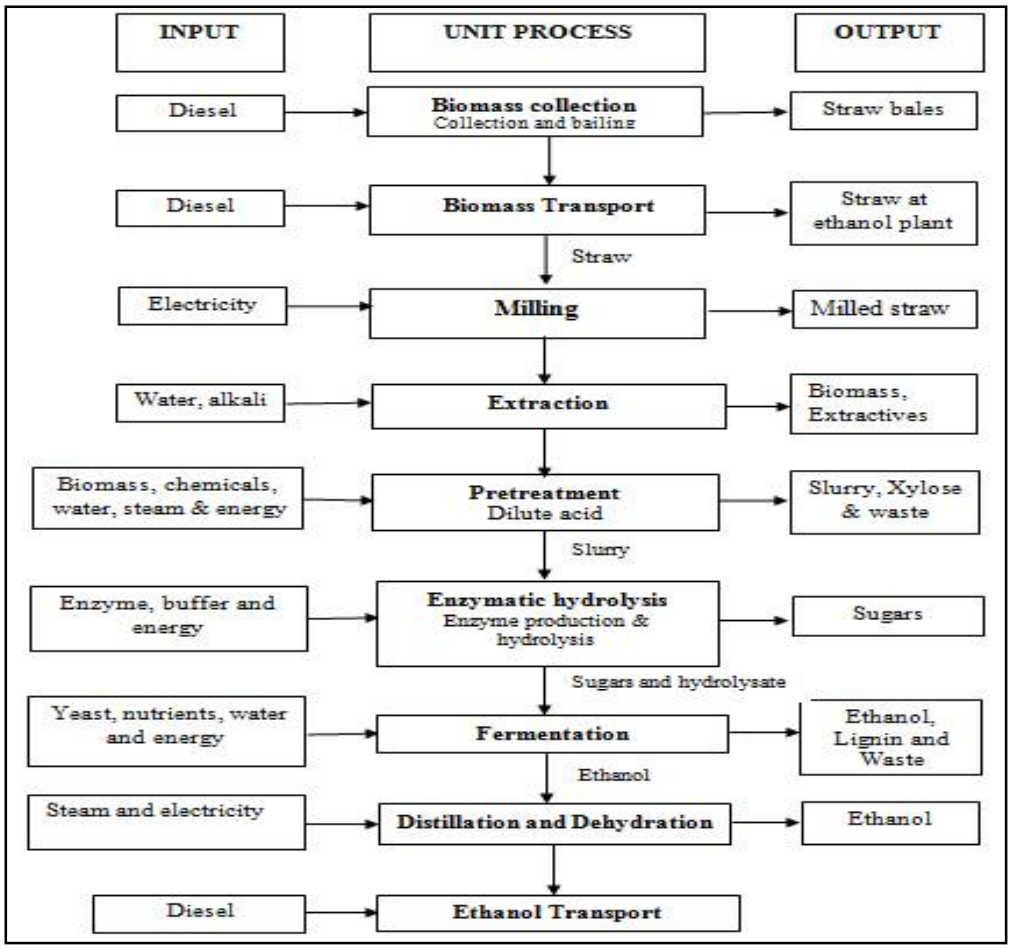

Figure 6.2 System boundary of ethanol production

The ethanol production (S2) includes milling, pretreatment, enzymatic hydrolysis, fermentation and distillation. The sugar recovery after pretreatment and enzymatic hydrolysis is the determining factor in calculating the ethanol yield. The input and output data of processing 1 ton straw is given in Table 6.4, which is based on the actual pilot and laboratory experiments. The detailed process parameters and sugar recovery of each process are summarized in Table 6.5. The lignin fraction of the straw and biogas produced from anaerobic digestion of wastewater is used internally in the plant in order to meet the energy requirement (electricity and heat) of the plant.

Table 6.3 Inventory of feedstock acquisition (S1) and ethanol transport (S3)

Sub-system	Process	Flow	Value	Remark
S1	Bailing	Diesel	1.6 L	Collection is manual, Bale size is and avg. mass of one bale is 20 kg
	Transport T1 (field to collection center)	Diesel	2.7 L	Carrying capacity of tractor is 1.5 ton
	T2 (collection center to ethanol plant)	Diesel	2.25L	Carrying capacity of truck is 20 ton
S3	Ethanol transport	Diesel	1.54L	Carrying capacity of truck is 20 KL

Table 6.4 Inventory of ethanol production (S2)

Input	Unit	CP	MP1	MP2	MP3	MP4
Biomass	kg	1000	1000	1000	1000	1000
Chemicals						
H_2SO_4*	kg	109	109	89	90	89
NaOH*	kg	10	10	30	50	60
$(NH_4)_2PO_4$*	kg	2.6	2.6	2.6	2.6	2.6
MgSO4*	kg	0.1	0.1	0.1	0.1	0.1
Yeast*	kg	1.2	1.2	1.2	1.2	1.2
Antifoam*	kg	0.4	0.4	0.4	0.4	0.4
Enzymes*	kg	23	19.7	17.6	18.0	19.0
Steam[a]	kg	1512	1609	1612	1634	1639
Electricity[c]	kWh	136	140	148	152	158
Cooling water[d]	KL	119	127	130	132	132
Process water[d]	KL	21	30	44	48	49
Output						
Ethanol*	L	218	242	256	262	267
Surplus electricity[e]	kWh	256	256	256	256	256

* 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 is assumed to be similar in all the processes as exact data is not available and these are underestimated values.

Table 6.5 Parameters and process efficiencies of different scenarios for ethanol production

Parameters	CM	MP1*	MP2	MP3	MP4
Alkali soaking					
NaOH concentration (%)	0	0	0.2	0.4	0.5
Time (mins)	0	60	60	60	60
Temperature (ºC)	0	60	60	60	60
Pretreatment					
Temperature (ºC)	162	162	162	162	162
Pressure (bar)	5	5	5	5	5
Acid concentration (%)	1.1	1.1	1	1	1
Residence time (min)	10	10	10	10	10
Glucose recovery (%)	95	99	100	99	91
Xylose recovery (%)	59	55	78	69.5	57.26
Enzymatic hydrolysis					
Temperature	50	50	50	50	50
WIS loading (%)	15	15	15	15	15
Enzyme (FPU)	8	8	8	8	8
Residence time (hrs)	48	48	48	48	48
Saccharification yield (%)	74	62	72	76	73
Fermentation					
Temperature (°C)	32	32	32	32	32
Pressure (bar)	1	1	1	1	1
Residence time (days)	2	2	2	2	2
Glucose to ethanol (%)	90	90	90	90	90
Xylose to ethanol (%)	80	80	80	80	80

* MP1 is soaking in water

6.3.4 LIFE CYCLE COSTING (LCC)

LCC of ethanol is estimated with both fixed costs (straight line depreciation on installation, labor, maintenance and interest on investment) and variable costs (feedstock, enzyme, chemicals and nutrients etc.). The similar system boundary and assumptions as applied in LCA study are used in LCC. In LCC, a steady state cost model is used and only production cost is taken into account. The feedstock cost is assumed to be 3000 INR/dry metric ton and other chemicals cost used in analysis are given in Table 6.6.

Table 6.6 Price used in economic evaluation of ethanol

Raw material	Unit	Price (INR)
Feedstock and handling	Rs/kg	4
Chemicals		
NaOH[a]	Rs/kg	40
H_2SO_4[a]	Rs/kg	20
Enzyme[a]	Rs/kg	250
$(NH_4)_2PO_4$[a]	Rs/kg	12
$MgSO_4$[a]	Rs/kg	35
Yeast[a]	Rs/kg	150
Utilities		
Electricity[b]	Rs/kWh	5
Cooling water[c]	Rs/L	1
Process Water[c]	Rs/L	1
Other		
Fixed cost[c]	Rs/L EtOH	2
Interest on CAPEX[c]	Rs/L EtOH	6

[a]Values are obtained from vendors supplying chemicals at IOCL, Faridabad
[b]The price is obtained from Dakshin Haryana Bijli Vitran Nigam (DHBVN) supplying electricity to the industries. [c] Obtained from Praj Industries Limited, Pune running commercial 2G ethanol plant

6.4 RESULTS AND DISCUSSION

Well to gate LCA of fuel ethanol from rice straw using CP and MP technologies is conducted and results are discussed in four environmental categories, i.e. GWP, EP, AP and POCP. The net results for different impact categories based on the FU i.e.1 L ethanol are given in Table 6.7. The ethanol yield in CP, MP1, MP2 and MP3 scenarios is 218, 242, 256, 262 and 267 respectively.

Table 6.6 Environmental impact of each scenario for producing 1L ethanol (FU)

Scenarios	GWP ($kgCO_2eq./L$)	EP ($kgPO_4eq./L$)	AP ($kgSO_2eq./L$)	POCP ($kgC_2H_6eq./L$)
CP	-0.42	$0.2x10^{-3}$	$-5.9x10^{-3}$	-0.1
MP1	-0.58	$7.6x10^{-5}$	$-6.8x10^{-3}$	-0.1
MP2	-0.47	$0.3x10^{-3}$	$-5.6x10^{-3}$	0.1
MP3	-0.32	$0.3x10^{-3}$	$-4.9x10^{-3}$	0.4
MP4	-0.26	$0.4x10^{-3}$	$-4.5x10^{-3}$	0.5

6.4.1 GLOBAL WARMING POTENTIAL (GWP)

GWP includes the emissions of CO_2, CH_4 and N_2O that are characterized to $kgCO_2eq.$ using characterization factor of 1, 25 and 298 respectively. The processing of 1 ton straw to ethanol resulted in the GHG emissions of 207, 168, 199, 222 and 235 $kgCO_2eq.$ in CP, MP1, MP2, MP3 and MP4 respectively and follow an increasing trend as: MP1< MP2< CP < MP3< MP4. Figure 6.3 shows the process wise emissions and contribution analysis in each scenarios as: enzymatic hydrolysis (40-66%) > alkali extraction (17-34%) > pretreatment (13-17%) > feedstock collection and transport (8-11%) > fermentation (3-4%) > electricity use (2-3%) > ethanol transport (0.5%). The variation in contribution is due to variation in input and output of ethanol yield in five different scenarios. For producing 1L ethanol MP1, MP2, MP3, MP4 scenario resulted in a reduction of 23, 27, 34, 39% enzyme as compared to CP and therefore, reduced GHG emissions. The reason for reduction in enzyme dosage in MP scenarios is attributed to the removal of extractives by 60-70% and lignin by 8-13% during extraction. The unwanted material leaches out during extraction in MP scenarios and hence, reducing burden on enzyme in hydrolysis step. This makes enzyme more accessible to the cellulose and gives an increased hydrolysis with higher production of fermentable sugars. Therefore, as compared to CP, ethanol yield increased to 10.5, 17.4, 20.2 and 22.2% in MP1, MP2, MP3 and MP4 respectively. An interesting thing to note here is that, although ethanol yield increased in MP3 and MP4 but, at the same time, input of alkali during soaking has increased overall GHG emissions to 7 and 13% respectively. Therefore, a trade off is seen between the ethanol yield and GHG emissions while opting for MP3 and MP4 scenarios in future.

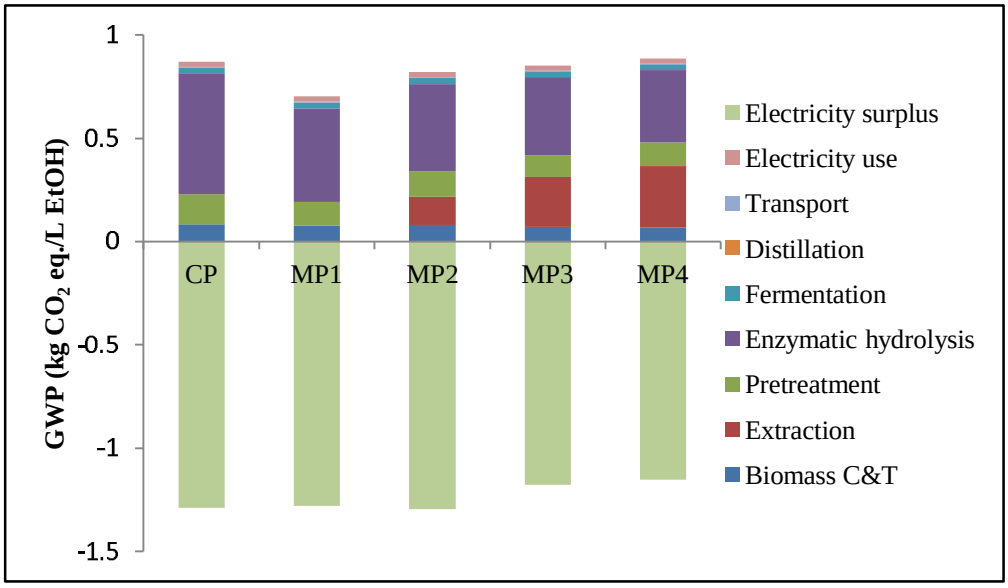

Figure 6.3 GWP of conventional and improved pretreatment method for ethanol production

Some authors have reported that enzyme and electricity use in the plant contributes significantly to the GHG emissions. However, in present study electricity is obtained from burning of lignin in all scenarios and hence emissions from electricity are not that significant. The surplus electricity from the plant is sold to the grid that replaces coal based electricity and result in credit of 207 kgCO_2eq. emissions. The excess electricity produced in all the five scenarios have been kept constant due to unavailability of actual estimation of electricity produced.

6.4.2 EUTROPHICATION POTENTIAL (EP)

Eutrophication is caused by the addition of anthropogenic inputs to the environment such as nitrogen, phosphorus and their oxides causing undesirable changes to the ecosystem's structure and function. Many studies have reported that the cultivation and harvesting of feedstock is the major contributor to the EP due to the addition of NPK fertilizers. However, in current scenarios agriculture phase is not included and analysis is based on emissions during production and use of chemicals, enzyme and nutrients used in ethanol production. The processing of 1 ton straw to ethanol resulted in the emissions of 0.20, 0.18, 0.24, 0.26 and 0.28 kgPO_4eq. in CP, MP1, MP2, MP3 and MP4 respectively. Figure 6.4 shows the process wise emissions per

functional unit and contribution analysis in each scenarios follows the trend: enzymatic hydrolysis (40-71%) > alkali extraction (17-39%) > pretreatment (13-17%) > feedstock collection and transport (8-12%) > electricity use (5-6%) > ethanol transport (0.5%).

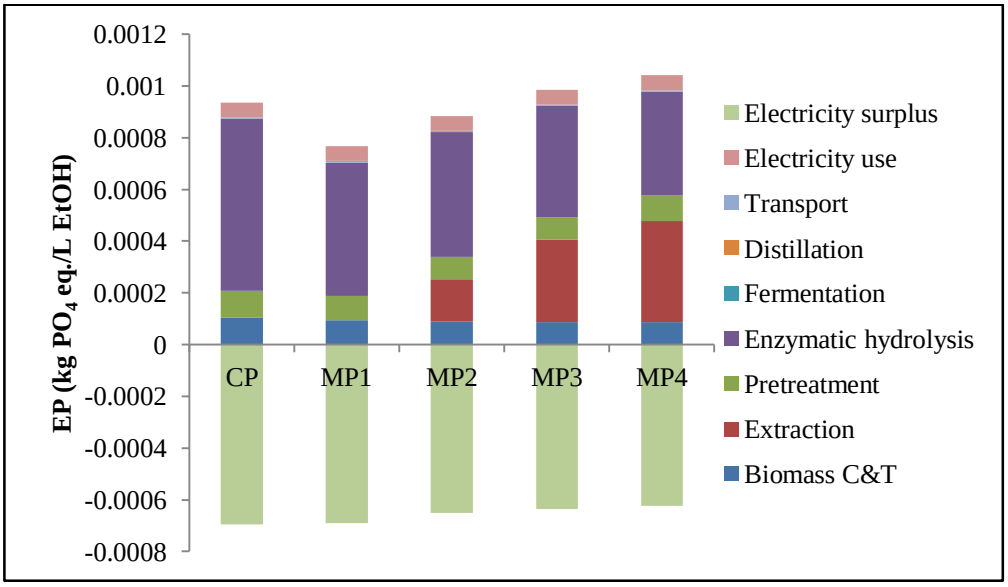

Figure 6.4 EP of conventional and improved pretreatment method for ethanol production

The major contribution to the impact is observed from enzymes and alkali use. CP consumes the largest amount of enzyme i.e. 23 kg/ton straw emits 0.14 kg emissions whereas MP4 requires 17 kg enzyme and emits 0.10 kg emissions during the production of enzyme. However, MP1 which uses only water as a soaking agent requires 20.0 kg enzyme and overall has least emissions. The input of alkali in MP 2-4 scenario lowers the enzyme requirements and improves the ethanol yield, but, same time contributes to the emissions by using alkali. The combustion of diesel during transportation activities releases NOx and is responsible for 8-12% to the EP. The substitution of ~256 units of coal based electricity with straw based electricity gives the credit of 0.16 kgPO_4eq. emissions in each scenario. The emissions of NOx during production of electricity and left over bottom ash are responsible for the eutrophication.

6.4.3 ACIDIFICATION POTENTIAL (AP)

The impacts of acidifying pollutants such as SO_2 and NOx emissions are measured in terms of AP and expressed as $kgSO_2eq$. The processing of 1 ton straw to ethanol resulted in the emissions of 1.20, 1.15, 1.37, 1.50 and 1.61 $kgSO_2eq$. in CP, MP1, MP2, MP3 and MP4 respectively and follow an increasing trend of emissions as MP1< CP< MP2<MP3<MP4. Figure 6.5 shows the process wise emissions and contribution analysis in each scenarios follows the trend: enzymatic hydrolysis (43-73%) > alkali extraction (15-31%) > pretreatment (7-10%) > feedstock collection and transport (8-11%) > electricity use (9-11%) > ethanol transport (0.5%). Emissions during enzyme and alkali production have highest impact on AP due to large amount of fossil energy consumed during their production. Processing of 1 ton straw to ethanol in CP uses 23 kg enzyme and gives 0.92 $kgSO_2eq$. emissions, which gets reduced to 0.78 in MP1, MP2, 0.71 in MP3 and 0.68 kg SO_2 eq. in MP4 scenario. In AP also, enzyme production has the highest impact and as the dosage of enzyme is reduced in MP scenarios, the emissions get reduced. However, the emissions from alkali production also increased in MP scenarios. The ethanol production using MP1 shows the highest benefit as enzyme dosages are reduced by 13% as compared to CP and the process does not use alkali in extraction process. The processing of 1 ton straw produces ~256 kWh surplus electricity which replaces equivalent amount of coal based electricity and results in credit of 1.6 $kgSO_2eq$. emissions. The coal based electricity releases 15 times higher SO_2 emissions than straw based electricity, therefore, bio based electricity is beneficial in reducing the acidification.

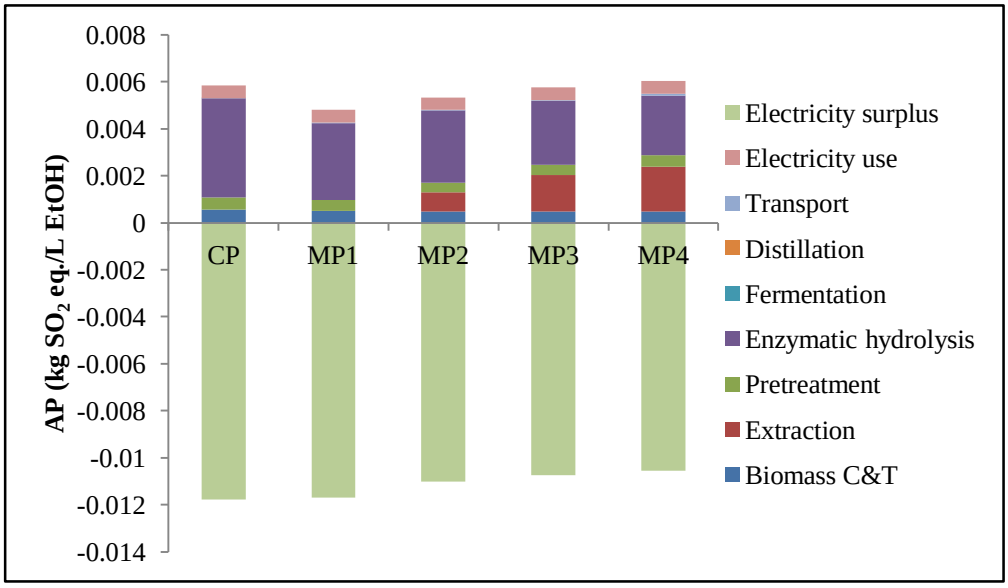

Figure 6.5 AP of conventional and improved pretreatment method for ethanol production

6.4.4 PHOTOCHEMICAL OXIDANT CREATION POTENTIAL (POCP)

The photochemical oxidation also referred as smog is the result of reactions between NOx and hydrocarbons or volatile organic carbons and expressed as kgC_2H_6eq. The processing of 1 ton straw to ethanol resulted in the emissions of 0.18, 0.17, 0.44, 0.70 and 0.86 kgC_2H_6eq. in CP, MP1, MP2, MP3 and MP4 respectively and follow an increasing trend of emissions as MP1< CP< MP2<MP3<MP4. Figure 6.6 shows the process wise emissions and contribution analysis in each scenarios follows the trend: alkali extraction (60-76%) > pretreatment (19-74%) > enzymatic hydrolysis (3-24%) > feedstock collection and transport (0.21-1.2%) electricity use (0.54-2.3%) > ethanol transport (0.5%). Emissions during enzyme and alkali production have highest impact on AP due to large amount of fossil energy consumed during their production. From Fig. 6 the following trend is obtained: CP < MP1< MP2< MP3. As compared to CP, MP performance is worst in all scenarios in POCP. This is due to production of alkali step is responsible for 80-85% of emissions followed by enzyme production 10-15%. Although there is an increase in yield using MP, but it does not favor any emissions benefit in this category.

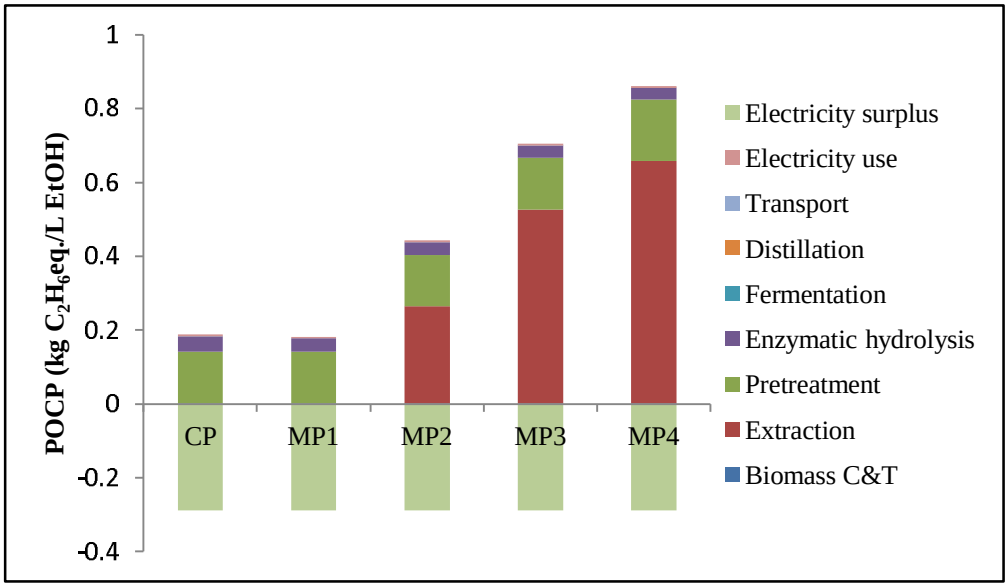

Figure 6.6 POCP of conventional and improved pretreatment method for ethanol production

6.4.5 LIFE CYCLE COSTING (LCC)

The production cost of ethanol in five different pretreatment scenarios is calculated based on the cost inventory data for the year 2016. In an ethanol plant, as shown in Figure 6.7, the production cost from different inputs follow the trend: enzyme (32%) > feedstock and handling (28%) > chemicals (25%) > interest (8%), fixed cost (3%). The ethanol production cost shown in Figure 6. 8 after excluding tax for CP, MP1, MP2, MP3 and MP4 scenarios is 58.7 (0.87), 48.0 (0.70), 49.1 (0.72), 49.0 (0.72) and 49.0 (0.72) INR/L ($/L) respectively. At the same level of enzyme loading (8FPU/g WIS), the lowest production cost is found for MP1 due to its minimal raw material consumption as compared to other MP scenarios. The CP has the highest ethanol cost due to higher dosage of enzyme whereas the cost gets reduced by ~26% in MP processes due to reduction in enzyme dosages. The ethanol cost arrives to similar figure in all MP scenarios because in scenarios where alkali cost increased, enzyme cost gets lowered down.

A wide range of Minimum Ethanol Selling Price (MESP) from 0.327 – 1.075 $/L is reported which reflect the differences in feedstock composition and conversion pathway. The result of rice straw derived ethanol using either CP or MP are within in this range. Moreover, the MP resulted in reduction in ethanol cost as compared to CP.

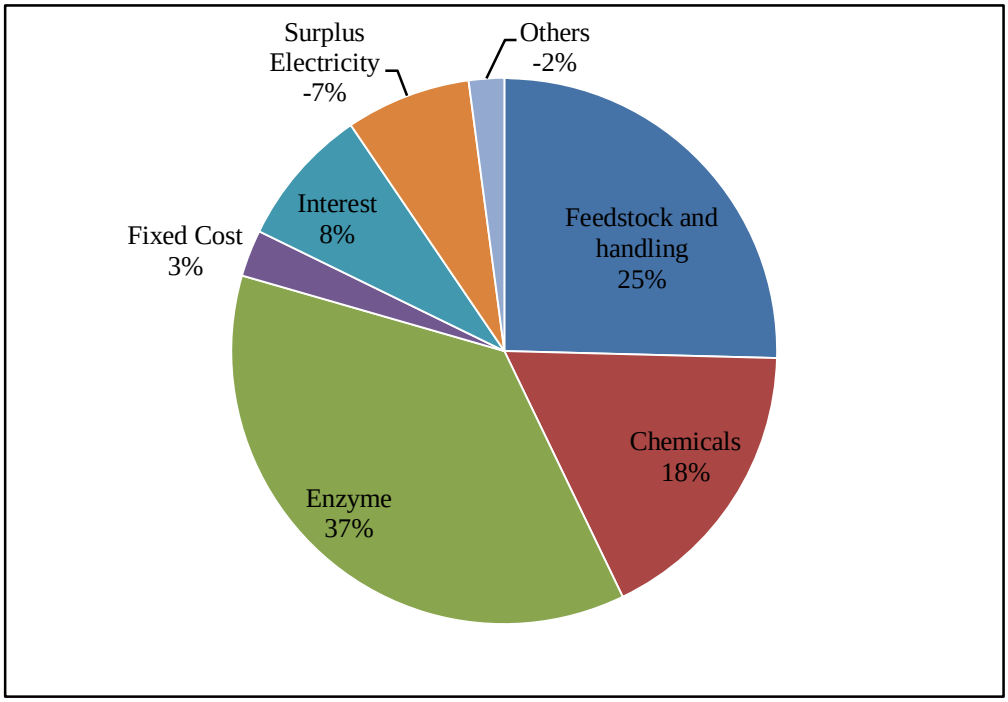

Figure 6.7 Conversion cost breakdown in an ethanol plant

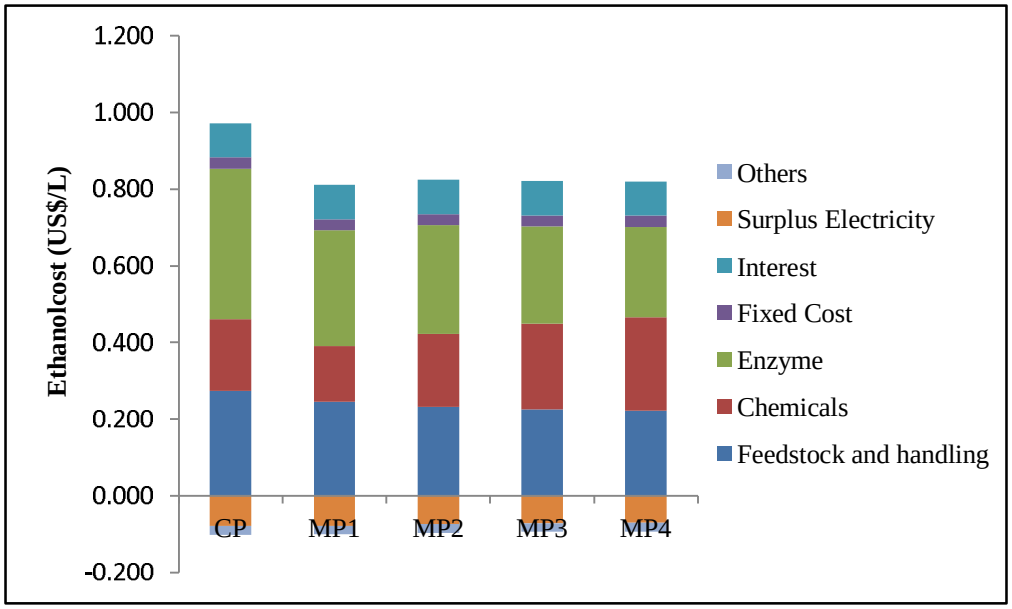

Figure 6.8 Life cycle costing of the ethanol produced in different pretreatment scenarios

6.5 CONCLUSIONS

Environment and economic assessment are performed for fuel ethanol from rice straw using five pretreatment scenarios; CP and MP (MP1, MP2, MP3 and MP4) followed by enzymatic hydrolysis and fermentation. By using water (MP1) and 0.2 (MP2), 0.4(MP3) and 0.5% (MP4) concentration of alkali in soaking media, ethanol production is 242, 256, 262 and 267 L as compared to 218 L in CP. The well to gate contribution analysis shows that enzyme production and use of alkali in soaking are the main contributors to the most impact categories, whereas surplus electricity sold to the grid provides major savings in emissions by replacing coal based electricity. The introduction of extraction step prior to DA pretreatment fulfills the objective of reducing enzyme dosage by 23, 27, 34 and 39% in MP1, MP2, MP3 and MP4 respectively. However, overall LCA results revealed that performance of MP2, MP3 and MP4 is on a negative side in all the environmental impact categories as compared to CP. This is due to the use of alkali, where a huge amount of emissions are released during the production stage. Overall, MP1 using water as a soaking media for extraction has GWP (-0.58 kgCO_2eq./L), EP ($0.7x10^{-4}$ kgPO_4eq./L), AP ($-6.8x10^{-3}$ kgSO_2eq./L), POCP (0.1 kg C_2H_6 eq. /L) and is the most environmentally suitable pretreatment process for ethanol production. Thus, modified pretreatment using alkali as an extraction media is not favorable for scale up of the technology.

The economic assessment of all the five pretreatment scenarios shows that major production cost of ethanol is from enzyme and feedstock. The ethanol cost gets reduced by 26% in MP scenarios as compared to CP due to reduction in enzyme dosages and higher yield. Among all the scenarios, MP1 has the minimum production cost of 0.70$/L EtOH (~48 INR/L). Thus, it is concluded that among all the pretreatment scenarios, MP1 is the best pretreatment strategy in order to have minimum environmental burden and minimum ethanol production cost.