CHAPTER 4

LIFE CYCLE ASSESSMENT OF FIRST GENERATION FUEL ETHANOL FROM SUGARCANE MOLASSES IN INDIA

India's ethanol blending programme (EBP) is based on the ethanol production from molasses and there existed a research gap in the area of sustainability assessment of fuel ethanol from molasses in India. The present study establishes the environmental profile of ethanol derived from sugarcane molasses using life cycle assessment (LCA). The study is essential not only for the industries but also for the stakeholders, customers and policy makers to make more meaningful decisions in future. The study quantifies GHG emissions and the energy consumed during each step of ethanol production and use. The functional unit is 1 ton of fuel ethanol produced in the northern region (NR) and western region (WR) of India. Four different allocation approaches, without allocation (WA), mass allocation (MA), energy allocation (EA) and market price allocation (MPA) are used to distribute emissions and energy consumption between product and the co-products. Sensitivity analysis is conducted on the effect of variation in sugarcane yield on GHG emissions and net energy ratio (NER).

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4.1 INTRODUCTION

Sugarcane, botanical name *Saccharum officinarum* is species of the tall perennial grass family Poaceae. Sugarcane is native of South Asia and can be grown in countries having warm temperate to tropical climate. It is an old important energy source for humans and recently identified as an alternative to fossil fuels. The crop requires longer time varying from 12 to 15 and even 18 months to mature. The crop growth is divided into four phases: germination (juvenile), tillering (formative), growth and ripening (harvesting). Sugarcane requires hot and humid temperature of 21-27°C and rainfall of 5-150 cm. The juice content and quality is increased, if temperature is above 20°C in growing stage [206]. During growth phase, high humidity of 80-85% helps in elongation of the cane and thereafter, moderate 40-45% along with limited water supply is required in the ripening phase. The entire cycle requires 10-12 irrigation, where rains are not sufficient enough to provide the required water. Flat plain land is an advantage for proper irrigation and transportation of cane from field to mills Heavy rainfall is not favorable for the growth phase as it results in lower sugar content. During ripening and harvesting, dry cool wintery season is ideal. In regions having freezing winters and frost like in Northern India, it is recommended to harvest the cane before frost. Sugarcane growth is most favorable in soils that have the capacity to retain water. Therefore, clayey and loamy soil is ideal for its growth. The soil rich in N, Ca and K and having a pH of 5-8.5 is favorable. Lime is required if pH is below 5 and gypsum is required if soil pH cross 9.5. The cultivation of sugarcane requires heavy dosage of fertilizers, manure, herbicides and insecticides [206].

Sugarcane is one of the most important crop in India with 7% share to total agricultural output. Sugar industry is the second largest agro-based industry of India in terms of economic returns and employment [207]. After Brazil, India is at second position among the world in sugarcane production. Sugarcane in India grows in two distinct geographical regions: tropical and subtropical. In northern region, Uttar Pradesh is the largest producer followed by Maharashtra in western region as shown in Figure 4.1.

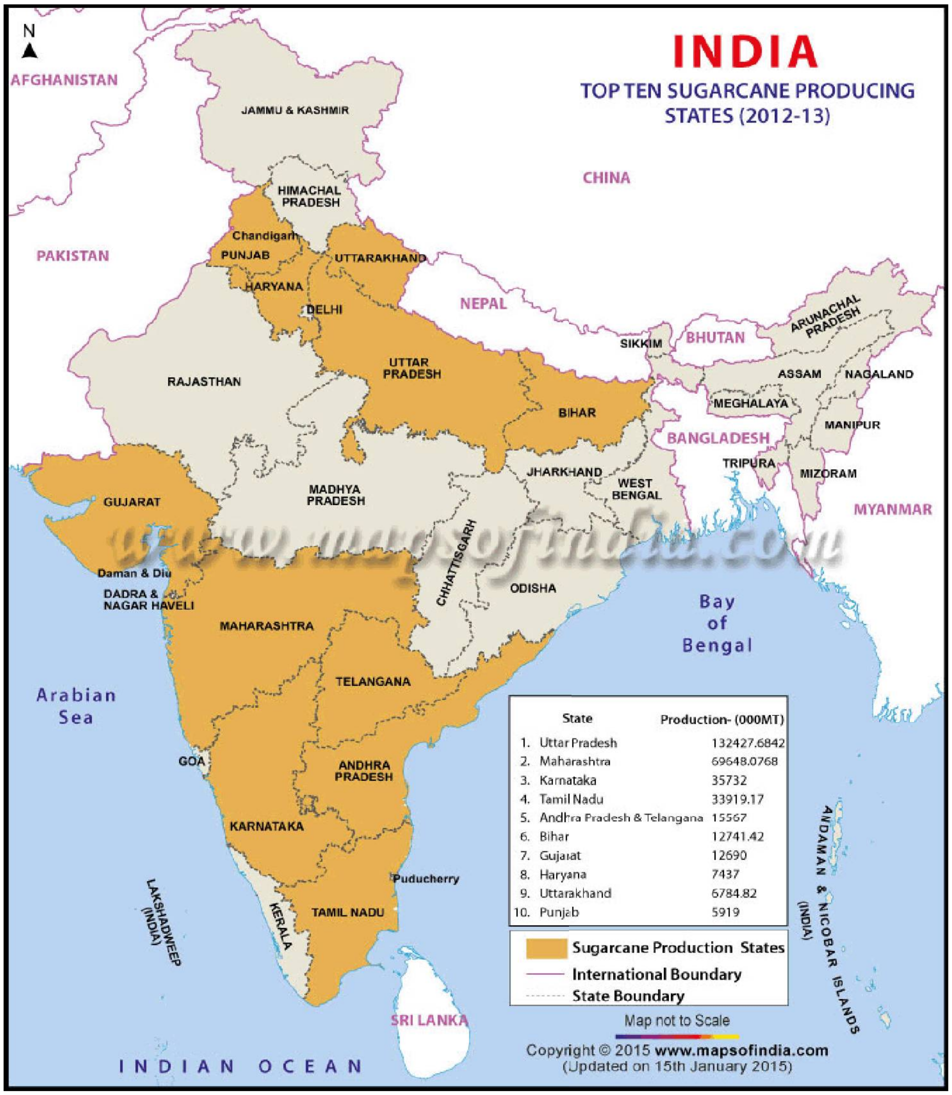


Figure 4.1 Top 10 sugarcane producing states of India (Source: Maps of India) [208]

These two states also have largest number of sugar refineries as shown in Figure 4.2. There is a difference in the area of plantation, production, agro-climatic conditions, agro-practices, sugarcane yield and sugar content among the states [209]. Today, India has 453 sugar mills, comprising 252 mills from the co-operative sector and 134 mills from the private sector. Molasses, a by-product of the sugar industry is mainly utilized for ethanol production [210].

The detailed production statistics of sugarcane, molasses and ethanol in last six years is given in Table 4.1. Due to limited availability of molasses, the 10% blending target could not be met and therefore, it was kept to 5% ethanol blending in gasoline across the country [211]. In India, sugarcane production is cyclical in nature and poorly organized. The price of sugarcane in India is decided by the demand and supply. Whenever, farmers observe higher rates, they all start growing sugarcane leading to surge in supply and plunge in prices and vice-versa. This can be seen in Table 4.1, where sugarcane production is lower in initial two years of 2007-09 and this rate increased again in 2009 and onwards, when farmers are paid higher for their crop. Higher sugarcane production leads to higher molasses leading to higher ethanol production. A significant part of the ethanol goes for potable use as liquor for human consumption and industrial use and the surplus is used for blending in gasoline.

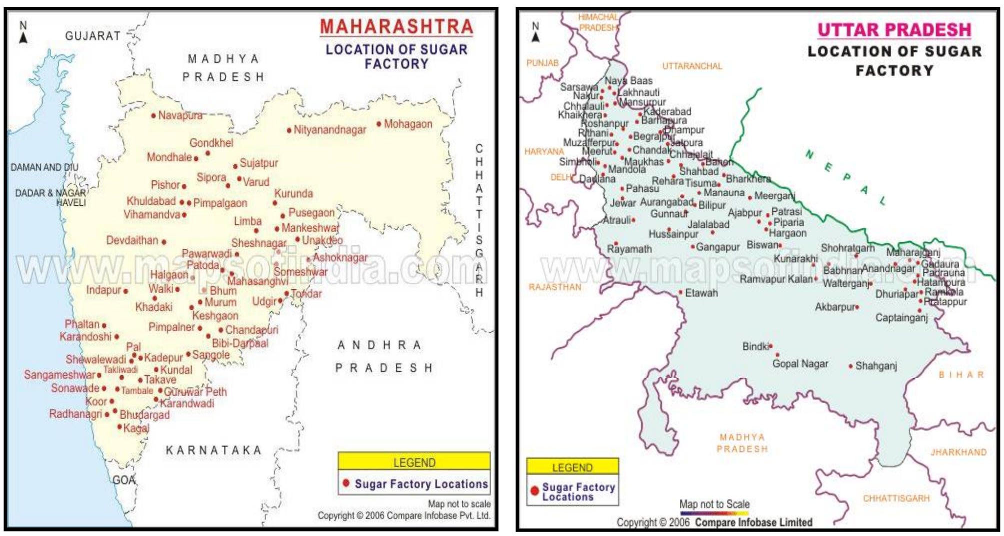


Figure 4.2 Sugar factory locations in (a) Maharashtra and (b) Uttar Pradesh, India (Source: Maps of India) [208]

LCA of ethanol based on molasses, with a focus on GHG emissions and energy balance has been conducted in different countries like Brazil [52, 212, 213], Australia [214], Thailand [215], Mexico [63], Argentina [216] and Nepal [61] but, the conclusions derived from these studies are not comparable due to a huge disparity in the design of system boundaries, fertilization, irrigation, harvesting and application of different methods for allocation. The sustainability of biofuels is dependent on emissions released and the consumption of energy during the production. Therefore, it is of prime importance to conduct life cycle assessment (LCA) in order to assess the environmental and energy benefits of producing molasses based ethanol in India.

Table 4.1 Sugarcane [217], molasses, ethanol production [218], gasoline consumption [219] and fuel ethanol requirement in India

Year	Sugarcanea	Molassesa	Ethanolb	Gasolinea	% Ethanol blends in gasoline[b]	
					5[b]	10[b]
2008	285.02	8.96	2150	10.33	689.6	1379.8
2009	277.80	4.47	1073	11.26	751.7	1503.3
2010	342.38	6.34	1522	12.82	855.8	1711.6
2011	357.67	7.00	1681	14.19	947.3	1894.5
2012	360.00	8.97	2154	14.99	1000.7	2001.3
2013	355.00	8.60	2064	15.74	1050.7	2101.5

[a]Production in million metric ton per annum (MMTPA), b Ethanol production is in million liters (ML) and requirement is calculated for 5% and 10% blending in gasoline; specific gravity of gasoline = 0.749 kg/L [220]

4.2 AIM OF STUDY

The aim of study is to conduct LCA of fuel ethanol in northern region (NR) and western region (WR) of India. This is the first study carried out in India, wherein, the comparison of LCA is done in two distinct regions of the country. To handle the impact and credit of co-products, allocation is applied based on mass, energy and the market price of the product and the co-products. System expansion is not used in this study as sugar is the main product, which neither has any alternative use nor it is being produced by an alternative process or other sources. LCA approach will throw light on the environmental impact and energy benefits of producing ethanol from molasses in India.

4.3 METHODOLOGY

The methodology used for conducting this LCA is based on the guidelines of ISO series 14040 and 14044 as described in Chapter 3. In this study, most of the data is secondary, obtained from various technical reports, government reports, websites, sugar industry reports and literature. However, due to limited availability of secondary data at various steps, primary data is obtained from personal communication with experts at National Sugar

Institute (NSI), Kanpur and Vasantdada Sugar Institute (VSI), Pune. These institutes have collection of data from local sugarcane farmers and almost different sugar mills of different regions in India. The data figures are generally average of values for last 5 years. While conducting this study, excel spreadsheets are used for data registration and to calculate emissions and energy balance. Detailed methodology, data and assumptions are described in the following sections:

4.3.1 GOAL AND SCOPE

Indian Oil Corporation Limited (IOCL) is the largest petroleum refining and marketing company owned by the state government under the Ministry of Petroleum and Natural Gas. We have conducted this study to find the reduction in GHG emissions and energy benefits using ethanol as a fuel in India. The functional unit (FU) considered in the study is 1 ton of ethanol. The results are calculated on the average sugarcane yields of 57.4 and 79.6 t/ha.yr from 2008 to 2013, in NR and WR respectively [221]. GHG emissions, energy consumption and NER are estimated for 1 ton of ethanol production, whereas GHG emissions reduction with respect to gasoline are estimated using the GHG emissions generated during production as well as combustion of ethanol and gasoline. As per the practice of LCA, the impacts associated with capital equipment and infrastructure are not included.

4.3.1.1 System boundary

The system boundary for this study is based on current technologies and practices used, illustrated in Figure 4.3; which includes the unit processes: sugarcane farming, sugarcane transport, sugar production, molasses transport, ethanol production, ethanol transport, blending and combustion in automobiles. Figure 4.4 shows the field photographs of sugarcane planting, transportation, molasses, sugar mill, machinery and ethanol plant. Allocation approach is used to distribute GHG emissions and energy between the product and the co-products. Manpower is considered only in the farming stage as in other processes, systems are mechanized and impact of manpower is insignificant.

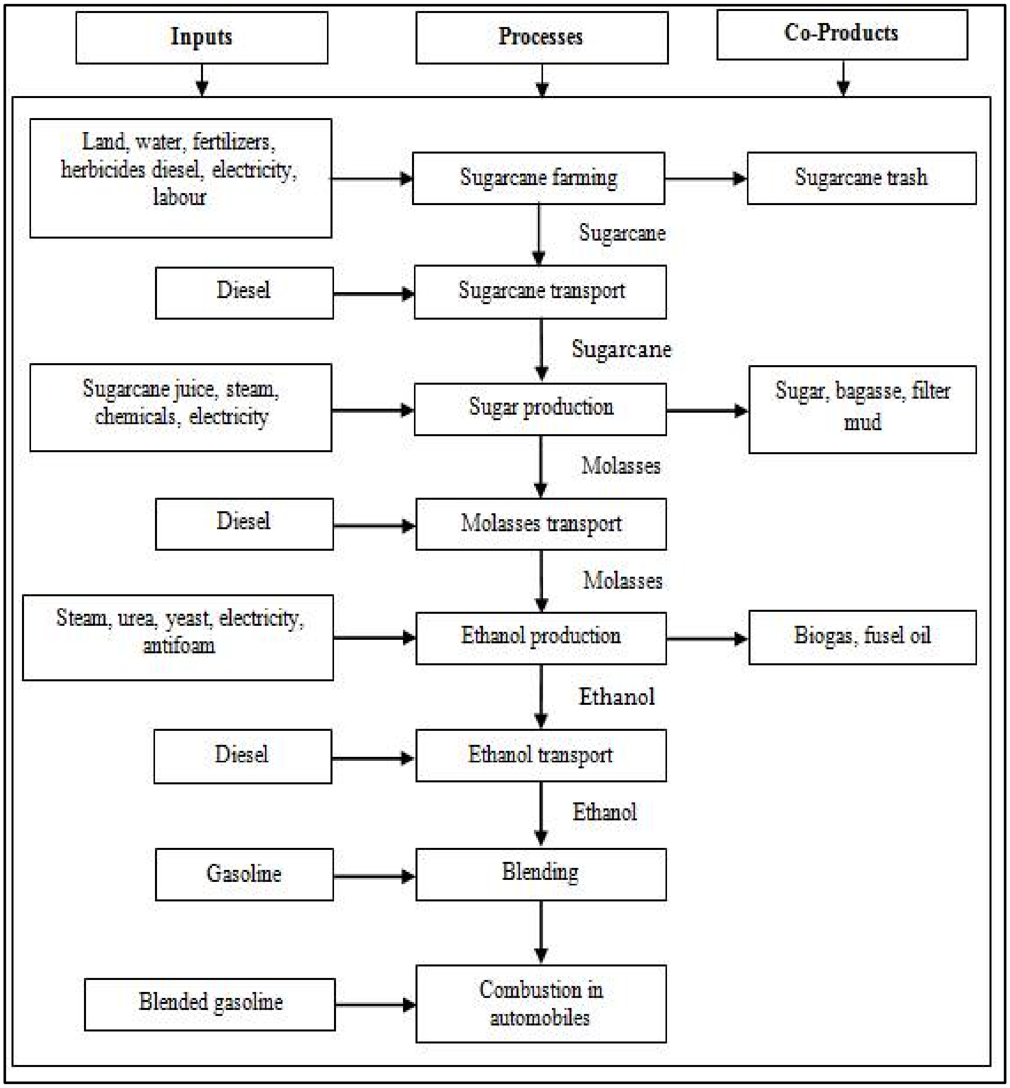


Figure 4.3 System boundaries for the 1G fuel ethanol production in India

Sugarcane farming

(i) (ii) (iii)

(b) Mode of transportation (i) Bullock cart (20%) (ii) Tractors (80%) (iii) Truck from collection center to sugar mills

(c) Sugar mill

(d) Crushing mill

(e) Molasses

(f) Clarifier unit

(g) Bagasse

(f) Evaporators

(g) Ethanol plant

Figure 4.4 Photographs of the sugarcane field, transportation vehicle, sugar mill and ethanol refinery (Source: Internet Images)

4.3.2 LIFE CYCLE INVENTORY (LCI) AND PROCESS DESCRIPTIONS

LCI is a process of quantifying energy and raw material requirements, atmospheric and waterborne emissions, wastes and other release for the entire life cycle of a product, process, or activity [222]. LCI of fuel ethanol includes eight unit processes, input and output data for each process is given in Tables 4.2-4.5.

4.3.2.1 Sugarcane Farming

Farming includes soil preparation, sugarcane plantation, cultivation and harvesting. Climatic conditions and land quality influence the agriculture to a great extent and, hence leads to variation in yield and quality of sugarcane and the inputs required from one region to another. Land requirement to produce sugarcane for 1 ton ethanol is 1.94 and 1.10 ha in NR and WR respectively, based on sugarcane yield, 57.4 t/ha.yr and 79.6 t/ha.yr respectively. Soil preparation involves ploughing and leveling wherein ploughing is totally mechanized in both the regions and tractors are used. Diammonium phosphate (as P) is applied as basal fertilizer, whereas urea (as N) and potash (as K) are applied in split doses The crop is maintained by regular irrigation, application of fertilizers, herbicides and detrashing to remove excess leaves from the plant. Attaining maturity after 9-10 months sugarcane crop is harvested manually by cutting down the stems and leaving the roots enabling it to regrow [223]. Sugarcane is allowed to regrow twice with the same stalk and this factor is applied for the inputs in soil preparation. Sugarcane is the product of this process and trash is the co-product, which is used as a domestic fuel in cooking in villages or as an animal feed. Detailed input and output of this process is given in Table 4.2.

Table 4.2 Inventory of sugarcane farming for sugarcane production of 111.4 ton in NR and 88.2 ton in WR to produce 1 ton of ethanol

Inputs	Unit	NR	WR	Outputs	Units	NR	WR
Land	ha	1.94	1.10	**Products**			
Water[a]	kg	18139	26400				
Urea (as N)[b]	kg	533.5	275	Sugarcane	ton	111.4	88.2
DAP (as P)[b]	kg	145.5	126.5	Sugarcane trash[g]	ton	16.3	13.2
K_2O (as K)[b]	kg	232.8	126.5				
Herbicides[b]	kg	3.9	1.1	**Emissions**			
Diesel[c]	L	53.3	30.25	CO_2[h]	kg	7113.9	6169.9
Electricity[d]	kWh	1636.6	3052.5				
Seed[e]	kg	5575.5	3850.0				
Labour[f]	Man-hr	2576.3	2288				

[a] Water requirement in NR is 17000 KL/ha (average value of 160-180 ha-cm is converted to KL/ha) [224], of which, 45% is met by rains and 55% through irrigation [225] and water requirement in WR is 30000 KL/ha (300 ha-cm is converted to KL/ha) [224], of which 20% is met by rains and 80% through irrigation [225]. Irrigation is considered through electric pumps only. [b] Data for NPK, diesel, herbicides and electricity is collected from the personal communication with experts at NSI, Kanpur and VSI, Pune. [c] 55 L/ha of diesel is consumed in soil preparation. [d]Total number of irrigations in NR are 7.6, whereas 25 in WR [225] and one irrigation requires 111 kWh/ha of electricity, the electricity consumption in both regions is calculated accordingly. [e] Average values of seed i.e. 5.0-6.5 ton/ha in NR and 6.0-8.0 ton/ha in WR [226]. [f] Labour requirement is 166 person-day/ha in NR and 260 person-day/ha in WR. Person-day/ha is converted to man-hr/ha, by multiplying these values by 8 [227]. [g] Trash includes sugarcane tops and leaves which is 30% of sugarcane, having 50% moisture [61]. [h] CO_2 emissions are from NPK fertilizers, herbicides, diesel, electricity and labour.

4.3.2.2 Sugarcane Transport

In NR, sugarcane is transported from farm to the sugarcane collection centre (6-8 km) followed by the centre to the mill (25 km). 80% transportation from farm to centre is carried by tractors (40 HP) and the rest by the bullock carts. Transportation from the collection centre to mill is by trucks. In WR, sugarcane from field is transported directly to the mill (30 km) and 40% transportation is by tractors and 60% by trucks. Transportation by tractor, of an average carrying capacity 5 ton consumes, 8 L/hr diesel in loaded and 7 L/hr unloaded conditions and transportation by truck of an average carrying capacity 12 ton, consumes 6 km/L diesel in loaded and 7 km/L in unloaded conditions. Assumptions of transportation distance and mileage are based on the discussions with experts at NSI, Kanpur and VSI, Pune. Although transportation of sugarcane, molasses and ethanol are different processes, but in order to make interpretation easy, these processes are clubbed (Table 4.3).

Table 4.3 Inventory of sugarcane (111.4 and 88.2 ton), molasses (5.0 and 4.0 ton) and ethanol (1 ton) transport in NR and WR

Input	Unit	NR	WR	Outputs	Unit	NR	WR
Sugarcane							
Diesel by tractor	L	135	225	Emissions			
Diesel by truck	L	69.6	37.1	CO_2	kg	736.7	943.7
Molasses[a]							
Diesel	L	17.7	4.4	CO_2	kg	61.8	15.7
Ethanol							
Diesel	L	1.8	1.8	CO_2	kg	6.7	6.7

[a] In NR, 43% distilleries are integrated with sugar mills and 57% stand-alone [228] whereas in WR, 70% distilleries are integrated with sugar mills and 30% stand-alone [228].

4.3.2.3 Sugar Production

The sugarcane is shredded using rotating knives or shredders. Sugarcane juice is extracted in the milling using three large milling rollers, in different stages. The extracted juice is clarified and processed by double sulphitation and heated to 75 ^{o}C followed by treatment with sulphur dioxide (SO_2) for bleaching and then by lime to remove impurities. pH of juice is adjusted to ~7 and passed through a heat exchanger to raise the temperature to its boiling point. Further, juice is clarified and evaporated to obtain concentrated syrup. Sediments from clarifier are sent to vacuum filters to obtain filter mud. The syrup from evaporator is again treated with SO_2 and then passed to vacuum pan where thickened syrup is boiled (3-4 times) in order to get maximum sugar crystals [229]. Sugar recovery is 9.05% in NR and 11.45% in WR, based on the average values from 2008 to 2013 [221]. Co-products are bagasse used in generation of electricity, molasses for ethanol production and filter mud as manure. Detailed input and output of this process is given in Table 4.4.

Table 4.4 Inventory of sugar production for processing 111.4 (NR) and 88.2 (WR) ton sugarcane in mill to produce 1 ton of ethanol

Inputs	Unit	NR	WR	Outputs	Unit	NR	WR
Sugarcane	ton	111.4	88.2	Products			
Sugarcane Juice[a]	ton	77.9	61.7	Sugar[f]	ton	10.0	10.0
Steam[b]	ton	50.1	34.7	Surplus bagasse[g]	ton	9.2	7.3
Lime[c]	ton	0.167	0.132	Molasses[h]	ton	5.0	4.0
Sulphur[c]	ton	0.055	0.044	Filter mud[i]	ton	0.87	0.68
Electricity[d]	kWh	2562.0	2027.9	Emissions			
Water[e]	ton	33.4	26.4	CO_2[j]	kg	260.6	206.6

[a] Juice obtained is 70% of sugarcane crushed. Data for juice, steam, electricity and water is from the personal communication with sugar technology expert at NSI, Kanpur.[b] Steam consumption is 45% of the sugarcane and is the waste of the mill. Therefore, energy consumption of this steam is not considered. [c] Lime consumption is 0.15% and sulphur 0.05% of sugarcane [230]. [d] Electricity consumption is 23 kWh per ton sugarcane and is obtained from bagasse. [e] Water consumption is 30% of the sugarcane. [f] Sugar recovery in NR is 9.05% and 11.45% of sugarcane in WR. [g] Bagasse is 30% of the sugarcane, having 50% moisture and is used to produce electricity [231]. 250 kg bagasse can generate 85.6 kWh electricity [232] and bagasse required to produce 2562.0 and 2027.9 kWh is 7.5 and 5.9 ton in NR and WR respectively. Surplus bagasse is calculated by subtracting used bagasse from the total. [h] Molasses is 4.5% of the sugarcane (average of 4-5%) [233]. [i] Filter mud is 3.0% of the sugarcane [231], having 26% dry matter [234]. [j] CO_2 emissions are from lime and bagasse combustion in boilers.

4.3.2.4 Molasses Transport

In India, distilleries producing ethanol from molasses are either integrated to sugar mill or are stand-alone [228]. In the later case, molasses is transported directly to the stand-alone distillery and the process energy demand is met by electricity generated from the biogas. The average distance of the distillery from mill is assumed to be 100 km and transportation is carried out by using truck of carrying capacity 12 ton. Input and output of this process is included in Table 4.3.

4.3.2.5 Ethanol Production

To produce ethanol, the molasses is first diluted to the concentration of fermentable sugars from 45% to 15%. Using a portion of the diluted molasses, a yeast culture is developed from an inoculum. Fermentation reaction is exothermic; the contents of the fermentation tank are kept at 30 ^oC by cooling.

After completion, the yeast sludge is removed from the bottom and the fermentor wash is pumped to the distillation unit. Alcohol with water is fed to rectification column, wherein rectified spirit is withdrawn [235]. Biogas generated from the anaerobic digestion of waste water and yeast sludge has about 50-75% of methane and is used as a co-product for heat generation [236]. Detailed inputs and outputs of this process are given in Table 4.5.

Table 4.5 Inventory of ethanol production of 1 ton, blending 1 ton ethanol with gasoline

Inputs	Unit	NR	WR	Ref.	Outputs	Unit	NR	WR
Ethanol production								
Molasses[a]	Ton	5.0	4.0	---	Products			
Steam[b]	Ton	3.1	2.4	[235]	Ethanol	ton	1	1
Urea[b]	Kg	0.71	0.71	[235]	Surplus biogas[d]	m^3	288.1	183.0
Dilution water[b]	KL	17.9	14.2	[235]	Fusel oil[e]	L	25.06	25.06
Yeast[b]	Kg	3.2	2.6	[235]	Emissions			
Electricity[c]	kWh	1253.0	990.4	---	CO_2 [g]	kg	8.0	6.3
Antifoam[b]	Kg	1.1	0.86	[235]				
Blending								
Ethanol	ton	1	1		CO_2[h]	kg	0.69	0.69
Gasoline[f]	ton	19	19					

[a] For producing 1 ton of ethanol, amount of molasses is dependent on sugar recovery which is different (9.05% in NR and 11.45% in WR) in both the regions and therefore requirement of molasses is different in both the regions. Ratio of 9.05:11.45 in WR is applied to calculate all the respective inputs. [b] Values given in [235] are for 1 KL ethanol. Using specific gravity of ethanol 0.796 kg/L [220], calculations are carried out for 1 ton ethanol. Ratio of 9.05:11.45 in WR is applied to calculate all the respective inputs. [c] Electricity consumption is 1 kWh/L of ethanol, accordingly calculations are for 1 ton of ethanol. Data is obtained from personal communication with alcohol technology expert at NSI, Kanpur. [d.] 15.6 m^3 spent wash is produced from 1 KL of ethanol [235] and 1 m3 of spent wash gives 35 m3 of biogas [237]. Waste water generated from 1 ton of ethanol is 19.55 m^3, which gives 684.21 m3 of biogas and 1m3 of biogas produces 2.5 kWh electricity [238]. [e] 1L ethanol produces 0.02 L fuel oil used in paint industry. This co-product has not been allocated due to its lesser quantity. [f] 1ton ethanol blending (5%) is carried out with 19 ton gasoline. [g] CO_2 emissions are from biogas combustion in boilers. [h] Data is from [220] and value given is for 5400 KL ethanol, accordingly converted for 1ton of ethanol.

4.3.2.6 Ethanol Transport

Blending of ethanol with gasoline is carried out at depot of oil marketing companies. The distance of ethanol distillery to depot is assumed to be 100 km [220] and tanker of carrying capacity 20 KL is used. Detailed input and output data of this process is included in Table 4.3.

4.3.2.7 Ethanol Blending

Blending of 5% ethanol in gasoline is carried out by mixing gasoline and ethanol. Input and output data of this process is given in Table 4.5.

4.3.3 ALLOCATION

One of the critical issues in LCA is multi product system allocation, which allows partition of the environmental and energy burdens associated with a multi-output process to its product and co-products [239, 240]. Without allocation (WA) is defined as wherein no allocation is carried out and the entire environmental burdens are attributed fully to the product. Mass allocation (MA), energy allocation (EA) and market price or economic allocation (MPA) are used to distribute the environmental and energy credits between the product and co-products. Molasses based ethanol is a multi-functional system, involving the simultaneous generation of co-products such as sugarcane trash in farming, sugar, bagasse and filter mud in sugar production and biogas in ethanol production. The MA approach, is based on the mass of co-products generated in different processes for 1 ton of ethanol production. The EA approach, is dependent on the energy content of product and co-products. The MPA approach uses the market price value of product and co-products to calculate the allocation factor [241-243] and relies on the fact that lower priced material has lower energy content and appreciable emissions. The details of product and co-products mass, energy and market price value used to calculate the allocation factor is given in Table 4.7.

4.3.4 GHG EMISSION AND ENERGY CONVERSION FACTORS FOR LCI

GHG emission is estimated in terms of CO_2 equivalent as, 1 kg CH_4 = 25 kg CO_2 and 1 kg N_2O = 298 kg CO_2 [61]. Materials used in the input of inventory are converted to their equivalent energy content using energy factors given in Table 4.6. The energy conversion factor of a material includes the non renewable energy used during the extraction, processing and transport [244]. Due to unavailability of certain factors specific to Indian conditions in scientific literature, the most relevant factors are adopted in this study after verification and evaluation for Indian context. These factors are applied to input materials of LCI to calculate the overall emissions and energy for production of 1 ton ethanol.

Table 4.6 GHG emission factors and energy equivalent factors used for inputs in LCI

Inventory	Unit	Emission factor	Ref.	Unit	Energy factor	Ref.
Urea (as N)	kg CO_2eq./kg	6.69	[220, 242]	MJ/kg	56.3	[245]
DAP (as P)	kg CO_2eq./kg	0.71	[220]	MJ/kg	7.5	[245]
K_2O (as K)	kg CO_2eq./kg	0.46	[220]	MJ/kg	7.0	[245]
Herbicides	kg CO_2eq./kg	5.4	[242]	MJ/kg	355.6	[245]
Diesel	kg CO_2eq./L	3.6	[242]	MJ/L	38.7	[245]
Gasoline	kg CO_2eq./L	2.81	[61]	MJ/L	33.18	[220]
Electricity	kg CO_2eq./kWh	0.81	[246]	MJ/kWh	3.6	[220]
Labour	kg CO_2eq./man-hr	0.697	[61]	MJ*	1.96	[220]
Lime	kg CO_2eq./kg	0.44	[247]	MJ/kg	0.1	[248]
Bagasse[a]	kg CO_2eq./kg	0.025	[61]	MJ/kg	16.80	[220]
Biogas[a]	kg CO_2eq./m^3	0.016	[61]	MJ/m^3	18.80	[220]
Ethanol[b]	kg CO_2eq./L	0.025	[61]	MJ/L	21.18	[220]

[a] Includes emissions from combustion of bagasse and biogas, [b] Ethanol combustion includes CH_4 and N_2O emissions [61]
*man-hr

4.3.5 RENEWABILITY OF ETHANOL

One of the most important aspect of LCA is to understand the extent of renewability of ethanol and there are several indicators reported in literature such as life cycle energy efficiency (LCEE), fossil energy ratio (FER) and net energy ratio (NER) [242, 249]. In this study, NER is used to measure the renewability which is defined as the ratio of output energy of the product to the total input energy used in process [245] and it is the most appropriate way to calculate energy gain or loss for process to find the extent of renewability. It is calculated on the basis of all four allocation approaches.

Table 4.7 Mass, energy and market price for estimating product and co-products allocation factor, for producing 1ton of ethanol

Co-products	Mass (ton)		Energy (MJ/kg)	Ref.	Price (Rs/kg)	Ref.
	NR	WR				
Sugarcane trash	16.30	13.22	15.80	[250]	2.25[d]	---
Sugar	10.0	10.0	15.83[a]	[220]	40.00	[251]
Surplus bagasse	9.22	7.32	16.80[a]	[220]	3.75[d]	---
Filter mud	0.87	0.68	8.85	[234]	0.50[d]	---
Surplus biogas[b]	0.21	0.33	21.66	[220]	20	[252]
Ethanol	1	1	26.76[c]	[220]	52.63[e]	[253]

[a] According to [220], energy values of bagasse and sugar are in kcal/kg. Conversion factor of 1 kcal = 0.0042 MJ is applied. [b] Calculated: m^3 of biogas is converted to ton, specific gravity =1.15 kg/m^3 [238]. Energy content of biogas *i.e.* 18840 KJ/m^3 is converted to MJ/kg. [c] According to [220], ethanol energy in MJ/L, converted to MJ/kg, specific gravity =0.796 kg/L [220]. [d] Market prices of sugarcane trash, bagasse and filter mud are from personal communication with experts at Bermaco Energy Ltd., Mumbai. [e] Market price Rs. 42 per L of ethanol [253] is converted to per kg.

4.4. RESULTS AND DISCUSSION

The results of study focus on estimating GHG emissions (ethanol vis-à-vis gasoline), energy consumption and net energy ratio (NER) of E5 and E10 blends using different allocation approaches. One of the objectives of this study is to find the factor which can significantly affect the LCA results. After discussions with experts and farmers in the field, it is observed that the sugarcane yield is the variable factor and variability in other factors such as farming diesel and fertilizers are neither documented in literature and nor could be gathered from farmers. Looking into recent 5 years sugarcane yield data, variation of ±10% was observed; hence it is selected for sensitivity analysis, taking current yields of 57.4 and 79.6 t/ha.yr in NR and WR respectively as a base case. The outcome of this study is discussed in five sections.

4.4.1 GHG EMISSIONS

During crop production fossil fuels are directly and indirectly consumed resulting in the emissions of GHG (CO_2, N_2O and CH_4) [254] and results are represented in kgCO_2eq./ton ethanol. Farming (Table 4.8) alone contributes 87.3% and 83.9% of the total GHG emissions, with contributions from N fertilizer (50.1, 29.8%), electricity (18.6, 40.0%), labour (25.2, 25.8%), diesel (2.7, 1.8%), K fertilizer (1.5, 0.94%), P fertilizer (1.5, 1.4%) and herbicides (0.3, 0.09%) in NR and WR respectively. Country wise agro-practices vary, but the general trend obtained from LCA studies of Argentina, Brazil and Mexico shows that farming process alone contributes 59-86% of overall GHG emissions [52, 63, 216]. For 1 ton of ethanol production, using WA, the overall GHG emissions in NR are 8146.5 kgCO_2eq. , that are 10.8% higher than WR (7349.0 kgCO_2eq). Apparently, it is due to higher inputs in sugarcane farming, sugar production, and molasses transport and ethanol production.

Table 4.8 Process wise GHG emissions (kg CO_2eq./ton of ethanol) in NR and WR

Process	NR				WR			
	Allocation				Allocation			
	Without	Mass	Energy	Market price	Without	Mass	Energy	Market Price
Farming	7113.9	401.7	650.3	4149.8	6169.9	433.7	695.8	3941.3
Sugarcane transport	736.7	34.6	56.4	78.2	943.7	49.4	80.0	102.6
Sugar production	260.6	12.2	19.9	27.7	206.6	10.8	17.5	22.4
Molasses transport	61.8	51.0	52.8	57.2	15.7	13.0	12.4	14.6
Ethanol production	8.0	6.6	6.8	7.4	6.3	4.8	5.0	5.6
Ethanol transport	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7
Ethanol blending	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69

To produce 1 ton of ethanol 1.94 and 1.10 ha land is required to produce 111.4 and 88.2 ton sugarcane in NR and WR respectively. This data clearly shows that to fulfill the desired requirement of ethanol, 0.84 ha extra land in NR is needed than in WR, hence, the process contribute more in the GHG emissions. Using MA approach, India average GHG emissions of NR and WR (0.55 kg CO_2 eq./kg ethanol) are almost comparable to Nepal (0.51 kg CO_2eq./kg ethanol), but higher than Brazil (0.37 kg CO_2 eq./kg ethanol). This may be attributed to the lower sugarcane yield and higher amount of electricity used in irrigation in India. The sugarcane yield in Brazilis 85-102 ton/ha and almost no irrigation is required [52, 61, 216].

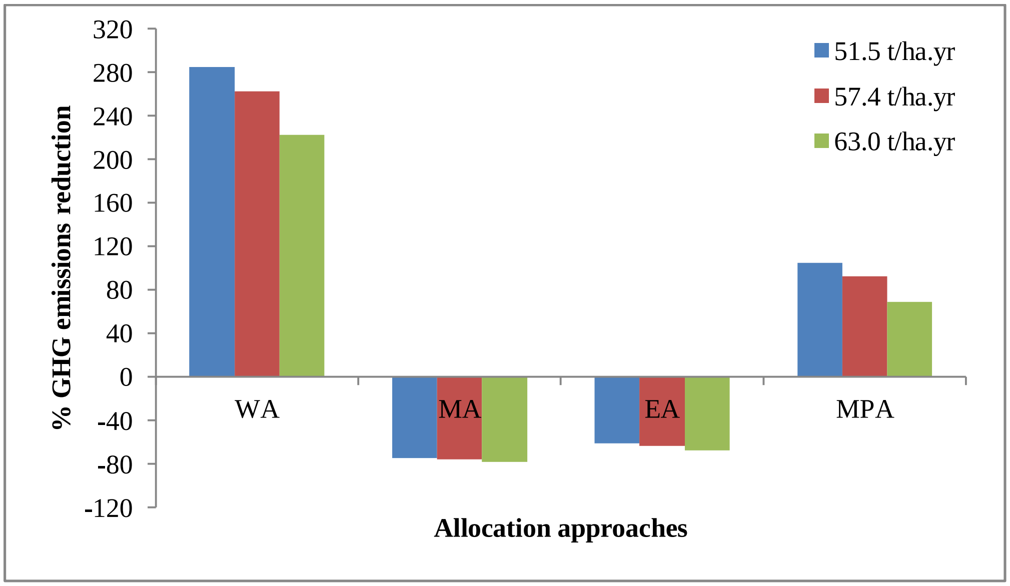
4.4.2 GHG EMISSIONS (ETHANOL VIS-À-VIS GASOLINE)

Since, gasoline and ethanol have different calorific values, therefore, equivalency between these is carried out corresponding to an equal amount of energy i.e. 1 kg ethanol = 0.603 kg gasoline, considering calorific of gasoline (44.30 MJ/kg) and ethanol (26.73 MJ/kg) [220]. Percent GHG emissions reduction is calculated using the Eq. 4.1 [240].

$$\%\mathbf{GHG\ reduction} = \frac{\mathbf{GHG\ emissions_{gasoline}} - \mathbf{GHG\ emissions_{ethanol}}}{\mathbf{GHG\ emissions_{gasoline}}} * \mathbf{100\%}\ \boldsymbol{Eq.4.1}$$

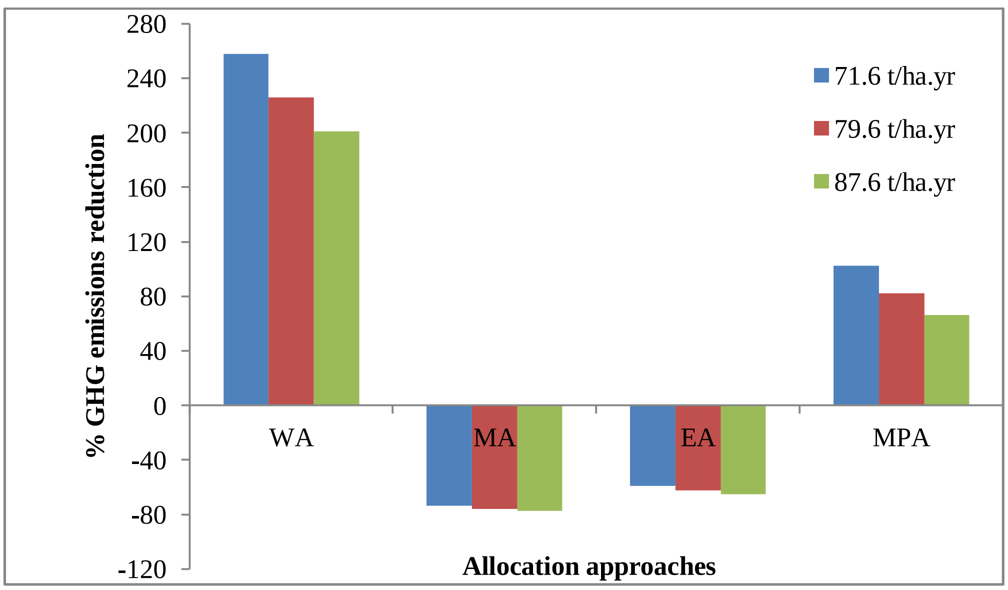
% GHG emissions with respect to gasoline for base case, and ±10% variation in sugarcane yield in NR and WR is calculated and results are presented in Figure 4.5 and 4.6, where negative bar represents reduction in GHG emissions and positive bar represents increase in GHG emissions. GHG emissions reduction with respect to gasoline depends on the allocation method used for distribution of allocation between product and co-products. Using WA approach, GHG emissions from ethanol are higher than gasoline, because all environmental burdens are attributed to the product leading to negative impact on the environment. MA and EA give significant GHG emissions reduction which is contrary to the MPA approach. MA approach reduce GHG emissions by -75.9% and -75.8% for base case in NR and WR regions respectively. Similarly, a reduction in GHG emissions is noticed while applying EA approach and percent reduction for the base case is -63.6% and -62.5 in NR and WR respectively. While using MA and EA approach, a significant part of emissions are attributed to co-products due to their higher mass and energy. It is evident from the results, that MA and EA approach, in both regions, have almost similar GHG emissions reduction. Although, in NR, GHG emissions are higher because of higher land use in farming, but the overall reductions are similar to the WR. The quantities of co-products in NR are higher and therefore, GHG emissions attributable to co-products are greater in NR, which nullify the difference of GHG emissions reduction among the regions. In all of the processes, a prominent difference is obtained in molasses transport (NR, 61.8 and WR, 15.7 kgCO_2eq.). Higher value for NR is due to that only 43% mills are integrated with distilleries whereas in WR, 70% are integrated. If the mills in NR are equally integrated to distilleries similar to WR, then GHG emissions reduction of about 46 kgCO_2/ton of ethanol can be achieved. In MPA approach, contrary results are seen with respect to MA and EA approach, resulting to 92.4% and 82.0% more GHG emissions with respect to gasoline. The difference in the market price of product and co-products results in lower allocation of emissions to the co-products and, hence, more emissions are attributed to the product. The data in Figure 4.5 and 4.6 points out that, WA approach does not represent the ground reality as co-products contribute to the energy consumption and GHG emissions. Additionally, MPA primarily depends upon process of product and co-product and these vary significantly.

It is also not a dependable approach with respect to base case for GHG emissions and NER evaluation. Both MA and EA approaches rely on sound fundamentals and can be considered as true indicators to calculate GHG emissions and energy consumption.



WA: without allocation, MA: mass allocation, EA: energy allocation, MPA: market price allocation

Figure 4.5 Percent GHG emissions reduction in NR with ±10% variation in sugarcane yield with respect to base case



WA: without allocation, MA: mass allocation, EA: energy allocation, MPA: market price allocation

Figure 4.6 Percent GHG emissions reduction in WR with ±10% variation in sugarcane yield with respect to base case

4.4.3 ENERGY CONSUMPTION

Table 4.9 shows that the farming alone contributes to 67.7% and 61.3% of total energy consumption in NR and WR respectively, that is because of the fertilizer use and irrigation consuming significantly higher energy. For 1 ton of ethanol, the overall energy consumption, in NR is 24.2% higher than WR, due to higher consumption of energy in the sugarcane farming, sugar production and molasses transport. For MA, the energy consumption follows the trend: ethanol production > sugarcane farming > sugar production, because in ethanol production, surplus biogas is minimum among all the co-products in LCI and hence, most of the energy is allocated to ethanol. The trend of EA and MPA is: sugarcane farming > ethanol production > sugar production. This can be explained on the basis that the attribution of energy is higher, where co-products have higher energy and market price.

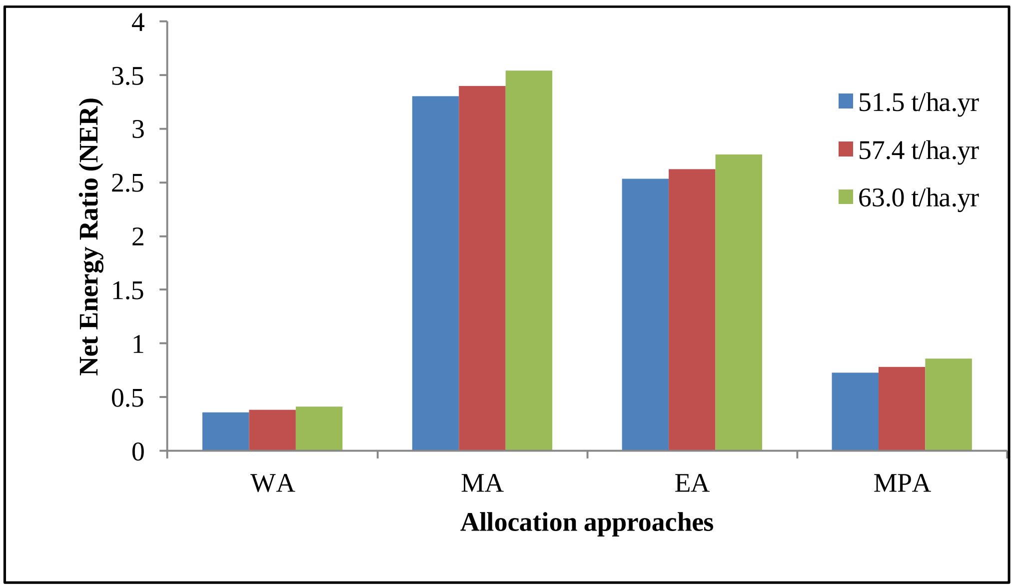
Although, sugarcane trash quantity is higher in both the regions but due to its lower energy content and lower market price than biogas, the energy attribution to co-product is lower. Sugar is the most valuable co-product with higher energy and market price, which is responsible for maximum energy consumption.

Table 4.9 Process wise energy consumption (MJ/ton of ethanol) in NR and WR

Process	NR				WR			
		Allocation				Allocation		
	Without	Mass	Energy	Market price	Without	Mass	Energy	Market price
Farming	47140.7	2662	4309.5	27498.7	34351	2414.7	3873.9	21943.5
Sugarcane transport	7912.5	371.5	606	840	10134.4	531	858.9	1101.6
Sugar production	9782.8	459.3	749.2	1038.5	7734.5	405.7	656.3	841.7
Molasses transport	663.6	549	566.9	614.4	169.2	139.8	133.4	156.7
Ethanol production	4510.8	3726.5	3853.4	4176.8	3565.3	2678.1	2810.6	3166.6
Ethanol transport	71.8	71.8	71.8	71.8	71.8	71.8	71.8	71.8
Ethanol blending	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002

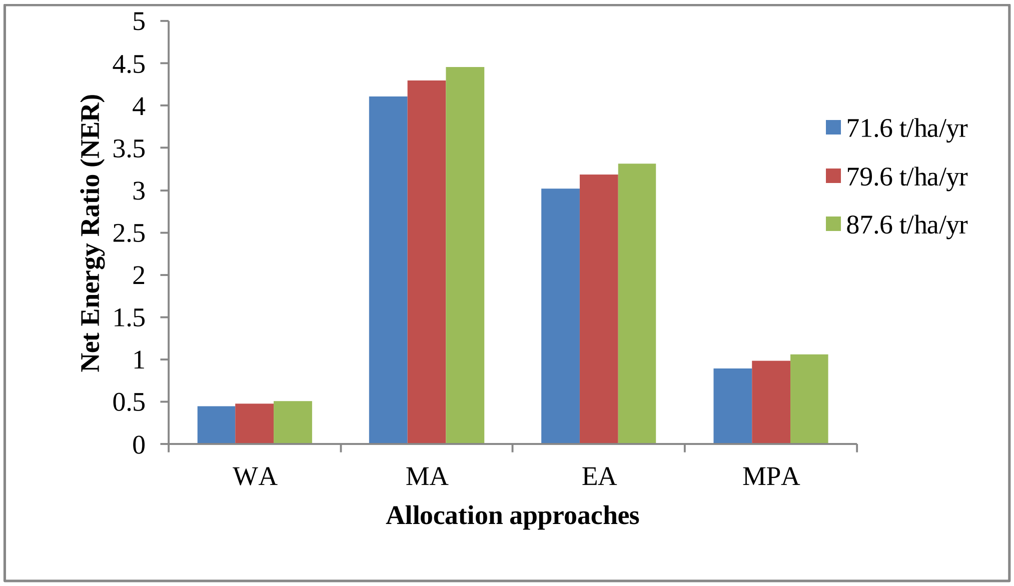
4.4.4 NET ENERGY RATIO (NER)

NER is calculated for the base case and ±10% sugarcane yield in NR and WR using four allocation approaches. NER vary according to the allocation approach used. In WA, NER is least i.e. 0.38 and 0.48 for the base case in NR and WR respectively, because all the energy consumption in the LCI is credited fully to the product. With MA, NER is 3.39 and 4.23 for base case in NR and WR respectively. Relatively less NER i.e. 2.62 and 3.18 for base case is obtained when EA is applied in NR and WR respectively. The NER values obtained for ±10% yield variation is shown in Figures 4.7 and 4.8. NER is higher in WR because of higher sugarcane yield and higher sugar recovery, which reduces the energy input in all processes of ethanol production. Using different allocation approaches, NER of fuel ethanol from molasses, for different countries have been reported in literature and are in the range of 1.56 to 4.1 [63, 215, 220, 245].



WA: without allocation, MA: mass allocation, EA: energy allocation, MPA: market price allocation

Figure 4.7 Net energy ratio (NER) for ethanol production in NR, with ±10% variation in sugarcane yield with respect to base case.



WA: without allocation, MA: mass allocation, EA: energy allocation, MPA: market price allocation

Figure 4.8 Net energy ratio (NER) for ethanol production in WR, with ±10% variation in sugarcane yield with respect to base case.

4.5 ENVIRONMENTAL BENEFITS OF E5 AND E10 BLENDS

Indian government has a mandate to use E5 and E10 blends in gasoline and therefore, this study is extended to find out the GHG emissions and energy consumption benefits using these blends in the transportation fleets. Accordingly, % GHG emissions reduction and NER is calculated (Table 4.10). Environmental and energy benefits are obtained when MA and EA are applied. Using MA, E5 blend in NR gives GHG emission reductions of -4.27%, slightly higher than -4.22% in WR and E10 blend gives -8.55% and -8.44% in NR and WR respectively. NER of gasoline in E5 and E10 blends increases from 0.80 to 0.94 and 1.08 in NR and to 0.98 and 1.15 in WR using MA approach. Using WA and MPA, the environmental and energy benefits are meager. It can be seen from the Table 10 that blending benefits in terms of GHG emissions are slightly higher in NR than WR. The replacement of gasoline attributes to more positive impact in the countries where there are ideal climatic conditions which result in higher sugarcane yields and technology for recovery of bagasse to supply the energy consuming process of ethanol refining.

Table 4.10 Percent GHG emissions reduction and NER using E5 and E10 blends

	NR				WR			
Blends	**E5**		**E10**		**E5**		**E10**	
Allocation	MA	EA	MA	EA	MA	EA	MA	EA
% GHG reduction	4.27	3.88	8.55	7.76	4.22	3.79	8.44	7.59
NER[a]	0.94	0.90	1.08	1.00	0.98	0.92	1.15	1.04

[a] NER of pure gasoline = 0.80 [255]

4.6. CONCLUSIONS

LCA study concludes that fuel ethanol produced from sugarcane molasses gives GHG emissions at each process of its production. If the allocation of GHG emissions and energy is not done for products, than on stand-alone basis, ethanol is more polluting and gives very little NER benefit as compared to gasoline. However, this is not real life situation and GHG are emitted at every step of ethanol production and hence, MA and EA represents the real scenario. Sugarcane farming is the highest contributing process to GHG emissions. Sustainability of the fuel ethanol is established using MA and EA, due to the GHG emissions reduction and higher NER. Variability in agro-climatic conditions, practices, yield and sugar recovery in NR and WR of India are reflected in the overall results of GHG emissions and NER. Lesser GHG emissions and higher NER are obtained in WR than the NR. Even at 5% and 10% blending, the current Indian scenario, translates into significant reduction in GHG emissions and higher NER. It can be safely concluded that LCA of fuel ethanol is influenced by regional differences.