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Life cycle environmental performance and energy balance of ethanol production based on sugarcane molasses in Ethiopia

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A B S T R A C T

The environmental sustainability of biofuel production is still a debated issue in the world bio-economy development. Therefore, different researches are undergoing to evaluate the sustainability of ethanol production in different countries. This study aimed at analyzing the environmental performance of ethanol production in Ethiopia, considering energy balance and emission reduction using a life cycle assessment approach. It is also intended to identify the environmental hotspots so that possible improvement option can be devised. The life cycle assessment methodology was applied considering three alternative scenarios: 1) Base Case, which is the current situation, 2) Alternative 1, which considers the utilization of biogas from vinasse and bioslurry, and 3) Alternative 2, which includes mechanical harvesting and avoids pre-harvest cane trash burning. The results show that agricultural stage is greatly contributing to the pollutant emissions. The contribution of cane trash burning was significant to all the impact categories considered and avoiding pre-harvest cane trash burning significantly reduced the emissions contributing to global warming, acidification, stratospheric ozone depletion, ozone formation, particulate matter and eutrophication. On the other hand, the introduction of mechanical harvesting to avoid pre-harvest cane trash burning increased ecotoxicity, human toxicity and resource consumption (land, water and mineral) impacts. The net energy balance is positive for all the alternatives considered. In addition to using by-products, proper management of fuel utilization at the agricultural stage can further enhance benefits from the sector. Sensitivity analysis revealed that the price of molasses highly influences both energy ratio and greenhouse gas emissions since it completely shifts the allocation of upstream emissions from sugar to molasses.

1. Introduction

Crude oil depletion, securing domestic energy supplies, and the increasing global temperatures are considered as major drivers for biofuel development worldwide. In developing countries, a further driver is the promotion of agricultural innovations and rural development (Chapman, 2013). Biofuels could technically substitute all fossil fuels (Gnansounou et al., 2009). However, their production must be constrained to systems ensuring sustainable benefits. There are several environmental concerns associated with bioenergy systems including land use change, deforestation, as well as human and ecological toxicity from chemicals and fertilizer use (von Blottnitz and Curran, 2007). The long-term sustainability should be considered; i.e. the bioenergy sector should at least show positive energy balance and environmental benefits (Farrell et al., 2006), and trade-offs with socio-economic impacts should be investigated.

Bioenergy accounts for about 14% of the world energy mix, 10% of which is consumed as traditional firewood (World Energy Council, 2016). Biofuels account for around 4% of global transportation fuels (IEA, 2016). In countries that are highly depending on agriculture, like Thailand, the promotion of bioenergy is a key in development strategies in order to ensure the domestic energy supply (Kulessa et al., 2009). Brazil is a pioneer in producing

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ethanol from sugarcane juice and molasses covering 25–30% of the world production (OECD/FAO, 2018).

African bioenergy development based on modern conversion technologies is at its infant stage (Mangoyana, 2009). Malawi was the pioneering producer of ethanol in Africa. Since the 1980s, it has been producing about 18 million liters of ethanol from sugarcane molasses per year (Maltsoglou et al., 2013). Subsequently, Malawi set an E20, 20% ethanol and 80% gasoline blend (Meon, 2014) mandate followed by Ethiopia with E10, 10% ethanol and 90% gasoline blend (ePURE, 2015), and South Africa, 2% of transport energy in 2007 (Arshad et al., 2017). Ethiopia is among the countries highly dependent on biomass to fulfill their daily energy requirements. Nearly 90% of the energy demand is still fulfilled by the traditional use of biomass energy (firewood, crop residues and animal dung) (Derbew, 2013). The total bioenergy potential of Ethiopia is estimated to be as high as 750 PJ per year from different agriculture and forest residues, but excluding bioenergy sources from further co-products such as ethanol from molasses (Gabisa and Gheewala, 2018). About 700,000 ha of land has been identified as a potential area for sugarcane plantation in Ethiopia, which has a potential of producing 6.8 PJ per annum of ethanol from the by-product molasses (Gebreyohannes, 2013). The current production is only 3.3% of the available potential.

The Ethiopian Government has made a lot of efforts to make the bioenergy sector attractive to investors while fostering the green economy of the country (National Planning Commission, 2015). Sugarcane molasses is used in several countries like Brazil, India, Thailand, Australia and Malaysia for ethanol production. Ethiopia aims at becoming one of the top ten sugar producers in Africa within the next five years (MoFED, 2010). The ultimate goal of the country when developing sugar project is to fulfill the domestic sugar demand, meanwhile increasing the production of ethanol to be used as a transportation fuel. Currently, ethanol is produced in two sugar factories, Finchaa, and Metehara, located in the Oromia regional state. Those factories are producing a total amount of about 11 million liters of fuel ethanol per year. Upon completion of the sugar production projects, the production of ethanol will also be boosted and the mixing of ethanol with gasoline will also increase from the current 10% mixing (MoFED, 2010).

Life cycle assessment is an important tool to evaluate and quantify the environmental performance of a product system (Klöpffer and Grahl, 2014). It allows identifying environmental hotspots in the production of biofuels (ethanol) at each life cycle stages (Botero et al., 2011). Even though the life cycle assessment of molasses ethanol is not a new idea (Tsiropoulos et al., 2014; Nguyen and Gheewala, 2008), there has been no study conducted in the case of Ethiopian molasses ethanol. To this end, this piece of research is the first of its kind to address the environmental performance of molasses ethanol production in Ethiopia. In the study, different alternative scenarios have been studied. The base case scenario, investigates the current practice of molasses ethanol production, which includes conventional farming, pre-harvest cane trash burning, and manual harvesting, sugar processing and ethanol production stages. In the second alternative, the utilization of wastewater from ethanol plant for energy (biogas) generation and bioslurry as organic fertilizer is considered. The last scenario investigates the introduction of mechanical harvesting in which pre-harvest cane trash burning is avoided and the cane trash is recovered for energy generation in the cogeneration plant.

The energy balance along the life cycle stages are also addressed in order to present the sector performance in a complete way. This paper presents the details of agricultural activities, which are contributing a greater impact than the other life cycle stages. The earlier studies on the area usually presented the total impact of agriculture in general while this study presents the specific activity among the agricultural activities. This helps to recommend the activities, which require greater attention along with mitigation measures on those activities. The paper first describes the methodology and applied assumptions, then presents the collected datasets and finally discusses the environmental impacts and the tracks for improving the production system by considering different alternative scenarios.

2. Methodological approach

Life cycle assessment (LCA) methodology was applied to analyze the environmental performance of ethanol production in Ethiopia. This ISO-standardized methodology has become mainstream in environmental impact assessments of supply chains (ISO, 2006a; ISO, 2006b). It has already been applied by various researchers to assess the impacts of ethanol production in several countries, e.g. in Nepal and Indonesia (Khatiwada et al., 2016), in Thailand (Nguyen et al., 2007a,b), in China (Wang et al., 2013) and in Brazil (Macedo et al., 2008). SimaProV8 was used to build up the process trees and compile the results based on the ReCiPe 2016 midpoint Hierarchist method for the impact characterization (Huijbregts et al., 2016)

2.1. Goal and scope definition

This study aimed to estimate the environmental performance of molasses-based ethanol production in Ethiopia. There is about 700,000 ha identified as potential land for sugarcane production throughout the country. The development of new sugar factories is undergoing and expected to be operational by 2030, which have integrated ethanol plants. At the end of those projects, the ethanol production will be increased to 326 million liters per annum, which has the potential to completely substitute the current gasoline consumption in spark ignition engines. Hence, we collected data from the current main producing region of Oromia in fields and factories that have been operated since 2007, in the time range of 2016–2018. Those production systems are representative of 45% of the total area. The produced ethanol is consumed as 10% blend with gasoline is spark ignition engines during this period. We also made some assumptions on the potential developments of new production pathways to be investigated through scenario testing. The selected functional unit is 1 GJ of ethanol produced.

The scope of the study was designed in order to identify environmental hotspots throughout the life cycle stages and recommend the possible improvement options.

2.2. System boundary and data sources

The supply chain investigated consists of three main stages included in the system boundary: sugarcane farming and transport, sugar processing (molasses generation) and ethanol conversion [Fig. 1]. Those stages are further detailed in the following subsections. Background processes, such as the manufacture and transport of inputs were also considered.

Foreground data were collected through field surveys of one of the two main sugar factories in the country and covered two seasons over the period 2016–2018. Some data were averaged over this period in order to account for some of the climatic variability (for example, fertilizer input and diesel consumption by agricultural machinery). In Ethiopia, sugarcane farming is owned and operated by the sugar industry itself and there are very few outgrowers (~1%). Therefore, the monthly report data aggregated per plot number, age of the cane and sugarcane variety were extracted from the department of agriculture operation planning and monitoring of the surveyed industry. Background data were taken from ecoinvent V3 (Nemecek et al., 2012).

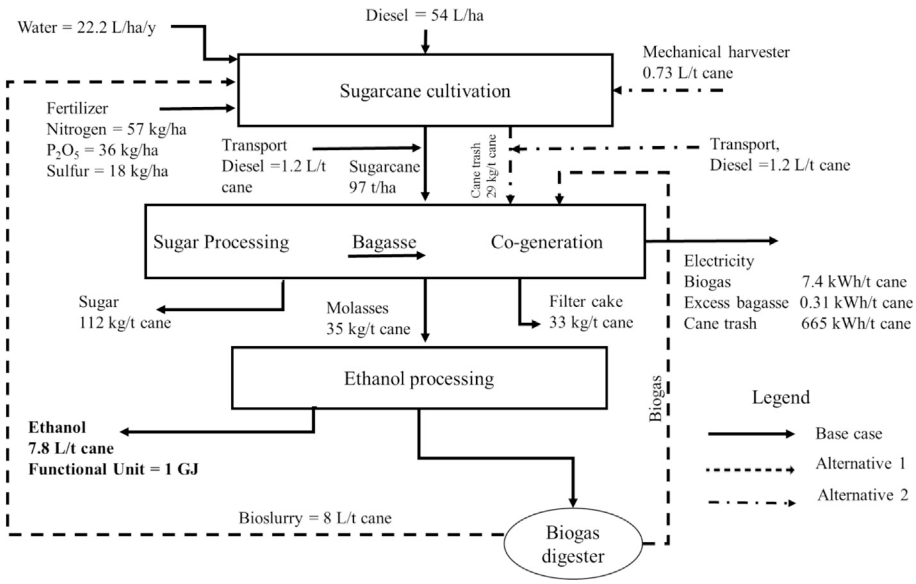

Fig. 1. System boundary and materials flow for sugarcane molasses-based ethanol production in Ethiopia for an average year (t cane refers to tonne of cane).

2.2.1. Alternative scenarios

Different alternative scenarios are developed to investigate the best possible scenario in relation to ethanol production and different by-product utilization in Ethiopia. The first scenario is the base case in which the current practice is evaluated for its environmental performance so that the other scenarios are evaluated comparatively. In this scenario, manual harvesting with pre-harvest cane trash burning is considered. In the second scenario (Alternative 1), the utilization of wastewater, vinasse, for biogas generation and bioslurry utilization as fertilizer is considered without changing the agricultural practices. In this scenario, we accounted for the avoided impact due to synthetic mineral fertilizers substituted by this bioslurry and biogas for excess electricity generation. In the third scenario (Alternative 2), cane trash burning is avoided and mechanical harvesting is added. The cane trash is consumed in combined heat and power plant to produce excess electricity to export to the national grid. The fuel consumption for the transportation of cane trash and the associated emissions are included.

2.3. Life cycle inventory

2.3.1. Sugarcane farming and cane transport to the factory

Sugarcane is a perennial crop (grass) with a shallow fibrous root system (DoA, 2014). The planted (first) crop is followed by three to five ratoon crops. Sugarcane is harvested in Ethiopia roughly 20 months after the first planting and after each ratoon regrowth. The first year is not productive, the whole crop cycle lasts for around 6.667 years in the case of one planted cane and three ratoons. Ratoon crop is the cane that grows from buds remaining in the stubble left in the ground after a crop has been harvested (NETAFIM, 2014). In terms of agricultural management, perennial crops mean that a) the land which is allocated to perennial crops is no longer part of the crop rotation for several years, and b) the agricultural activity is planned over years or sometimes decades (Bessou et al., 2013). For example, land preparation is conducted once for sugarcane cultivation for more than three harvesting seasons, and accordingly, the fuel consumption during this activity has to be shared over the whole cropping cycle and other inputs as well.

Therefore, it is critical to analyze the agricultural activities over the complete perennial cropping cycle, when performing LCA of products based on raw material from a perennial crop like sugarcane. During the cropping seasons, there are both productive and non-productive phases [Fig. 2]. In LCA modeling of sugarcane, all these phases must be considered (Renouf et al., 2018). Different modeling choices for perennial crops, for instance, the choice to model a single year model or the whole crop cycle model, has a significant influence on the final LCA results (Bessou et al., 2016). Accordingly, in this study, the whole crop cycle was accounted for applying spatial modeling (Bessou et al., 2016), i.e. gathering data over two years from different plots at different development stages, hence representing all the stages over the crop cycle. In the production area, sugarcane is usually produced over 6.667 years; only small patches of very productive plots may be kept to exploit one or two further ratoons but they were considered as marginal and not accounted for in the study in order not to model a too optimistic production cycle.

2.3.1.1. Land preparation. Land preparation is done when a new production area is developed for replanting after the ratoon system is exhausted, which is done when the agricultural productivity becomes very low (mostly after 4 or 5 harvesting seasons). From the total area of 19,600 ha, new planting (land preparation) was performed on 2723 ha in the year 2016/17 and 2141 ha in the year 2017/18: representing 14% and 11% of the total area, respectively. The remaining area 16,877 ha (2016/17) and 17,459 ha (2017/18) was covered by underage (<20 months) crops and harvested crop [Fig. 2].

2.3.1.2. Assumptions. To make the study more robust and reasonable, some important assumptions are made. Water, land (occupation) and sulfur are assumed as inputs from nature. The water consumed during irrigation is from the hydroelectric power dam installed upstream of the plantation area. The irrigation type is flood irrigation by gravity. The land covered by the plantation was not allocated for any purpose before the development of the factory since the area is lowland (shrub land), which is difficult to live in. Sulfur is assumed to be extracted from the desert area of Afar regional state and used as a granular mixture with di-ammonium

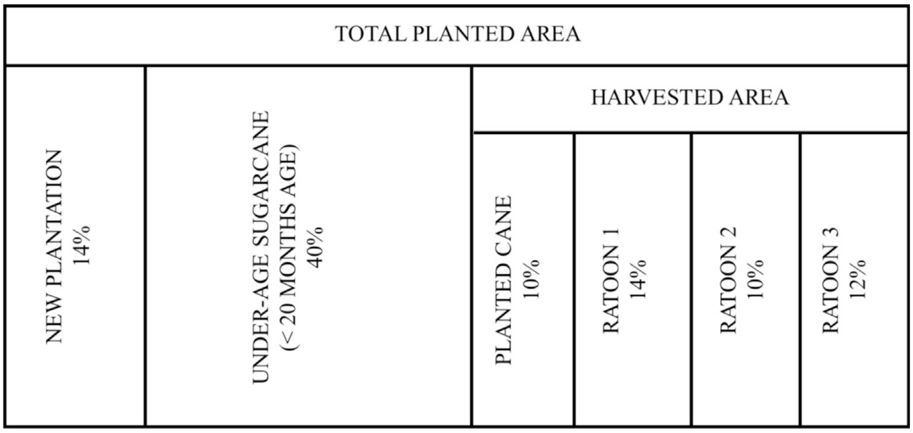

Fig. 2. Percentage of land coverage for different plantation categories based on the total area of sugarcane plantation.

fertilizer. Fertilizers and fuels consumed in agricultural machinery are assumed as inputs from the technosphere. Urea fertilizer containing 46% of nitrogen and di-ammonium phosphate fertilizer with 20% P_2O_5 and 6% of nitrogen is assumed as a source of nutrients for sugarcane plantation. For the calculation of emissions from fertilizer application, IPCC default emission factors are employed (De Klein et al., 2006). In the case of bioslurry application as a fertilizer, it is assumed to displace 10% of nitrogen and 7% P_2O_5 production. The replacement is based on the N and P content of the bioslurry as compared to the chemical fertilizers. For the calculation of the amount of inputs, the average yield of 97 t/h is considered. Road transportation by truck is assumed for the transportation of sugarcane and cane trash from the field to the factory over an average distance of 15 km. The amount of diesel consumed for mechanical harvesting, 0.73 L/t cane is adopted from the study in Brazil (Macedo et al., 2008). The caloric value and density of diesel are assumed 43.1 MJ/kg and 832 kg/m^3 respectively based on the energy and fuel datasheet of the University of Birmingham (Staffell, 2011).

2.3.1.3. Cane trash burning and harvest. Before harvesting, the sugarcane is burned to remove the leaves so that manual harvesting becomes easier. The cane trash burning is performed once the sugarcane is identified as matured, i.e. after roughly 20 months of vegetative growth. This sugarcane trash burning greatly contributes to atmospheric pollution since it is burned in the open without any control. The amount of the trash burned is considered to be in the range of 30–32% of the harvested sugarcane with a dryness fraction of 88% (Jain et al., 2014). The burning emissions were calculated based on emission factors from Nguyen and Gheewala (2008) [Table 1].

Even though harvesting is performed manually, the harvested cane is loaded and unloaded by grab loaders which have an operational capacity of 0.56 ha/h and specific theoretical fuel consumption of 13 L/ha. However, we used the actual fuel consumption recorded on site, which is 32.3 L/ha.

Sugarcane transport from field to factory.

The fuel consumption for the transport of one tonne of cane to the factory was calculated based on the factory data (Eq. (1))

$$Fuel_{l/t\ cane} = \text{Total fuel (L) / Total transported cane (t)} \quad (1)$$

We selected the EURO 1 standard within the ecoinvent database to model the types of transportation. The trucks used by the Ethiopian sugar industry are dated back to 20–60 years since the establishment of the sugar factory. Inputs for the farming stage are summarized in Table 2.

2.3.2. Sugar processing and molasses generation

The harvested sugarcane is transported to the sugar mill within 24 h in order to prevent inversion of sucrose to simple sugars that are impossible to crystallize and form sugar. Hence, the delay in sugarcane delivery will increase the amount of molasses that is not the mainly desired product. Since the primary goal of the sugar factory is sugar production, the sugarcane delivery date is strictly controlled and managed. After delivery, the sugarcane is crushed to

Table 2
Sugarcane farming material and energy inputs per year.

Items/description	Unit	Amount		
Fertilizer (chemical)		2016/17	2017/18	Average
Nitrogen, N	kg/ha	56.02	57.76	56.89
Phosphorous, P_2O_5	kg/ha	35.93	35.93	35.93
Sulfur, SO_2	kg/ha	17.96	17.96	17.96
Diesel				
For farm machinery	L/ha	26.995	39.2	32
Cane Transportation	L/ha	96.12	80.6	88.36
[a] Service	L/ha	12.2	8.2	10.2
[b] Water	m^3/ha a	364.6	364.6	364.6

[a] It is fuel consumption for transportation of supervisors and regular workers to the field.
[b] Water is used for irrigation. The irrigation system in the Ethiopian sugarcane farms is flood irrigation.

Table 1
Substances emission determination from sugarcane trash burning per dry matter of the trash.

Amount of cane trash burned, t/y						348348.5
Substances	CO	CH_4	N_2O	NO_x	NMOC	SO_2
Emission factors, g/kg dry matter	73.8	3.5	0.07	2.5	2.6	1.2
Emissions, t/y	20566.5	975.4	19.5	696.7	724.6	334.4
Emissions, kg/t cane	16.6	0.79	0.016	0.56	0.59	0.27

separate the juice from the fiber called bagasse. The juice is heated in the first heater and transferred to the clarification process where lime and phosphoric acid are added as clarifying agents [Table 3]. The extracted juice contains sugars (sucrose, fructose, and glucose) and excess water. The latter is evaporated through heating, evaporation and pan boiling. The crystallizable sugar, i.e. sucrose, starts to form crystals in the pan boiling and completed in crystallizer upon cooling. The sugar crystals are separated from the black liquor (molasses) by centrifugation. After multiple crystallization and centrifugation steps, the final molasses, from which no more crystals can be extracted, is sent to a storage tank for further processing (ethanol production). The bagasse is burned in boilers to generate steam and electricity in a cogeneration plant. The electricity produced satisfies the entire demand for the sugar mill and ethanol factory. The cogeneration power plant is designed in a way to export excess electricity to the public grid. Exported electricity is regarded as a coproduct whose allocation has been solved by expanding the system boundaries retrieving the necessary data from the ecoinvent database. Grid electricity from reservoir hydropower (100%) has been assumed to be displaced.

The sugar mills (Fincha and Metehara sugar factories) have a combined crushing capacity of 17,300 t/d day and the energy comes from the bagasse-fueled boilers. The overall system could deliver a considerable amount of excess electricity to the national grid, but there is a very small amount of electricity export to the grid due to the use of inefficient boilers as well as the old turbines.

2.3.2.1. Allocation procedure. There are three co-products from sugar processing industries: sugar, molasses, and bagasse. Therefore, it is not fair to allocate all the upstream energy use and associated emissions fully to a single product (Klöpffer and Grahl, 2014). ISO standards also recommend allocating burdens between co-products whenever system expansion is not possible (ISO 14040, 2006). Different researchers have applied different allocation methods to share fairly the upstream burdens between the co-products. Most of the studies on molasses ethanol shared burdens based on economic values. Assuming bagasse is consumed internally for energy generation and the system is expanded in case of excess electricity export to the grid, the allocation was done between sugar and molasses only (Khatiwada and Silveira, 2011; Nguyen et al., 2010; Silalertruksa and Gheewala, 2009). The studies also highlighted that such allocation can appreciate the local utilization of molasses since the cost is very low and it also helps to distinguish the economically viable option on the utilization of co-products for the decision makers (Wang et al., 2013). Accordingly, this method is followed in this study to share the burdens from sugarcane farming, sugar processing and cane transportation between sugar and molasses, based on the yield and market value of the products [Table 4].

2.3.3. Ethanol conversion

The conversion of sugar into ethanol consists of a two-stage process: fermentation and distillation. During the fermentation process, the conditioned molasses will be converted to beer and carbon dioxide with the help of yeast (Rutz and Janssen, 2007). Urea is used as a nitrogen source for the yeast and sulfuric acid is applied to maintain the fermentation media pH level [Table 5]. The produced beer is transferred to a distillation column where the alcohol is separated from the water by its volatility difference (boiling point). In the distillation column, the alcohol is normally concentrated to 95.6% (hydrated ethanol), which is further dehydrated to 99.5% alcohol (dehydrated ethanol) (Jacques et al., 2003) by using either cyclohexane (solvent) or molecular sieve. The factories in Ethiopia use a molecular sieve for dehydration.

The data were gathered from Fincha and Metehara ethanol factories that are an integral part of the sugar factories. Both the factories combined are producing 20,000 m^3/y. The energy used for conversion also comes from the bagasse-fueled combined heat and power plant (CHP). The wastewater from the ethanol plant is simply discharged to the nearby river without treatment. In the next two alternatives, the wastewater is channeled to an anaerobic digester for biogas production. The produced biogas is consumed in a gas boiler to produce electricity and the bioslurry from the digester is transported to the field as a fertilizer.

Table 3
Sugarcane processing (milling) material inputs.

Items	Unit	Amount
Sugarcane crushed	t/y	2,111,417
Chemicals		
Lime	kg/t cane	2.1
Phosphoric acid	kg/t cane	3

Table 4
Average yield and market prices of sugar and molasses in Ethiopia.

Yield (t/t cane)		Price (ETB/kg)	
Sugar	Molasses	Sugar	Molasses
0.12	0.03	14	0.85

Note: 1 USD = ~28 ETB

2.4. Primary energy consumption and energy balance

Primary energy, by definition, is the sum of fuel energy content and the energy inputs along the life cycle of the product or service (MoWEI, 2015). The energy inputs in the production of ethanol in Ethiopia are diesel, gasoline, bagasse, and hydropower electricity. In Ethiopia, a large amount of chemical fertilizers is imported from Russia (until 2 years ago) and Morocco these days. Data on energy used during fertilizer production were taken from the fuel consumed during fertilizer production in Russia for the year 2013 (Yara, 2014) and some are from the well-known databases, like GREET 1.7 (Wang, 2012).

It is defined as the difference between the energy content of the product ethanol and the total energy inputs in the fuel production cycle (DG Ener, 2015; Yara, 2014). The expected implication from the energy balance determination is whether ethanol production from molasses comes up with a gain or loss of energy. Since biomass is an energy carrier, net energy balance and net renewable energy ratio (renewability) are two very important parameters to determine the sector sustainability (Gheewala, 2013; EPA, 2014). The net energy balance (NEB) is the difference between the total energy output (heating value of ethanol) and total energy input over the life cycle of the biofuel. Generally speaking, the NEB must be positive (net energy gain) to reasonably produce biofuel, which contradicts the first law of thermodynamics. However, this is

Table 5
Ethanol conversion materials and energy inputs.

Item/description	Unit	Amount
Molasses	t/t cane	0.03
Chemicals		
Urea [a]	t/t cane	0.0016
Sulfuric acid [b]	t/t cane	0.07

[a] Urea is used as a nutrient for yeast growth during fermentation and yeast incubation stages.
[b] Sulfuric acid is added during fermentation to adjust the pH of the media when the acidity level is low.

possible because the solar energy input is not accounted for as an energy input. Net renewable energy ratio (NRER) is the ratio of the total energy output to the total non-renewable energy input over the life cycle of the production of ethanol (Khatiwada and Silveira, 2009; Nguyen et al., 2007a,b).

3. Result and discussion

3.1. Life cycle impact assessment of the three alternatives

Considering the price and yield of sugar and allied product, molasses, in 2016–2018, 20% of pollutant emissions in sugarcane cultivation and sugar processing are allocated to molasses, which is the raw material for ethanol production. All midpoint impact categories included in the ReCiPe 2016 life cycle impact assessment method are considered in this study. For simplicity of discussion of the results, after discussing the well-known impact categories such as global warming, acidification, eutrophication, ozone depletion, ozone formation (human health and terrestrial ecosystems), and particulate matter formation,the other impact categories are grouped into two groups. The first group includes impact categories related to toxicity such as terrestrial eco-toxicity, freshwater eco-toxicity, marine eco-toxicity, human carcinogenic-toxicity, and human non-carcinogenic toxicity. The second group includes impact categories related to resources such as land use, water consumption, mineral resource scarcity, and fossil fuel scarcity. All impacts for each life cycle stage for the three alternative scenarios are shown in [Table 6].

3.1.1. Global warming

Sugarcane farming is the biggest contributor to this impact category having a share of more than 75% in the base case and Alternative 1, and 58.2% in Alternative 2 [Table 6]. The different alternatives show that there is a great contribution from sugarcane trash burning to the impact category global warming. Renouf et al. have conducted a similar study to analyze the performance of Australian sugarcane sector following LCA methodology. According to their results, sugarcane agriculture has a greater contribution to the global warming impact category than molasses generation and ethanol production, which is due to field emissions from lime and fertilizer application (Renouf et al., 2010). A study conducted in Argentina also showed similar results; the contribution from sugarcane agriculture having a higher contribution to most of the impact categories. It contributed 59% to the global warming impact category due to the fossil fuel utilization in the agricultural machinery. A study on molasses ethanol production in Indonesia considering GHG emission and energy balance along the life cycle of the product system showed that agriculture contributes 38% to the life cycle GHG emissions (Silveira and Khatiwada, 2010). Similarly, the same researchers investigated the GHG emissions and energy consumption of the Nepalese ethanol production system. They concluded that about 80% of GHG emissions come from agricultural stage, which is contributed by fossil fuel consumption in fertilizers/chemicals production (52%), and field emission from fertilizers/chemicals application (26.8%) (Khatiwada and Silveira,2011). Our study is in agreement with those studies regarding the contribution of agricultural stage. Avoiding pre-harvest burning of sugarcane trash can reduce the GHG emissions by 59% as compared to the base case [Fig. 5]. The other higher contribution comes from fertilizer production and application, which contributes about 40% to this impact category [Fig. 3]. The other significantly contributing activity is the fuel consumed in agricultural machinery. The activities consuming diesel at this stage are land preparation (5%), services for workers (33.6%) and cane loading and unloading (61.4%) for all the scenarios. The land preparation is done once every four cropping cycles that take more than six and a half years that is why its contribution is less here. The contribution from cane loading and unloading is one of the alarming activities that possibly needs an intervention. This activity, sugarcane loading and unloading, consumes 2.5 times more than the equivalent activity in Brazil (De Souza et al., 2012). The service providing sector fuel consumption also needs proper management since 24% of the fuel is consumed transporting supervisors to the field from their office on a daily basis. The partial replacement of DAP (Diammonium Phosphate) by the bioslurry and the transportation of the slurry to the field over 15 km did not show a significant increase in GHG emissions, only a 2% increment. The emission from the transportation of bioslurry in the case of Alternatives 1 and 2 is offset by the replaced chemical fertilizer emission reduction. The other 20% emission contributing to this impact category is due to the consumption of lime and phosphoric acid during molasses generation in the base case and Alternative 1. In the case of Alternative 2, the

Table 6
Impact categories in different alternatives to produce 1 GJ of Ethanol.

Impact categories	Unit	Base case			Alternative 1			Alternative 2		
		Agri.	Molasses generation	Total	Agri.	Molasses generation	Total	Agri.	Molasses generation	Total
Global warming	kg CO_2 eq	41.2	12.6	54.8	42.2	12.6	55.67	20.67	12.6	35.27
Stratospheric ozone depletion	kg CFC11 eq	$4.1.10^{-4}$	$1.2.10^{-4}$	$5.3.10^{-4}$	$4.2.10^{-4}$	$1.16.10^{-4}$	$5.4.10^{-4}$	$2.1.10^{-4}$	$1.78.10^{-4}$	$3.3.10^{-4}$
Ozone formation, Human health	kg NOx eq	$9.0.10^{-1}$	$3.8.10^{-2}$	$9.4.10^{-1}$	$9.5.10^{-1}$	$3.8.10^{-2}$	$9.9.10^{-1}$	$1.7.10^{-1}$	$5.45.10^{-2}$	$2.3.10^{-1}$
Fine particulate matter formation	kg PM2.5	$4.3.10^{-1}$	$2.6.10^{-2}$	$4.6.10^{-1}$	$4.5.10^{-1}$	$2.6.10^{-2}$	$4.8.10^{-1}$	$2.9.10^{-1}$	$2.8.10^{-2}$	$3.3.10^{-1}$
Ozone formation, Terrestrial ecosystems	kg NOx eq	$9.6.10^{-1}$	$3.8.10^{-2}$	1.0	1.01	$3.85.10^{-2}$	1.07	$1.7.10^{-1}$	$5.51.10^{-2}$	$2.3.10^{-1}$
Terrestrial acidification	kg SO_2 eq	2.56	$7.2.10^{-2}$	2.8	2.7	$7.24.10^{-2}$	2.8	2.16	$7.9.10^{-2}$	2.26
Freshwater eutrophication	kg P eq	$2.1.10^{-3}$	$6.8.10^{-3}$	$9.4.10^{-3}$	$7.1.10^{-4}$	$9.75.10^{-4}$	$9.3.10^{-3}$	$9.4.10^{-4}$	$9.8.10^{-4}$	$1.1.10^{-2}$
Marine eutrophication	kg N eq	$7.6.10^{-2}$	$2.1.10^{-3}$	8.10^{-2}	8.10^{-2}	–	$8.1.10^{-2}$	$8.1.10^{-2}$	–	$8.1.10^{-2}$
Terrestrial ecotoxicity	kg 1,4-DCB	31.3	43	77.1	33	43.72	77.2	47.12	49.5	93.6
Freshwater ecotoxicity	kg 1,4-DCB	2.10^{-1}	$5.2.10^{-1}$	$7.7.10^{-1}$	$1.1.10^{-2}$	$2.14.10^{-2}$	$7.53.10^{-1}$	$1.5.10^{-2}$	$3.6.10^{-2}$	$8.7.10^{-1}$
Marine ecotoxicity	kg 1,4-DCB	3.10^{-1}	$7.7.10^{-1}$	1.13	$3.9.10^{-2}$	$7.14.10^{-2}$	1.11	$5.1.10^{-2}$	$8.1.10^{-1}$	1.3
Human carcinogenic toxicity	kg 1,4-DCB	$3.4.10^{-1}$	$8.68.10^{-1}$	4.02	$8.3.10^{-2}$	$8.68.10^{-1}$	4.01	$1.7.10^{-1}$	3.66	4.39
Human non-carcinogenic toxicity	kg 1,4-DCB	15.6	13.3	30.4	14.57	12.5	30	21.15	13.85	43.7
Land use	m^2 a crop eq	151,300	1,230	162,000	159,600	1,340	162,000	159,600	1,340	163,000
Mineral resource scarcity	kg CU eq	$5.0.10^{-2}$	$6.1.10^{-2}$	$1.1.10^{-1}$	$5.1.10^{-2}$	$6.1.10^{-2}$	$1.1.10^{-1}$	$9.9.10^{-2}$	$6.1.10^{-2}$	$1.6.10^{-1}$
Fossil resource scarcity	kg oil eq	2.4	2.736	5.25	2.76	2.736	5.53	4.17	3.2	7.4
Water consumption	m^3	3,500	520	4,270	3,710	518	4,260	3,740	520	4,260

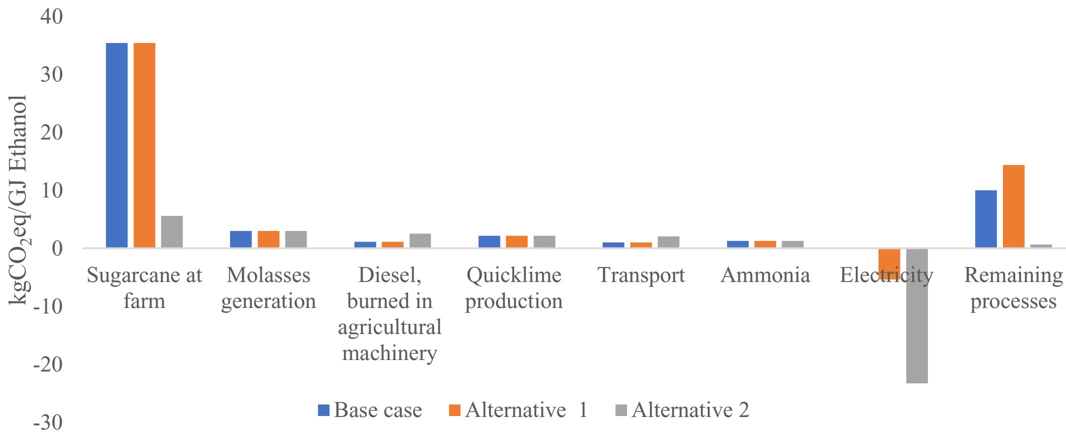

Fig. 3. Processes contribution to global warming for the three Alternative scenarios of 1 GJ ethanol production.

contribution from molasses generation rises to 33% since the actual value of the emissions at this stage remains as it is while the emission at agricultural stage decreases, and the other 9% comes from ethanol processing, which is from consumption of urea in the fermentation process.

The no pre-harvest cane trash burning no trash recovery (no mechanical harvesting) case also showed a slight reduction in GHG emission compared to Alternative 2 (15%) and a significant reduction from the base case scenario (45%).

3.1.2. Terrestrial acidification

The largest contribution to terrestrial acidification impact category comes entirely from agricultural stage, which is from fertilizer application (87%) during sugarcane farming process in all the scenarios including base case [Fig. 4]. A similar study in Argentina showed that agricultural stage contributes more than 90% to the impact category acidification, which is due to NO_x emission during cane trash burning and field emissions from fertilizer application (Amores et al., 2013). This is because of increased acidity in the soil due to the increased nitrogen concentration from (López-Aparicio et al., 2013). The application of nitrogen fertilizer to farmland is responsible for the acidification of the soil via oxidation of ammonia compounds that generate H+, which decreases the soil pH (>80%). Even though the rate of application of fertilizers is low as compared to other countries, the emissions are significant. The other source is pre-harvest burning of sugarcane trash, which is responsible for the emission of gaseous compounds like NOx and SO_2 to the atmosphere. This has a contribution of 20% in the base case and Alternative 1 while it is avoided in the case of Alternative 2 [Fig. 5]. Silalertruksa and Gheewala (2009) also concluded that avoiding cane trash burning reduces acidification by 41%. Phosphoric acid used during the clarification process of molasses generation has also a contribution to this impact category to some extent (2%).

3.1.3. Ozone formation, fine particulate matter, and stratospheric ozone depletion

Here the two-ozone formation impact categories, human health and terrestrial ecosystem, are analyzed. More than 80% of ozone-formation is contributed from cane trash burning, while molasses generation contributes 4% and other activities in sugarcane agriculture contribute the remaining. Similarly, a study in Thailand also revealed that cane trash burning has as large as 93% contribution to ozone formation (Silalertruksa and Gheewala, 2009). Therefore, avoiding cane trash burning will contribute to above 80% reduction in ozone formation in both cases (human health and terrestrial

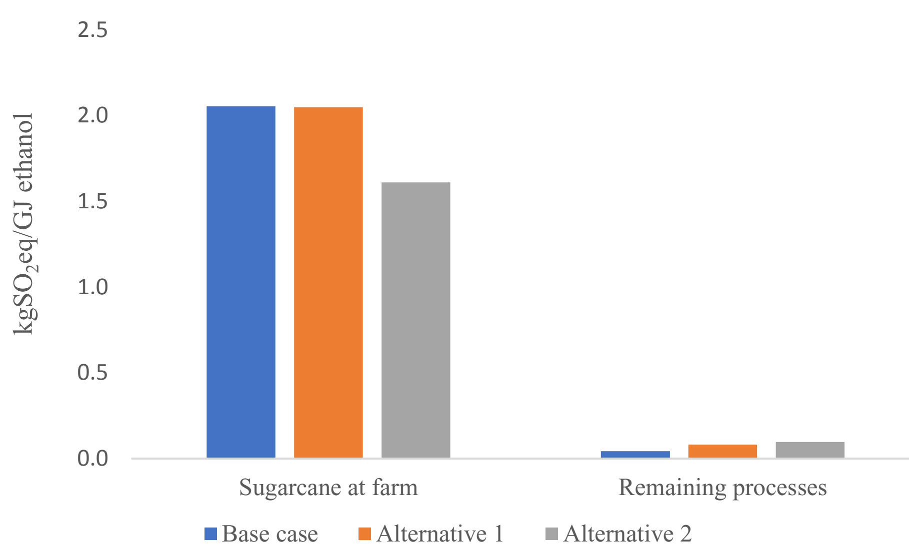

Fig. 4. Process contributing to acidification for the three alternative scenarios.

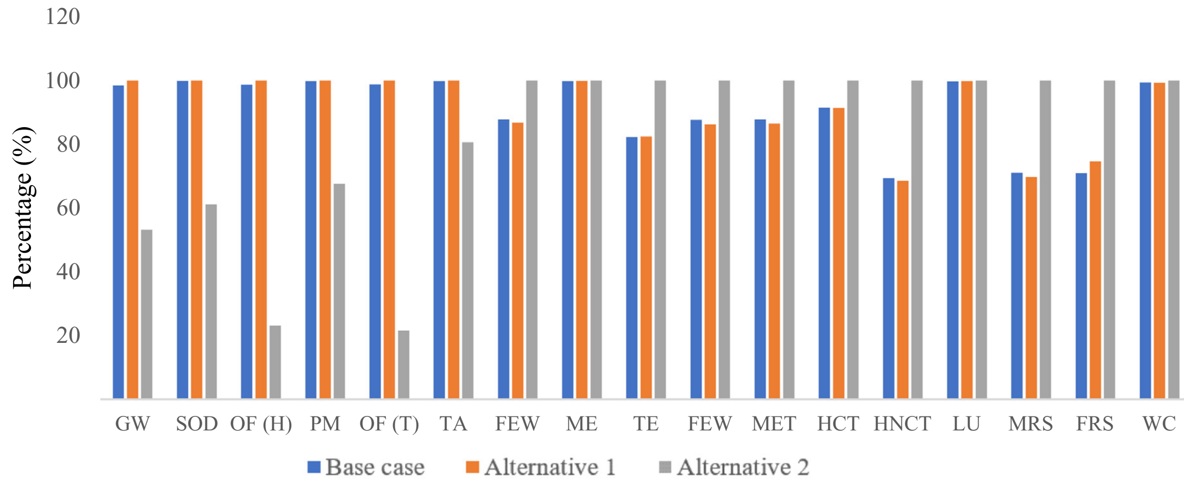

Fig. 5. Life cycle environmental performance of sugarcane molasses ethanol production in Ethiopia - Comparison of the three scenarios. Global warming (GW), Stratospheric ozone depletion (SOD), Ionizing radiation (IR), Ozone formation(Human health) (OF (T)), Fine particulate matter formation (PM), Ozone formation (Terrestrial ecosystems) (OF (T)), Terrestrial acidification (TA), Freshwater eutrophication (FE), Marine eutrophication (ME), Terrestrial ecotoxicity (TE), Freshwater ecotoxicity (FWET), Marine ecotoxicity (MET), Human carcinogenic toxicity (HCT), Human non-carcinogenic toxicity (HNCT), Land use (LU), Mineral resource scarcity (MRS), Fossil resource scarcity (FRS) and Water consumption (WC).

ecosystem). The stratospheric ozone depletion also significantly decreases by avoiding cane trash burning (~31%) [Fig. 5]. Fertilizer application is the major contributor to particulate-matter formation impact category contributing 76%. The nitrogen compounds (NO, NH_3) emitted during agriculture are the major contributor to particulate matter. For example, the study on the UK's agriculture shows that NH_3 contributes about 88% to particulate matter emission (AQEG, 2018.) Fine particulate will also be reduced by 34% by avoiding pre-harvest cane trash burning. A study conducted in South America showed that particulate emission is influenced by temperature, humidity and wind speed; areas where those parameters are low, the particulate matter concentration is found to be higher (Le Blond et al., 2017). The source of stratospheric ozone-depleting substance in ethanol production is mainly fertilizer application and production, which contributes 46% and 21% comes from molasses generation stage and the remaining unit processes contribute the balance. The study of Wang et al. (2013) also showed that the contribution of fertilizer production to ozone depletion is signicant (~50%). The study by Amores et al. (2013) also showed that 95% of the stratospheric ozone depletion comes from fertilizer production and application.

3.1.4. *Eutrophication*

Freshwater eutrophication and marine eutrophication are considered in this analysis. Phosphoric acid production contribution (75%) is a significant contributor to the freshwater eutrophication impact category; phosphoric acid is used for clarification during molasses generation. Fertilizer (phosphate) production unit process contribution (11.4%) to freshwater eutrophication is also significant followed by diesel burned in agricultural machinery (10%) during sugarcane agriculture. The other 2.6% comes from fertilizer application and pre-harvest cane trash burning. A study in Australia focusing on sugarcane processing revealed that field emissions contribute about 90% to the eutrophication impact category from P-loss by runoff and NO_3 by leaching from fertilizer application (Renouf et al., 2011). A study in Thailand also showed that agriculture and wastewater from ethanol processing stage contributed significantly to eutrophication due to the nutrients applied to the soil via fertilizer application and vinasse, which has higher organic content.This source difference between the current study and the literature may be the soil composition of the land. In the case of the current study, phosphoric acid is mandatory to use in the clarification process since the cane from field comes with substances which have to be removed by forming settlable compounds in phosphate salt form. This can be either by wet deposition with rain or settling out of the air as dry deposition of NO_x depending on the season. Substances contributing to marine eutrophication come entirely from fertilizer application. Generally, the molasses generation stage is regarded as the major source of pollutants contributing to freshwater eutrophication while sugarcane farming is the major pollutant source for marine eutrophication.

3.1.5. *Toxicity*

The molasses generation stage has a significant contribution to all toxicity impact categories due to the consumption of phosphoric acid for clarification unit process. Phosphoric acid production and consumption contributes 52%, 71.5%, 91% and 45% to the impact categories terrestrial ecotoxicity, freshwater (marine) ecotoxicity, human carcinogenic toxicity, and human non-carcinogenic toxicity, respectively. Using acids in the production process has a great contribution to toxicity impact categories (Wang et al., 2013). The production and application of fertilizers highly contribute to the impact category of terrestrial eco-toxicity, freshwater eco-toxicity as well as marine eco-toxicity followed by diesel production and consumption during sugarcane farming. Human carcinogenic and non-carcinogenic toxicity are primarily contributed by diesel consumption in agricultural machinery. This is because of the emission of toxic substances at different lifecycle stages of diesel production and use. There is a significant increment of emission of toxic substances in Alternative 2 as compared to the base case and Alternative 1. All the toxicity impact categories increased between 30 and 50% in the case of Alternative 2 due to the addition of diesel for mechanical harvesting.

3.1.6. *Mineral resource scarcity, fossil resource scarcity, land use, and water consumption*

The contribution of molasses generation is high to mineral resource and fossil resource scarcity contributing 53% and 52% respectively, which comes from phosphoric acid consumption

[Fig. 5]. Diesel burned in agricultural machinery follows by contributing 28% to mineral resource scarcity and 18% to fossil resource scarcity. Fertilizer production has also a great share of contribution to these two impact categories contributing 18% and 29% to fossil resource scarcity and mineral resource scarcity, respectively.

Water consumption and land use are almost entirely taken by the sugarcane farming stage, as it is the land used to cultivate sugarcane and water for irrigation (81%). The remaining water is consumed in ethanol production.

3.2. Energy performance of molasses ethanol production

Considering the price and yield of sugar and allied product (molasses) in 2016–2018, 20% of energy use in sugarcane cultivation and sugar processing is allocated to molasses, which is the raw material for ethanol production. Taking the conversion rate of molasses to ethanol as 7.8 L ethanol of per tonne of cane, the analysis of energy input per liter of ethanol produced is presented in Table 7.

1 MJ of molasses-based ethanol consumes 0.43 MJ of fossil energy, while each MJ of energy in gasoline and diesel consume 1.24 and 1.19 MJ of fossil fuel, respectively. This reveals that the fossil energy input to produce ethanol in the country is much less as compared to others, for example, Thailand, which is about 0.72 MJ of fossil energy input to produce a liter of ethanol (Nguyen and Gheewala, 2008).

3.3. Sensitivity analysis

Fig. 5 shows the relative environmental performance of ethanol production considering each impact category for the three different alternatives. The impact category, which has caught global attention and is very important, global warming, is considered to see how sensitive it is in response to varying input parameters and allocation methods. Therefore, a detailed sensitivity assessment is performed considering the base case scenario. The parameters considered in the sensitivity analysis are molasses price, agricultural inputs (urea and diesel in agricultural machinery) and finally testing the effect of mass allocation.

3.3.1. Variation of different input parameters (molasses price, diesel input for farm machinery, fertilizer)

Greenhouse gas emissions are highly influenced by the price of molasses. An increase in molasses price leads to a higher allocation of resources and burdens to molasses from the upstream processes, thereby increasing GHG emissions associated with molasses ethanol. This indicates that ethanol production from sugarcane molasses is highly sensitive to molasses price as compared to other input parameters [Fig. 6]. For example, a 50% increase in molasses price increases the GHG emission by 23% and vice versa, while it is only 3.7% and 3% for urea and diesel input increment by 50%.

Currently, the price of molasses is very low and that of sugar is very high as compared to other countries. However, there is an increasing demand for molasses to produce alcohol (human consumption) as well as ethanol fuel, which in turn increases the price of molasses as well. As the price of molasses increases, the emission saving reduces. This will make the production of ethanol from molasses to be environmentally as well as economically less sustainable. The effect of input of urea fertilizer and diesel in agricultural machinery on GHG emission is lower as compared to the molasses price. However, this does not mean their contribution to GHG emission is less, rather it shows, as there is a need of the interlinkage effect analysis with other parameters, for example yield. The yield parameter interaction with fertilizer input and the issue of favoring for pest development within the soil needs to be intensively analyzed. The soil property integration in life cycle assessment is also very important and significantly in need of addressing. It is also very important to consider the characteristics of the sugarcane nutrient uptake capacity for proper optimization of fertilizer input planning. The combination of all these issues should be analyzed for the collective contribution of GHG emission along the life cycle.

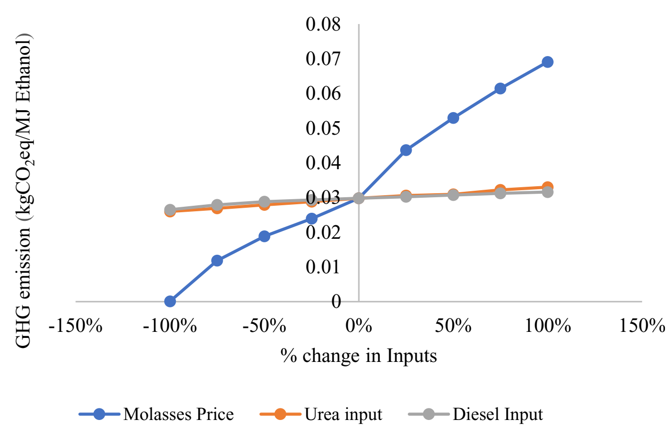

Fig. 6. Effect of molasses price, urea input and diesel input in agricultural machinery of GHG emission.

Table 7
Energy inputs in sugarcane cultivation and sugar processing (after allocation).

Components	Total energy input, MJ/L	Energy category	Data source
Cultivation			
Fertilizer production and application	1.4	Fossil	Khatiwada et al. (2016)
Agricultural machinery & services	0.6	Fossil	Field Record
Transportation of cane	1.26	Fossil	Field record
Sugar processing			
Electricity and steam	−3.57	Renewable	Factory record
Lime and phosphoric acid production	0.69	Fossil	(Wood and Cowie et al., 2004)
Ethanol production			
Electricity and steam	10.4	Renewable	Factory record
Net energy input	10.78		
Net fossil input	3.95		
Net renewable energy input	6.83		
NEB/NREB (MJ/L)	10.22/17		
NRER (Renewability)	5.32		

a The lower heating value of ethanol of 21 MJ L^{-1} is assumed in the energy analysis.

3.3.2. The effect of mass allocation on GWP as compared to economic allocation applied in the study

The objective of this subsection was to investigate the effect of allocation types on GWP considering the base case alternative. The allocation used in the study was economic allocation and now mass allocation was applied to check whether the implication is different from the economic allocation. In the case of economic allocation, the GWP for 1 GJ of ethanol production was 55 $kgCO_2eq$ while it is 68.8 $kgCO_2eq$ in case of mass allocation. This shows that there is 25% increment in the allocation of upstream burdens to molasses. Therefore, applying economic allocation favors ethanol production in Ethiopia. Furthermore, the choice of economic allocation can be justified as a good choice since it shows the effect of market volatility of the cost of the products. This has a socio-political implication of government policy on the sector market regulation as well as to devise incentive mechanisms.

4. Conclusions and recommendations

Sugarcane agriculture is the most contributing life cycle stage to all the impact categories. Within this life cycle stage, the highest contribution comes from sugarcane pre-harvest burning and fertilizer application. The sugar processing (molasses generation) stage contribution is very small as compared to the agricultural stage. The major contribution to sugar processing comes from phosphoric acid and lime production. Those two products are used in the clarification process of the extracted juice. A positive net energy balance and renewability greater than unity imply that ethanol production is promising in the country. However, the fossil consumption at the agricultural stage still shows a need of proper management so that the fuel consumption can be reduced. For instance, cane loading and unloading activity consumes a huge amount of fuel, which is about 60% greater than the equivalent activity in Brazil.

Generally speaking, shifting from manual harvesting to mechanical harvesting increases the burden to the toxicity impact categories while decreases the other impact categories like global warming, stratospheric ozone depletion, ozone formation and acidification since it avoids sugarcane pre-harvest burning. The substitution of chemical fertilizer with bioslurry has a benefit in terms of increasing soil moisture content rather than emission reduction. It is clearly seen from the comparison of the base case and Alternative 1 that there is no a significant difference of substituting chemical fertilizer by bioslurry and also there is as such no contribution from the transportation of the bioslurry to the farm. Therefore, we can deduce that the emission from bioslurry transportation is offset by avoiding the production of an equivalent amount of chemical fertilizer. In the case of Ethiopian sugarcane agricultural lands, there is no need for additional potassium fertilizer. Therefore, the potassium content of the fertilizer is not credited for, which is in high amount in the bioslurry. The accounting of this nutrient as a fertilizer may also favor the utilization of bioslurry on sugarcane field.

In conclusion, the production of ethanol in Ethiopia is promising. To get the best from it, employing mechanical harvesting is a good option as long as it does not come with increased unemployment within the sugar producing region as well as the country at large. The utilization of the byproducts, cane trash and vinasse, improve the sustainability of the products as it reduces the associated emissions. Furthermore, proper management of fuel utilization in the transportation, loading and unloading of cane can significantly improve the sustainability.

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