

Environmental benefits on a life cycle basis of using bagasse-derived ethanol as a gasoline oxygenate in India

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Abstract

Bagasse is the fibrous residue generated during sugar production and can be a desirable feedstock for fuel ethanol production. Excess bagasse left after satisfying the mills' energy requirements can be used in a bioconversion process to make ethanol. A life cycle assessment (LCA) was conducted to quantify the environmental benefits of diverting excess bagasse to ethanol production as opposed to disposing it through the current practice of open-field burning. The LCA results demonstrated lower net values for the ethanol scenario for the following: carbon monoxide, hydrocarbons (except methane), SO_x, NO_x, particulates, carbon dioxide, methane, and fossil energy consumption.

Reduced carbon dioxide and methane emissions for the ethanol scenario also lower its greenhouse potential. Additional drivers are the lower values observed for the following impact assessment categories for the ethanol scenario: depletion of natural resources, air acidification potential, eutrophication potential, human toxicity potential, and air odor potential. Specifically, deployment of the bioethanol option, due to its significantly lower greenhouse potential, can be facilitated via the Clean Development Mechanism, as specified under the Kyoto Protocol. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Worldwide economic development will lead to increased emissions of greenhouse gases (GHGs) well into the next century. Developing countries like India and China are expected to be major contributors to atmospheric carbon dioxide (CO₂) build-up and are potential targets for the deployment of biomass-based technologies, given the large amounts of biomass available within their borders.

India is the world's sixth largest and second fastest growing producer of GHGs. In 1992, India's carbon emissions were 177 Mt (million metric tons), the third largest among non-OECD (Organization for Economic Cooperation and Development) countries. Fossil fuel energy consumption was about 7.5 quadrillion Btu, 15% of which was attributable to the transportation sector. About the same fraction of the total carbon emissions was associated with the transportation sector. Hence, significant carbon emissions arise from the use of fossil fuels for transportation in India. Vehicular emissions

also contribute to local air pollution. Delhi, Mumbai (formerly Bombay), and Chennai (formerly Madras) are three of the world's ten most polluted cities. For the specific case of Mumbai, the National Environmental Engineering Research Institute in Nagpur, India, estimates that motor vehicles will contribute nearly 90% of the 255,000 tons/yr of carbon monoxide (CO) emissions. Oxygenating the gasoline with ethanol can reduce CO emissions and provide other environmental benefits such as reduced GHG emissions.

2. Sugarcane production in India

Brazil and India are the world's two largest sugarcane (*Saccharum officinarum*) growers with production of 300 and 285 Mt/yr, respectively (Lower and Barros, 1999; Singh, 2000). India's leading sugarcane-producing states are Uttar Pradesh, Maharashtra, and Tamil Nadu, together accounting for about 70% of the national output (Smouse et al., 1998).

Bagasse is the fibrous residue left after extraction of sugar from the cane and can be a good feedstock for bioethanol (i.e., biomass-derived ethanol) production.

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Bagasse is preferably used by the sugar mills for steam and power generation to satisfy internal needs; however, about 15–25% of the bagasse is left after satisfying the mills' energy requirements, and this excess is not burned in the mill boilers. Steam consumption in Indian sugar mills is as high as 50–55% on cane compared to 40% in Hawaii. With improvements in or replacement of existing boilers, the excess bagasse figure could be higher.

Based on the data available for the VSSK sugar mill in Sangli, Maharashtra (Smouse et al., 1998), the mill capacity is 5000 tons/day, and bagasse produced is 284,422 tons/yr. This mill is considered as a typical candidate mill pertaining to ethanol production. An ethanol plant could be centrally located to utilize bagasse from several sugar mills within a reasonable distance. Although the focus of this study is Maharashtra State, which is the second largest sugarcane producing state with annual cane production of 40–45 Mt, similar ethanol-producing facilities are possible in Uttar Pradesh and Tamil Nadu, and these could provide ethanol for an E10 blend, respectively, for Delhi and Chennai. This study quantifies, on a life-cycle basis, the potential environmental benefits of using bagasse-derived ethanol in India.

3. Study objective and methodology

The objective of the current life cycle assessment (LCA) study is to quantify and compare, over their life cycles, the comprehensive sets of flows to and from the environment (raw material and energy use, wastes, emissions, etc.) associated with the options of converting excess bagasse to ethanol versus discarding it as waste. Introduction of an E10 fuel blend (containing 10% bioethanol by volume) for motor vehicle use in Mumbai is compared with the gasoline currently being consumed. All of these flows are examined over the product life cycle, from production and extraction of raw materials through intermediate conversion processes, transportation, distribution, and use.

3.1. Life cycle assessment principles

LCA is a technique for assessing the environmental aspects and potential impacts associated with a product. Basic aspects of LCI (life cycle inventory) and LCIA (life cycle impact assessment) and information about LCA methodology is provided in a number of publications from the Society of Environmental Toxicology and Chemistry (SETAC, 1991, 1993a, b, 1994), the US Environmental Protection Agency (EPA, 1993a, b, 1995a), the International Organization for Standardization (ISO, 1996, 1997), as well as other sources (Heijungs et al., 1992; SETAC–Europe, 1992).

3.2. Methodology

3.2.1. General system boundaries

Sugar mills generally use the boilers as incinerators to get rid of their bagasse. However, after satisfying their energy needs, the leftover bagasse is essentially a waste stream. Excess bagasse, which is 15–25% of the total generated, is usually burned on the land, i.e., open-field burned (Wayman and Parekh, 1990). All the three Indian mills in the USAID study considered excess bagasse as a problem (Winrock International, 1993), and they currently operate under conditions where excess bagasse causes operational problems of storage and handling with no economic benefits as an energy source. Also, the same study mentions decomposing as a current alternative for bagasse disposal. Hence, it is reasonable to set decomposition or open-field burning as an existing scenario representing the *status quo*; the latter is used as the existing disposal mode in this study. Diversion of excess bagasse to ethanol production represents the alternative scenario.

Fig. 1 shows the general system boundaries for the two scenarios considered in this study. In Scenario 1 (*status quo*), bagasse is disposed of by burning and gasoline is used for transportation needs. In Scenario 2 (alternative being studied), bagasse is converted into ethanol and used in reformulated gasoline. This LCA compares bagasse conversion to ethanol with the *status quo*.

3.2.2. Functional unit

The comparison of different industrial systems can only be achieved if they perform the same function. Once this shared function is defined, a unit has to be chosen in order to compare the systems on the same quantitative basis. All the energy and mass flows in the inventory are normalized to this functional unit.

The functional unit of this study is the disposal of a defined amount of bagasse, i.e., 1 dryton. Bagasse-derived ethanol is used in reformulated gasoline (E10), which replaces current gasoline on an energy-equivalent basis. The equivalency between current gasoline and E10 blend is explained in Table 1. The environmental burdens are calculated on a differential basis in the case of gasoline. The gasoline burdens of both the scenarios are reduced by the amount of gasoline required in the ethanol scenario. This is further illustrated in Fig. 2.

3.2.3. Modeling biomass-based CO₂ emissions

The carbon in the biomass portion of the ethanol is derived from the CO₂ absorbed by plants during photosynthesis. These carbon atoms are released at the end of the products' life, predominantly in the form of CO₂, but also in the form of CO, hydrocarbons, or methane (CH₄) molecules. These carbon releases are offset (though not all at the same rate) by the CO₂

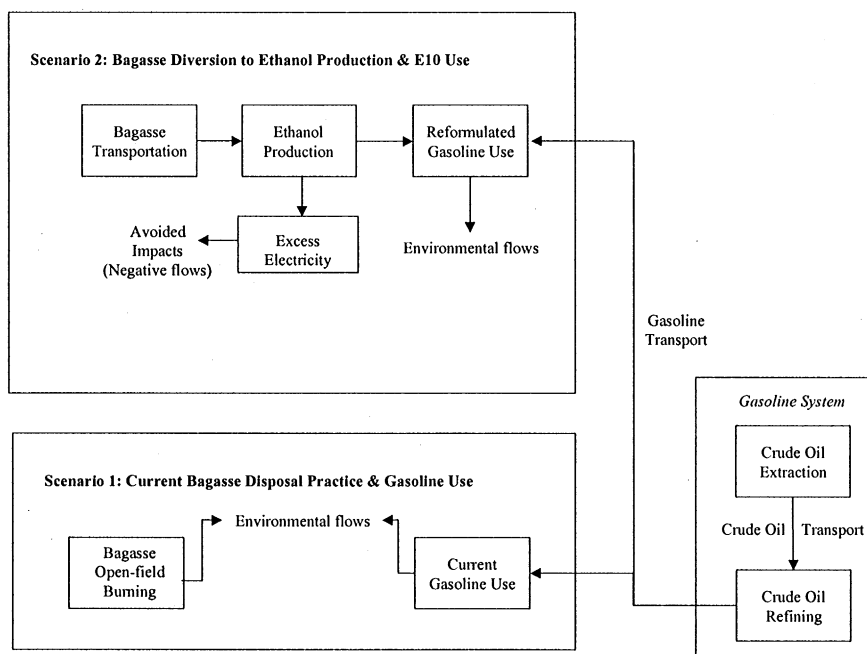


Fig. 1. General system boundaries for the comparison of burning of excess bagasse versus its diversion to ethanol production.

Table 1
Equivalency between current gasoline and E10 blend

	Current gasoline	E10 blend
Heating value, MJ/l	31.1	30.1
Oxygen content, wt%	0	3.50
Density, kg/l	0.750	0.754
Weight fraction ethanol	0	0.105
Weight fraction gasoline	1	0.895
Volume to achieve 31.1 MJ/l	1.000	1.035
Total fuel, kg	0.750	0.780
Gasoline, kg	0.750	0.698
Ethanol, kg	0.000	0.082
Equivalency:	1 kg ethanol + 8.555 kg gasoline (9.555 kg E10 blend) equivalent to: 9.188 kg current gasoline	
On a differential basis:	1 kg ethanol equivalent to: 0.633 kg current gasoline	

uptake or sequestering during plant growth. A distinction was made between net carbon emissions from the production and subsequent combustion of biomass products and carbon emissions from the combustion of fossil fuels. The carbon uptake by plants was accounted for as a credit. Only fossil CO₂ is used in estimating greenhouse potential.

4. Life cycle modeling

The TEAM™ software (version 3.0) developed by Ecobalance Inc. (Bethesda, Maryland, USA) was used in this analysis. Justification for selecting Ecobalance Inc. is given below. The University of Tennessee's Center for Clean Products and Clean Technologies has prepared an impartial report entitled, *Evaluation of Life-*

Cycle Assessment Tools (sponsored by Environment Canada, Hazardous Waste Branch, Ottawa, ON, Canada, K1A 0H3). The Center looked at 37 software tools and selected five, Ecobalance's TEAM™ being one of them, for in-depth evaluations. They concluded that, "TEAM™ is the most powerful and flexible of the tools evaluated in this in-depth study." Unique features of TEAM™ include the following:

- Systems and sub-systems can be defined as modules, allowing highly detailed and complex systems to be simplified.
- Inventory calculations can be propagated from anywhere within the system.
- Allocation rules can be defined within the lowest process/unit level for any flow.

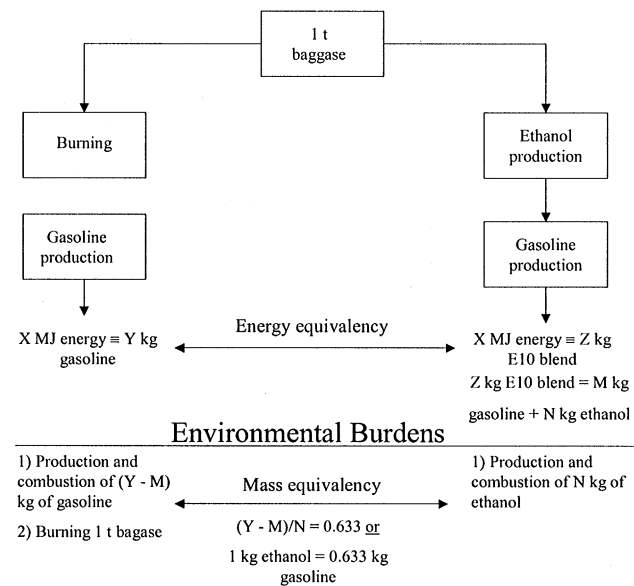


Fig. 2. Energy and mass equivalency between current and future scenarios in the context of the functional unit.

- The various data protection and data access levels allow easy maintenance of data integrity.
- Based on this analysis, and the fact that it has been used for other LCA projects at NREL (Kadam et al., 1999), TEAM™ software was selected for this study as well.

4.1. General bagasse data

Composition of Hawaiian bagasse used in this study (based on NREL laboratory analysis) is as follows (dry wt%): 40.6 glucan, 0.8 galactan, 0.2 mannan, 20.0 xylan, 1.7 arabinan, 25.5 lignin, 1.8 extractives, 3.7 ash, and 5.7 uronic acids. Johnson et al. (1994) studied the changes in bagasse composition due to storage; their data did not predict significant sugar loss. In this analysis no change in bagasse composition upon storage is assumed.

4.2. Bagasse burning

As mentioned earlier, the standard disposal option for bagasse was determined to be burning, which represents the *status quo*. Since no data were available for bagasse burning, a surrogate data set was used. The air emissions were calculated using emission factors provided by the EPA (EPA, 1995b) for biomass burning. Sulfur dioxide and carbon dioxide emissions for each scenario were based on the estimated sulfur and carbon contents, respectively, of green feedstock and ligneous residues. The reason for deviating from the EPA data for sulfur dioxide emissions is the relatively high sulfur content of bagasse.

4.3. Bagasse storage

Crushing season for Maharashtra can be assumed as 200 days, running from October to May. Bagasse during the crushing season can be used as is, i.e., at 50% moisture. Whereas, for the rest of the 165 days, bagasse may need to be dried. Although bagasse drying with flue gases is an idea that is attractive in theory, it may not be feasible in India. Field experience in Hawaii has shown the potential for high maintenance and energy costs from parasitic power needed to operate the dryer and accessory equipment (Winrock International, 1993). Solar drying is an attractive and potentially feasible option (Winrock International, 1993, Rao, 1997). Bagasse could be solar dried and stored before the onset of monsoon to last during the rainy season, which is finished by the beginning of the crushing season. A detailed discussion of this operation is beyond the scope of this analysis. An annual weighted-average moisture of 34% is used in process modeling.

4.4. Ethanol production

Ethanol production from corn or molasses is a well-established technology with several plants located in the Midwestern United States and Brazil. Using lignocellulosic biomass as a substrate to make ethanol is also a promising approach. Many sources of lignocellulosic biomass, such as agricultural residues, forestry residues, pulp and paper waste streams, and municipal solid waste, are abundant and underutilized resources, which can be converted to ethanol.

The production of ethanol from biomass requires the following basic steps: pretreatment to hydrolyze the hemicellulose, hydrolysis of cellulose to produce glucose, fermentation of sugars to ethanol, and ethanol recovery. There are different process configurations, both enzyme based and nonenzyme based that can be used to achieve the overall goal. In the nonenzyme based approach, acid is used for both hemicellulose and cellulose hydrolysis, and the mode is separate hydrolysis and fermentation (SHF); both six-carbon (hexoses, i.e., glucose, mannose, and galactose) and five-carbon sugars (pentoses, i.e., xylose and arabinose) are fermented to ethanol. In the enzymatic approach, dilute-acid pretreatment is used to hydrolyze the hemicellulose portion. The saccharification (hydrolysis) of cellulose to cellobiose and eventually to glucose is catalyzed by the synergistic action of cellulase and β -glucosidase enzymes. The mode of operation used is simultaneous saccharification and cofermentation (SSCF); cofermentation refers to the fermentation of both six-carbon and five-carbon sugars to ethanol. In this study the following two specific biomass-to-ethanol conversion technologies are used: (1) enzyme-based process, and (2) two-stage dilute-acid process.

4.4.1. Enzymatic process

A generalized process was modeled based on *Trichoderma reesei*-derived cellulases for cellulose hydrolysis and an appropriate recombinant ethanologen for cofermentation of six-carbon and five-carbon sugars to ethanol. The enzyme-based process, which is a relatively long-term option, consists of four basic unit operations:

- (1) Pretreatment
- (2) Cellulase production
- (3) Ethanol production
- (4) Product purification

4.4.2. Two-stage dilute acid process

The two-stage dilute acid process, which is a short-term option appropriate for a plant in India, consists of four basic unit operations:

- (1) First stage hydrolysis
- (2) Second stage hydrolysis
- (3) Ethanol fermentation
- (4) Product purification

The flow diagrams for the two technology options are shown in Figs. 3 and 4, and process descriptions and details are provided by Kadam (2000).

4.5. Data summary for bagasse-to-ethanol processes

The estimates of inputs and outputs for the two processes were developed using Aspen[®]-based (Aspen

Technology, Inc., Cambridge, MA) models, with technology targets established for the middle of the decade (Wooley et al., 1999). These estimates, using 1 kg of dry bagasse or 1 l of ethanol as the basis, are reported in Table 2.

4.5.1. Electricity production

Electricity production was based on Ecobalance Inc.'s data for India. This database was considered to be applicable to electricity production in Maharashtra. Details of the electricity grid modeling are provided by Kadam et al. (1999).

4.5.2. Steam production

The energy necessary to convert water to steam is based on the enthalpy of the steam (2.6 MJ/kg at approximately 150 psi and 350°F) and a boiler efficiency of 80%. Steam is assumed to be produced by combusting fuel in industrial boilers. The fuel can consist of coal, natural gas, heavy fuel oil, or ligneous residue (from ethanol fermentation). The emission factors for industrial boilers were obtained from the AP-42 report by the EPA (EPA, 1995b). These numbers were compared with a study done by the Argonne National Laboratory (Wang, 1996), to verify and expand on the EPA emission factors.

4.5.3. Gasoline system

This system includes precombustion data for gasoline. The precombustion steps include extraction of crude oil from the ground, transportation of the crude oil to a refinery, and refining the crude oil into finished refinery

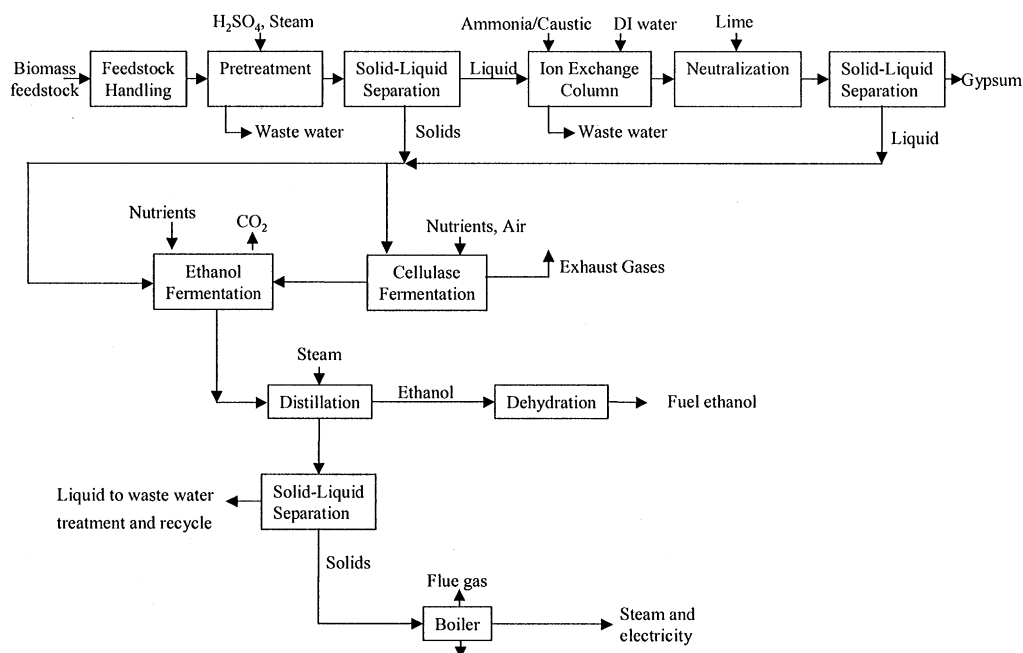


Fig. 3. Enzymatic process flow diagram.

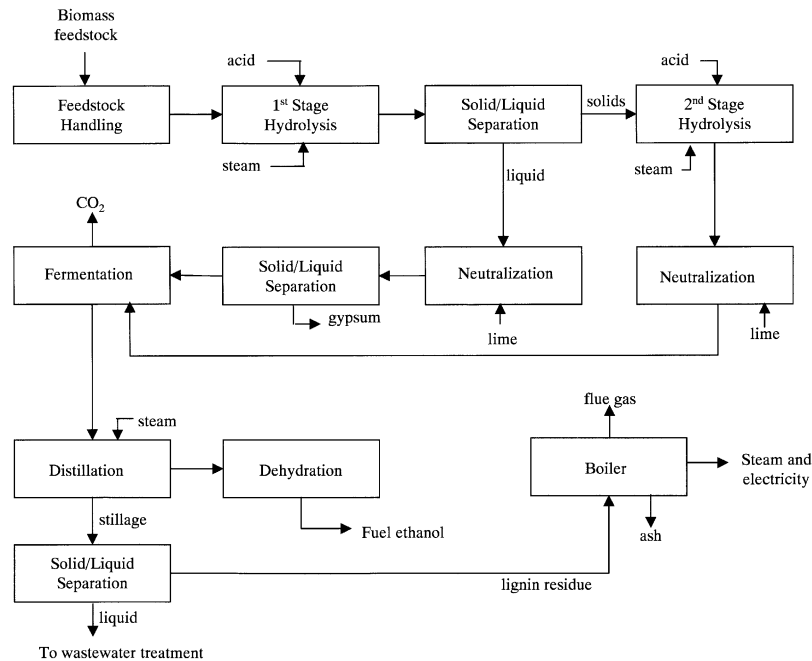


Fig. 4. Two-stage dilute-acid process flow diagram.

Table 2
Data summary for bagasse-to-ethanol processes

Environmental flows	Enzymatic process		Two-stage dilute acid process	
<i>Inputs</i>	(kg/kg bagasse)	(kg/l ethanol)	(kg/kg bagasse)	(kg/l ethanol)
Biomass	1.000	3.318	1.000	4.242
Lime	0.009	0.030	0.013	0.057
Water	1.966	6.525	3.591	15.232
NH ₃	0.028	0.093	0.025	0.106
Diesel	0.005	0.017	0.004	0.019
H ₂ SO ₄	0.044	0.146	0.048	0.202
<i>Outputs</i>				
Ethanol	0.238	0.789	0.186	0.789
Gypsum	0.025	0.083	0.031	0.132
Ash	0.040	0.132	0.077	0.328
Ligneous residue	0.444	1.472	0.600	2.542
Biogas methane	0.015	0.051	0.016	0.070
Total CO ₂	1.170	3.883	1.307	5.545
Net electricity	(MJ/kg biomass)	(MJ/l ethanol)	(MJ/kg biomass)	(MJ/l ethanol)
	0.859	2.849	1.146	4.863

products. Transportation of the finished refinery products to the point of use is also included at this stage. Since there is no official commitment yet to adopt unleaded gasoline in India, leaded gasoline was assumed to be the “current gasoline” in this analysis.

The production and combustion of reformulated leaded gasoline, E10 fuel (10% ethanol and 90% leaded gasoline), was assumed to occur in Maharashtra. Currently, there is no biomass-derived ethanol being produced in India, and gasoline data from India is not readily available. Hence, surrogate data were used in the

analysis. Leaded gasoline data was from Ecobalance Inc.’s database for European leaded gasoline production and use.

4.6. Gasoline and E10 fuel combustion

Toxic air pollutants can be emitted from motor vehicle systems by two emission-producing processes: combustion products from the exhaust system and evaporation from the fuel storage and delivery system. An overall emissions profile from the exhaust system

Table 3
Apportioned emissions for E10 blend

	Current gasoline, g/kg	E10 blend, g/kg	Apportioned emissions E10 blend, g/kg blend		Ethanol contribution, g/kg ethanol
			Gasoline	Ethanol	
Benzene	1.53	1.37	1.37	0.00	0.00
Benzo(a)pyrene	5.00E-05	4.50E-05	4.50E-05	0.00	0.00
Carbon dioxide, biomass	0	200.2	0.00	200.2	1913.0
Carbon dioxide, fossil	2775	2584	2584.0	0.00	0.00
Carbon monoxide	198	158	148.0	10.03	95.9
Ethanol	0	0.38	0.00	0.38	3.63
Hydrocarbons (except CH ₄)	38	37.5	35.12	2.38	22.8
Lead	0.2	0.18	0.18	0.00	0.00
Methane	1.5	1.34	1.25	0.09	0.81
Nitrogen oxides (NO _x as NO ₂)	31	32.6	30.53	2.07	19.8
Nitrous oxide (N ₂ O)	0.13	0.13	0.12	0.01	0.08
Sulfur oxides (SO _x as SO ₂)	0.26	0.23	0.23	0.00	0.00

and evaporation is given in Table 3 for the current gasoline and E10 blend. Overall emissions for the current leaded gasoline are from Ecobalance Inc.'s database for European leaded gasoline, and those for the E10 blend were estimated by incorporating the potential changes in emissions for low-level ethanol blends, such as E10 (CRFA, 1999). For example, a 20% reduction in CO for the E10 blend yields 158 g CO per kg fuel (198 × 0.8). Components specific only to gasoline combustion, e.g., benzene were reduced by 10% for the E10 blend. Although some data are available for emissions of ethanol blends (Harvey and Adler, 1988; Taylor et al., 1997; CARB, 1998), these are for very specific cases, and the estimates generated in Table 3 were considered to be generally more applicable.

Unlike in the United States, where ethanol blends have a regulatory waiver (in most parts of the country) and are allowed to have increased volatility, Canadian regulations require that the volatility of ethanol blends must match that of standard gasoline (CRFA, 1999). Hence, the evaporative emissions of volatile organic compounds (VOCs) from ethanol blends in Canada are approximately equal to those from conventional gasoline. It is assumed that the Canadian regulatory model is followed in India.

Since the environmental burdens are calculated on a differential basis, i.e., 1 kg ethanol in Scenario 2 versus 0.633 kg gasoline in Scenario 1, combustion emissions of Scenario 2 were modified as discussed here. Emissions that were solely from gasoline were omitted from those for ethanol. Those that were common emissions were apportioned to gasoline and ethanol-based on their carbon contribution to the blend. Ethanol's contribution to these emissions was then 6.4% of the total blend. This was then expressed based on a unit kg of ethanol (Table 3). This approach was considered to be better for a fair comparison of the two scenarios.

5. Results and discussion

5.1. Presentation of results

The results are presented here for the two different scenarios: burning versus diverting bagasse to ethanol. For each scenario, two methods of ethanol production are evaluated: dilute acid process and enzyme process. As mentioned earlier, the basis chosen for the comparison of the two different biomass disposal options is 1 dry ton of bagasse.

5.2. Negative flows

There are negative values in the summary tables for some environmental flows; these arise from the electricity offset of the ethanol scenario. Besides actual flows, percentage differences are also included, which indicate the degree to which the values for the ethanol scenario (Scenario 2) were different from those for the burning scenario (Scenario 1), i.e.,

$$\% \text{ Difference} = \frac{\text{Scenario 1 value} - \text{Scenario 2 value}}{\text{Scenario 1 value}} \times 100.$$

A positive value indicates the percentage by which the values for the ethanol scenario were lower than those for the burning scenario, and vice versa.

5.3. Hydrocarbon emission

As individual speciated emissions data are not available for all process modules, all speciated non-methane hydrocarbon flows have been aggregated to give a value for the net hydrocarbon emissions. These include VOCs, ethanol (air emissions), furfural, hydroxymethyl furfural (HMF), aldehydes, benzene, and hydrocarbons (except methane).

5.4. Time-space implications of emissions

It should be noted that this study shows the life-cycle emissions of the two options without considering the spatial and temporal attributes, meaning that the results are aggregated over different locations and different time frames. Therefore, it does not take into account the fact that open burning results in a pulse of emissions at one time and location versus ethanol combustion in a vehicle that takes place over a period of time and at different locations. This LCA only shows the difference in the total emissions of the two options and does not account for concentrations of pollutants at a given time.

5.5. Life cycle energy balance

The energy use of the competing scenarios is one measure of their overall environmental performance. LCIs provide an opportunity to quantify both the total energy demands and the overall energy efficiencies of processes and products. In this study, several different types of energy flows are tracked through each life cycle. For clarity, each of these energy flows is defined below.

- *Total primary energy.* All raw materials extracted from the environment can contain energy. The energy “contained” in a raw material is the amount of energy that would be released by the complete combustion of that raw material. The energy content used is based on the lower heating values for each material. In estimating the total primary energy inputs to each life cycle, the cumulative energy content of all resources extracted from the environment is considered.
- *Feedstock energy.* Energy contained in raw materials that end up directly in the final product is termed “feedstock energy.” For ethanol production, feedstock energy includes the energy contained in the biomass. Feedstock energy is a subset of the primary energy inputs.
- *Process energy.* The second major subset of primary energy is “process energy.” This is limited to energy inputs in the life cycle exclusive of the energy contained in the feedstock (as defined in the previous bullet). It is the energy contained in raw materials extracted from the environment that does not contribute to the energy of the product itself, but is needed in the processing of feedstock energy into its final product form. Process energy is primarily from coal, natural gas, uranium, and hydroelectric power consumed directly or indirectly in the product life cycle.
- *Fossil or nonrenewable energy.* The primary energy that comes from fossil sources specifically (coal, oil, and natural gas) is tracked because it is important to distinguish between fossil and non-fossil energy. All

three of the previously defined energy flows can be categorized as fossil or nonfossil energy.

- *Renewable energy.* Renewable energy refers to energy obtained from biomass sources and also to electricity production from renewable sources such as biomass and hydroelectricity.

In the summary tables, the following energy values are reported: (1) process energy, (2) fossil or nonrenewable energy, (3) renewable energy, and (4) total primary energy. Criteria air pollutants are linked to the use of both nonrenewable and renewable energy, whereas natural resource depletion is affected by fossil energy consumption. Renewable energy use in Scenario 1 refers to renewable resources used to produce a portion of electricity used. Process energy indicates the net energy input to the process and can be useful in comparing process options.

5.6. LCI for burning versus diverting bagasse to ethanol: enzyme process

For the enzyme process, Scenario 2 leads to a decrease from Scenario 1 for almost all of the key environmental flows (Table 4). The various environmental flows and their implications of these are discussed below.

5.6.1. Resource depletion

Depletion of nonrenewable resources is an important criterion in judging alternative scenarios. Coal and lignite usage is negative for Scenario 2 due to offset credits from excess electricity. Natural gas usage is higher and crude oil usage is significantly lower for Scenario 2 compared to Scenario 1. The reason that natural gas usage is higher for Scenario 2 is because of the ammonia use during ethanol production, which is absent in Scenario 1. Water usage is also negative for Scenario 2 owing to offset credits. Depletion of non-renewable resources is also captured in the impact assessment section.

5.6.2. Air pollutants

CO emissions for Scenario 2 are a third of those for Scenario 1, which is a significant benefit for Scenario 2. Nonmethane hydrocarbon emissions are slightly higher for Scenario 2 than those for Scenario 1. About half of the Scenario 2 hydrocarbon emissions are from ethanol, furfural, and HMF emitted during ethanol production, which is absent in Scenario 1. SO_x emissions for Scenario 2 are lower by about 30%, while NO_x emissions for Scenario 2 are lower by about 50%. Also, particulate emissions are lower for Scenario 2 by a factor of about 30, again a large reduction for an important air pollutant. It should be noted that most of the particulate emissions and a bulk of the CO emissions are from biomass burning in Scenario 1. Lead emissions

Table 4
Life cycle inventory for burning versus diverting bagasse to ethanol: summary for enzyme process

Flow	Units	Scenario 1: burning + gasoline use	Scenario 2: ethanol production + E10 use	Change from scenario 1 to scenario 2
		Per ton of bagasse		%
Inflows				
Coal (in ground)	kg	5.5	−100.7	1938
Lignite (in ground)	kg	0.02	−0.01	149
Natural gas (in ground)	kg	17.7	23.1	−30
Oil (in ground)	kg	172.9	4.4	98
Water used (total)	l	761	−73	110
Outflows				
<i>Air</i>				
Carbon dioxide (CO ₂ , biomass)	kg	1706	1625	5
Carbon dioxide (CO ₂ , fossil)	kg	521	−77	115
Carbon monoxide (CO)	g	69	23	66
Hydrocarbons (except methane)	g	8.7	10.2	−17
Lead (Pb)	g	30.9	−0.14	101
Methane (CH ₄)	g	8465	−149	102
Nitrogen oxides (NO _x as NO ₂)	kg	8.5	4.5	47
Nitrous oxide (N ₂ O)	g	20	21	−3
Particulates (unspecified)	g	4195	148	97
Sulfur oxides (SO _x as SO ₂)	g	2622	1774	32
<i>Water</i>				
COD (chemical oxygen demand)	g	25.8	123.8	−381
Lead (Pb ²⁺ , Pb ⁴⁺)	g	0.0085	−0.0034	140
Nitrates (NO ₃ [−])	g	2.3	−0.05	102
<i>Solid</i>				
Waste: total	kg	41.0	−13.7	134
Waste: hazardous	kg	0.20	−0.01	107
Waste: radioactive total	kg	0.017	−0.0002	101
Energy				
Process energy	MJ	21,114	12,625	40
Nonrenewable energy	MJ	8508	226	97
Renewable energy	MJ	8.4	18,841	NM ^a
Total primary energy	MJ	27,517	19,068	31

^aNot meaningful to report.

are lower for Scenario 2 due to the partial displacement of gasoline by ethanol.

5.6.3. Waste generation

Nitrates and lead (water-borne) emissions are lower but COD values are significantly higher for Scenario 2 compared to those for Scenario 1. The higher COD values for Scenario 2 stem from the ethanol production step. However, water emissions do not occur during the actual process, but rather during upstream production of raw materials used in the process, e.g., ammonia, sulfuric acid, lime, etc. COD values are especially high for ammonia, which is used only in Scenario 2. Moreover, electricity offsets for COD are very low.

Total solid waste, hazardous waste, and radioactive waste are lower for Scenario 2 compared to that for Scenario 1. Lime is a big contributor to the total solid

waste, while ammonia and sulfuric acid production also are responsible for some of the waste generation. These raw materials are used only in Scenario 2. In spite of this, solid wastes are lower for Scenario 2 compared to those for Scenario 1, mainly because of electricity offsets.

5.6.4. Energy consumption and GHGS

Due to electricity offset credits, negative CO₂ and CH₄ emissions are encountered, thereby more than mitigating all the CO₂ and methane emissions from Scenario 1. The slightly higher nitrous oxide emissions for Scenario 2, if considered significant, can be explained by the use of diesel in transporting bagasse. This burden is absent in Scenario 1, and electricity offsets do not affect nitrous oxide emissions. Process energy required is less for Scenario 2 by 40%, and its nonrenewable energy

consumption is 97% lower compared to that for Scenario 1. As expected, the renewable energy consumption is very high for Scenario 2 and very low for Scenario 1.

5.7. LCI for burning versus diverting bagasse to ethanol: dilute acid process

Similar results for key environmental flows are obtained using the dilute acid process (Table 5), the specific changes from Scenario 1 to Scenario 2 being affected by the inherent differences in the two processes.

5.7.1. Resource depletion

Coal, lignite, and water usage is again negative due to offset credits. Natural gas usage is again higher; however, crude oil usage is significantly lower. The

reason for higher natural gas usage is the same as in the case of the enzyme process.

5.7.2. Air pollutants

CO₂ emissions for Scenario 2 are again a third of those for Scenario 1. Also, particulate emissions are lower for Scenario 2 by a factor of about 15. As in the case of the enzyme process, most of the particulate and CO₂ emissions are from biomass burning in Scenario 1. SO_x emissions for Scenario 2 are lower by a factor of about 2, while NO_x emissions for Scenario 2 are lower by 55%. In general, reductions are higher for the dilute acid process as compared to the enzyme process, because of the higher offsets enjoyed by the former. More of the bagasse is sent as fuel residue to the boiler. This leads to lower SO_x, NO_x, and fossil CO₂ emissions because of the correspondingly high electricity offset

Table 5
Life cycle inventory for burning versus diverting bagasse to ethanol: summary for dilute acid process

	Units	Scenario 1: burning + gasoline use	Scenario 2: ethanol production + E10 use	Change from scenario 1 to scenario 2
		Per ton of bagasse		%
Inflows				
Coal (in ground)	kg	4.3	-135.4	3265
Lignite (in ground)	kg	0.017	-0.014	184
Natural gas (in ground)	kg	13.8	18.8	-36
Oil (in ground)	kg	135	2.5	98
Water used (total)	l	595	-137	123
Outflows				
<i>Air</i>				
Carbon dioxide (CO ₂ , biomass)	kg	1706	1663	3
Carbon dioxide (CO ₂ , fossil)	kg	407	-147	136
Carbon monoxide (CO)	g	62	19	70
Hydrocarbons (except methane)	g	7.1	8.8	-24
Lead (Pb)	g	24	-0.2	101
Methane (CH ₄)	g	7206	-459	106
Nitrogen oxides (NO _x as NO ₂)	kg	7.4	3.4	55
Nitrous oxide (N ₂ O)	g	16.0	15.6	2
Particulates (unspecified)	g	4169	274	93
Sulfur oxides (SO _x as SO ₂)	kg	2.5	1.5	39
<i>Water</i>				
COD (chemical oxygen demand)	g	20	109	-442
Lead (Pb ²⁺ , Pb ⁴⁺)	g	0.0067	-0.0046	168
Nitrates (NO ₃ ⁻)	g	1.8	-0.1	104
<i>Solid</i>				
Waste: total	kg	40	5	88
Waste: hazardous	kg	0.16	-0.02	112
Waste: radioactive total	kg	0.01	-0.0003	102
Energy				
Process energy	MJ	20,652	13,269	36
Nonrenewable energy	MJ	6,649	-470	107
Renewable energy	MJ	6.6	18,787	NM ^a
Total primary energy	MJ	25,656	18,317	29

^aNot meaningful to report.

credits. Again, about 50% of the Scenario 2 hydrocarbon emissions are from ethanol, furfural, and HMF emitted during ethanol production, which yields higher hydrocarbon emissions for Scenario 2 compared to Scenario 1.

5.7.3. Waste generation

As in the enzyme case, COD values are significantly higher for Scenario 2 compared to those for Scenario 1. The explanation given above for higher COD values for Scenario 2 applies here as well.

Total solid waste, hazardous waste, and radioactive waste are again lower for Scenario 2 compared to that for Scenario 1, but the decrease for Scenario 2 is lower than that for the enzyme case. This is because the acid process uses more lime than the enzyme process, and lime is the single largest contributor to total solid waste generation.

5.7.4. Energy consumption and GHGS

Process energy required is less for Scenario 2 by 36% compared to that for Scenario 1. As in the enzyme case, the nonrenewable energy offset yields a negative value for Scenario 2 giving negative CO₂ and methane emissions. The nitrous oxide emissions are about the same for both scenarios.

5.8. LCIA for burning versus diverting bagasse to ethanol

In addition to the environmental flows, impact indicator values were also calculated for the above scenarios. These indicators are used to give a broader insight into the environmental impacts of the competing scenarios, by examining the potential impacts beyond the initial release. The indices calculated are greenhouse potential, natural resources depletion, acidification potential, eutrophication potential, human toxicity potential and air odor potential (see Kadam, 2000 for definitions). It should be emphasized that only fossil

CO₂ was taken into account in calculating greenhouse potential. Tables 6 and 7 give the overall values for these impact indicators. It is evident from these tables that for all the indicators, Scenario 1 is worse than Scenario 2, using either of the ethanol production schemes.

5.8.1. Greenhouse potential

The greenhouse potential values for Scenario 1 are predominantly larger than the values for Scenario 2. The reason behind this is the higher fossil energy use in Scenario 1, which leads to higher fossil CO₂ emissions. The difference between the two methods of producing ethanol is due to the higher electricity offsets for the acid process, i.e., higher credit for CO₂ emissions.

5.8.2. Natural resource depletion potential

The natural resource depletion values are driven to a large degree by how much of a designated natural resource the system consumes, e.g., coal, oil, phosphate, natural gas, uranium, bauxite, iron, etc. The natural resource depletion values for Scenario 1 are driven by gasoline production. Once again, the amount of lignin residue produced during ethanol production leads to electricity offsets, which results in a reduction in natural gas, oil, and coal consumption. Hence, natural resource depletion index for Scenario 1 is larger than that for Scenario 2.

5.8.3. Air acidification potential

Scenario 1 generates a larger acidification impact than the comparative ethanol production scenario. For Scenario 1, the use of electricity in gasoline production process generates most of the emissions that contribute to the acidification values. The burning of the bagasse itself also contributes to this impact value because bagasse has a relatively large sulfur content. However, both the scenarios experience the SO_x release when either bagasse is burned (Scenario 1) or the lignin residue is burned during cogeneration (Scenario 2).

Table 6
Life cycle impact assessment for burning versus diverting bagasse to ethanol: summary for enzyme process

Impact	Units	Scenario 1: burning + gasoline use	Scenario 2: ethanol production + E10 use	Change from scenario 1 to scenario 2
		Per ton of bagasse		%
IPCC-greenhouse effect (direct, 100 years) ^a	kg equivalent CO ₂	731	-73	110
Depletion of nonrenewable resources (CML) ^b	Fraction of reserve	8.7×10^{-13}	1.5×10^{-13}	82
Air acidification (CML) ^b	g equivalent H ⁺	266	155	42
Eutrophication (CML) ^b	g equivalent PO ₄	1120	596	47
Human toxicity (CML) ^b	kg toxic compounds	16.8	5.7	66
Air odor (CML) ^b	m ³ air	609	-611	200

^a IPCC = Intergovernment Panel on Climate Change, United Nations.

^b CML = Centre of Environmental Science, Leiden University, The Netherlands.

Table 7
Life cycle impact assessment for burning versus diverting bagasse to ethanol: summary for dilute acid process

Impact	Units	Scenario 1: burning + gasoline use	Scenario 2: ethanol production + E10 use	Change from scenario 1 to scenario 2
		Per ton of bagasse		%
IPCC-greenhouse effect (direct, 100 years) ^a	kg equivalent CO ₂	586	−152	126
Depletion of nonrenewable resources (CML) ^b	Fraction of reserve	6.8×10^{-13}	9.5×10^{-13}	86
Air acidification (CML) ^b	g equivalent H ⁺	238	120	49
Eutrophication (CML) ^b	g equivalent PO ₄	972	441	55
Human toxicity (CML) ^b	kg toxic compounds	14.4	4.3	70
Air odor (CML) ^b	m ³ air	476	−2817	692

^a IPCC = Intergovernment Panel on Climate Change, United Nations.

^b CML = Centre of Environmental Science, Leiden University, The Netherlands.

Similar to the greenhouse potential, the air acidification indicator values are affected by the electricity offset from lignin-based cogeneration. This is because electrical plants generate large amounts of SO_x and NO_x.

5.8.4. Eutrophication potential

Eutrophication impact values are also higher for Scenario 1 than for Scenario 2. The production of the fuel used to produce gasoline as well as that used during the transportation of the biomass were the main contributors to this impact value. The eutrophication values for Scenario 2 are also driven by the water-borne emissions from ethanol production. It should be noted that, unlike in the case of air-related impacts, the eutrophication potential is not greatly affected by the higher electricity offset credits. Despite this, Scenario 2 has lower eutrophication potential.

5.8.5. Human toxicity potential

The human toxicity potential is higher for Scenario 1 than for Scenario 2. Gasoline production and burning activities in Scenario 1 contribute to its higher index value. This is not unexpected since this impact takes into account all the toxic compounds, both in air and water, and most of these emissions are higher for Scenario 1 than for Scenario 2.

5.8.6. Air odor potential

Although less obnoxious than the toxic emissions, this impact is also important to consider. The air odor index is higher for Scenario 1 than for Scenario 2. Again, the burdens from gasoline production and burning in Scenario 1 play a role in its higher index value. Scenario 2 actually has negative index values, meaning that it offsets the odor impact of Scenario 1, and still has credits left in this realm.

6. Policy issues

Using bagasse-derived fuel ethanol is a strategy that is relevant to India, not only in terms of GHG emissions and improved air quality in major urban centers such as Mumbai, but also as an instrument to provide rural economic development and improve the country's energy security by reducing its exposure to risks associated with foreign oil. Petroleum consumption is growing at a pace of 8–10% per annum, and 70% of the requirements are fulfilled via imports (MPNG, 2000).

The Indian Ministry of Petroleum and Natural Gas (MPNG) recently approved the use of ethanol in gasoline blends, removing a potential regulatory hurdle (Winrock International, 2000). In deploying the bagasse-to-ethanol option, the Kyoto Protocol—which was recently endorsed by major industrialized countries, with the exception of the United States—can be used to advantage. This stratagem is discussed below.

6.1. Clean development mechanism

The Kyoto Protocol provides two mechanisms, GHG emissions trading (ET) and Clean Development Mechanism (CDM); the latter affords an opportunity for developing countries that did not accept binding emissions reductions at Kyoto to participate in GHG mitigation. The CDM was created as a successor to “joint implementation” (JI), which constitutes a bilateral agreement between two entities toward a GHG mitigation venture. However, collaborative projects to reduce emissions or sequester carbon in developing countries are now to be implemented via the CDM route (Toman and Cazorla, 2000).

The CDM poses some special coordination issues by virtue of its unique structure, which differs from that of other two trading mechanisms under the Kyoto Protocol. For example, the CDM, like JI but unlike ET, is a project-based form of credit trading, and unlike both JI

and ET, trading under this mechanism is to take place between a party with a firm national emission cap (Annex-1 party) and one without such a cap (Non-Annex-1 party). Article 12 of the Kyoto Protocol subjects the projects under the CDM to a number of eligibility criteria, foremost being that the projects have to meet the overall objective of additional financing for sustainable development (for Non-Annex-1 countries) and cost-effective emission reductions (for Annex 1 countries) (Aslam, 2000).

6.2. CDM application in India

India's approach to the CDM has been discussed by Hausker and McGinty (2000). Biomass-to-ethanol projects are in the planning/development stage in the United States and other countries. Hence, the technology for producing bagasse-derived fuel ethanol exists. The extent of technology transfer is one of the criteria for selection of CDM projects (Toman and Cazorla, 2000); the deployment of the bioethanol option in India would be a sound project for CDM (or a similar instrument).

7. Conclusion

This study provides specific quantitative data on environmental implications of bagasse disposal options in Maharashtra. The LCA performed in this study demonstrates the potentially significant benefits of using ethanol derived from excess bagasse. Overall, the results show that there is a significant difference between Scenarios 1 and 2 (burning as a disposal option versus conversion to ethanol, respectively); the magnitude of this difference varies with the type ethanol production process. However, in all cases, the comparison of Scenario 1 with Scenario 2 revealed a fundamental difference in energy derived from renewable sources, and the concomitant benefits of reduced greenhouse gas emissions.

Specifically, the prevailing trends observed for the ethanol scenarios were lower net values for:

- CO
- Hydrocarbons (except methane)
- SO_x and NO_x
- Particulates
- CO₂ and methane
- Fossil energy consumption

Hence, important advantages are associated with the ethanol scenario in regard to reductions in air emissions and energy consumption, and implementation of the ethanol scenario would facilitate air quality improvement. In terms of water phase emissions, however, COD levels were somewhat higher for the ethanol scenario.

This is due to the use of ammonia during ethanol fermentation. The lower carbon dioxide and methane emissions, although not regulated or mandated by state or national laws, are desirable attributes. The lower greenhouse potential of Scenario 2 can be important if GHG trading is possible.

Additional drivers for the ethanol scenario are the lower values observed for the following six impact assessment categories: eutrophication potential, depletion of natural resources, greenhouse potential, air acidification potential, human toxicity potential, and air odor potential. It should be emphasized that the ethanol scenario shows a lower eutrophication potential despite higher COD values.

Hence, the ethanol scenario is shown to commonly exhibit lower burdens than the burning scenario for key environmental criteria, both regulated and unregulated. This information would be useful to public policy makers. Specifically due to the lower greenhouse potential, the CDM or a similar mechanism can be used to help deploy the bioethanol option in India.

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