

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 Indian 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. 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.

Key words: bagasse, ethanol, gasoline oxygenate, India, life cycle assessment

Introduction

Worldwide economic development will lead to increased emissions of greenhouse gases (GHGs) well into the next century. Developing countries such as 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 greenhouse gases. 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. Significant carbon emissions arise from the use of fossil fuels for transportation in India. Oxygenating the gasoline with ethanol can reduce CO emissions and provide other environmental benefits such as reduced GHG emissions. This study quantifies, on a life-cycle basis, the potential environmental benefits of using bagasse-derived ethanol in India.

Sugarcane production in India

Brazil and India are the world's two largest sugarcane (*Saccharum officinarum hybrids*) 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.*, 1988). 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.

Bioethanol production in Maharashtra

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. 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.

Study objective and methodology

Study objective

The objective of the current LCA study is to quantify and compare, over their life cycles, the comprehensive sets of flows to and from the environment 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.

Life cycle assessment methodology

LCA is a technique for assessing the environmental aspects and potential impacts associated with a product. The basic methodology used is described below.

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). Figure 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 con-

verted into ethanol and used in reformulated gasoline. This LCA compares bagasse conversion to ethanol with the *status quo*.

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 normalised to this functional unit.

The functional unit of this study is the disposal of a defined amount of bagasse, i.e. one dry ton. 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.

Life cycle modeling

The TEAM™ software (version 3.0) developed by Ecobalance Inc. (Bethesda, Maryland, USA) was used in this analysis.

Ethanol production process

A generalised 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 consists of four basic unit operations: pretreatment, cellulase production, ethanol production, and product purifi-

cation. The process flow diagram and technology details are provided by Kadam (2000).

Data summary for bagasse-to-ethanol process

The estimates of inputs and outputs for the enzyme-based ethanol process 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 one kg of dry bagasse or one litre of ethanol as the basis, are reported in Table 2.

Gasoline and E10 fuel combustion

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 are not readily available. Hence, surrogate data were used in the analysis. Leaded gasoline data were from the Ecobalance Inc database for European leaded gasoline production and use.

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 and evaporation is given in Table 3 for the current gasoline and E10 blend. Overall emissions for the current leaded gasoline are from the Ecobalance Inc 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 x 0,8). Components specific only to gasoline combustion, e.g. benzene, were reduced by 10% for the E10 blend.

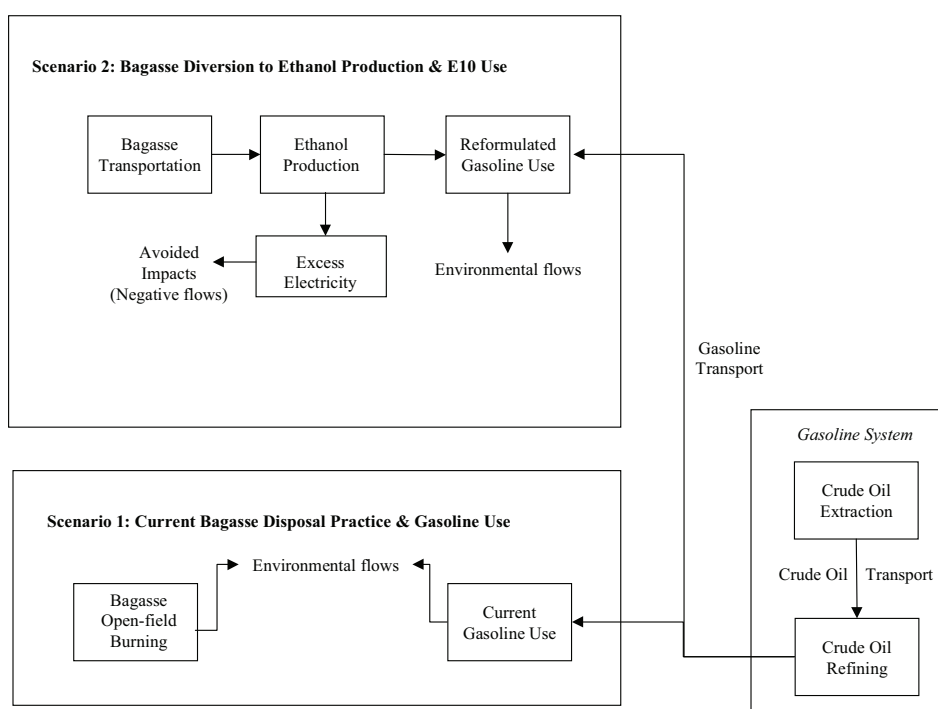


Figure 1. General system boundaries for the comparison of burning of excess bagasse versus its diversion to ethanol production.

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		

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.

Results and Discussion

LCI for burning versus diverting bagasse to ethanol

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

Resource depletion

Depletion of non-renewable resources is an important criterion in judging alternative scenarios. Coal and lignite usage are 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 than for 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.

Air pollutants

CO emissions for Scenario 2 are a third of those for Scenario 1, which is a significant benefit for Scenario 2. Non-methane 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 hydroxy-methyl-furfural (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%. In addition, 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 are lower for Scenario 2 due to the partial displacement of gasoline by ethanol.

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, sulphuric 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 than for Scenario 1. Lime is a big contributor to the total solid waste, while ammonia and sulphuric acid production are also responsible for some of the waste generation. These raw materials are used only in Scenario 2. Despite this, solid wastes are lower for Scenario 2 than to those for Scenario 1, mainly because of electricity offsets.

Table 2. Data summary for bagasse-to-ethanol process.

Environmental flows	Enzymatic process	
	(kg/kg bagasse)	(kg/l ethanol)
Inputs		
Biomass	1,000	3,318
Lime	0,009	0,030
Water	1,966	6,525
NH ₃	0,028	0,093
Diesel	0,005	0,017
H ₂ SO ₄	0,044	0,146
Outputs	(kg/kg bagasse)	(kg/l ethanol)
Ethanol	0,238	0,789
Gypsum	0,025	0,083
Ash	0,040	0,132
Ligneous residue	0,444	1,472
Biogas methane	0,015	0,051
Total CO ₂	1,170	3,883
	(MJ/kg biomass)	(MJ/l ethanol)
Net electricity	0,59	2,849

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	5,0x10 ⁻⁵	4,5x10 ⁻⁵	4,50x10 ⁻⁵	0,00	0,00
Carbon dioxide, biomass	0	200,2	0,00	200,2	1913,0
Carbon dioxide, fossil	2775	2584	2584	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

Table 4. Life cycle inventory for burning versus diverting bagasse to ethanol.

Flow		Units	Scenario 1: Burning + gasoline use	Scenario 2: Ethanol production + E10 use	Change from Scenario 1 to Scenario 2
			Per t 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)	litre	761	-73	110
Outflows					
Air	Carbon dioxide (CO ₂ , biomass)	kg	1 706	1 625	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	8 465	-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	4 195	148	97
Water	Sulfur Oxides (SO _x as SO ₂)	g	2 622	1 774	32
	COD (Chemical Oxygen Demand)	g	25,8	123,8	-381
	Lead (Pb ²⁺ , Pb ⁴⁺)	g	0,0085	-0,0034	140
Solid	Nitrates (NO ₃ ⁻)	g	2,3	-0,05	102
	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	8 508	226	97
	Renewable energy	MJ	8,4	18 841	NM ^a
	Total primary energy	MJ	27 517	19 068	31

^aNot meaningful to report.

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 non-renewable 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.

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 centres 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.

The Indian Ministry of Petroleum and Natural Gas recently approved the use of ethanol in gasoline blends, removing a potential regulatory hurdle (Winrock International, 2000). Furthermore, Clean Development Mechanism (CDM) as specified under the Kyoto Protocol can be used to advantage in deploying the bagasse-to-ethanol option.

Conclusions

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. 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. This information would be useful to public policy makers. Specifically due to the lower greenhouse potential, the CDM can be used to help deploy the bioethanol option in India.

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REFERENCES

- CRFA (1999). *Emissions Impact of Ethanol*. Canadian Renewable Fuels Association (CRFA), Guelph, Ontario, Canada.
- Kadam, KL (2000) *Environmental Life Cycle Implications of Using Bagasse-Derived Ethanol as a Gasoline Oxygenate in Mumbai (Bombay)*; NREL Report no. NREL/TP-580- 28705, National Renewable Energy Laboratory Golden, CO.
- Lower, ME and Barros, S (1999) *Brazil Sugar Semi-Annual Report 1999*; GAIN Report #BR9022, Sao Paulo, Brazil.
- Singh, SK (2000). *India Sugar Annual Report 2000*; GAIN Report #IN0019, U.S. Embassy, New Delhi, India.
- Smouse, SM, Staats, GE, Rao, SN, Goldman, R and Hess, D (1998). *Fuel Proc. Technol.* 54: 227-247.
- Wayman, M and Parekh, SR (1990) *Biotechnology of Biomass Conversion*; Prentice Hall, Engelwood Cliffs, NJ.
- Winrock International (2000). *Indian Government Approves the Use of Ethanol*. Winrock International, New Delhi, India; Press release.
- Wooley, R, Ruth, M, Sheehan, J, Majdeski, H and Galvez, A (1999). *Lignocellulosic Biomass to Ethanol Process Design and Economics, Utilizing Co-current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis: Current and Futuristic Scenarios*; NREL Report no. TP-580-26157, National Renewable Energy Laboratory, Golden, CO.