Fuel ethanol production from Indian agriculture

Opportunities and constraints

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Abstract: *Fuel ethanol use is being encouraged in many countries, including India, to reduce dependence on imported fossil fuels and to reduce local pollution and greenhouse gas emissions, as well as to provide support to stagnating sugarcane-based industries. Indian public policy is to use a blend of 10% ethanol with petrol within the next few years. This translates into a large requirement for fuel ethanol. This paper examines the potential suitability of various carbohydrate-based agri-resources for ethanol production in India, and the resources required for this in different agroclimatic regions. The results show that sugarcane has the highest ethanol potential, followed by cassava, potato and cereals. On the basis of growing time (days) in the field, however, the large differences among crops disappear and their ranking at state and district level also changes. It was calculated that the biomass as well as land requirement for fuel ethanol for 2010–11 in India would be small, taking into account the total food grain production and land used for agriculture. Utilization of only 3–7 million tons of damaged food grains or surplus food stocks could meet the requirement for fuel ethanol up to 2010. This may, however, involve trade-offs with food security. Agricultural residues, especially rice straw, currently burnt in north-western India, and causing air pollution and global warming, could be a useful and cheap resource, if the technology for cellulose conversion is made available and is cost-effective. A proper auditing of costs involved in producing biomass for gasohol, their implications for energy security and the environment, and trade-offs with food security is required for policy consideration.*

Keywords: *ethanol; biomass; renewable energy; cereals; gasohol; India*

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There has been rapid growth in the world's energy consumption during the last few decades. The main source of growth in energy use is in fossil fuels ((FAO, 2000). This increased usage of fossil fuels is now being held responsible for local air pollution leading to health problems. Together with other anthropogenic activities, this has also led to increased concentrations of CO_2 and other greenhouse gases in the atmosphere and a 0.4–0.7°C increase in temperature during the last 100 years. Continued anthropogenic activities may further increase the temperature by up to 5.4°C in the next 100 years (IPCC, 2007). Since overall economic development remains the primary goal of society, with a consequent increased use of energy, especially in developing countries, it is important that alternative sources of energy are evaluated urgently to mitigate the considerable extent of local and global environmental problems.

Gasohol, a 5–10% blend of ethanol with gasoline (petrol), has been used in the transport sector in Brazil, the USA and many other countries (FAO, 2000). Ethanol, being a low-carbon fuel, also appears to have large potential benefits in minimizing the risk of greenhouse gas (GHG) emissions. The use of ethanol has helped to create rural jobs in Brazil, improve air quality and provide a carbon substitution route. Since sugars are easier to convert to glucose than the cellulosic or lignocellulosic substrates, the majority of the ethanol currently produced in these countries is made from sugarcane and corn, which contain large quantities of simple sugars.

In 2003, the Government of India made a policy decision to blend 5% ethanol with petrol for the transport sector. It is proposed to increase this to 10% in the next few years. This public policy is largely targeted at reducing the dependence on imported fossil fuels, reducing local pollution and greenhouse gas emissions, as well as providing support to stagnating sugarcane-based industries. Taking into account the current use of petrol in India, a 10% blend translates into a requirement for more than 1,000 million litres of ethanol (Gokaran *et al*, 2002). This requirement would grow rapidly in future due to a projected increase in the consumption of fossil fuels.

Utilization of agricultural land for producing biomass for ethanol production has been advocated as a policy option. Pimentel (2003, 2005) has been critical of ethanol production from agricultural biomass such as corn in the USA, since his analysis showed a negative net energy balance, increasing the costs to society in terms of subsidies and the environmental impact of the whole process. Other studies, however, have indicated that the net energy values of corn-based ethanol have risen over time due to technological advances in ethanol conversion, as well as increased efficiency in farm production (Shapouri *et al*, 2003). The situation may be even better in low-energy intensive agricultural biomass production, such as in India, where energy use efficiency is known to be relatively higher (Sinha, 1986).

The main source of ethanol production in India at present is molasses from the sugarcane industry. The process, although cost-effective, leads to several pollution problems. Corn, wheat, other cereals and tuber crops have not yet been utilized for ethanol production on a large scale due to their primary requirement for meeting food demands. Often, however, there is a considerable surplus of food grain production. Although such stocks may not remain forever because of increasing demands for food, and the effect of climatic fluctuations, alternative uses for surplus food grains and of the land producing these grains are important. Since the primary aim of agriculture in meeting the food requirements of the ever-increasing population would remain, we need simultaneously to explore options for using agricultural land to meet the biomass requirement for ethanol production. The production of biomass also needs land, water, nutrients, capital and other resources. It is therefore imperative to quantify the available agri-bioresources for ethanol production within economic and ecofriendly perspectives. In this paper, we examine the potential of Indian agriculture to provide biomass for additional ethanol production. The specific objectives of this study were: (1) to review the potential suitability of various carbohydrate-based agri-resources for ethanol production in India, and (2) to analyse the resources required for the production of agri-biomass-based ethanol in different agroclimatic regions.

Materials and methods

Area cultivated and biomass production of important carbohydrate crops

Wheat, rice, maize, pearl millet, sorghum, potato, cassava and sugarcane – crops with a high carbohydrate content and well acclimatized to India – were selected for this analysis. The data for the area cultivated and biomass productivity for these crops at country, state and district levels were collected from published sources of the Government of India (Ministry of Agriculture). For the best experimental yields, reports of crop-based research institutes in the country for 1995–2000 were scanned and the highest reported yields noted. The estimates of food grain stocks were noted from the records of the Food Ministry, Government of India.

Ethanol productivity of agri-resources

To calculate the potential ethanol yield, the carbohydrate equivalent of one ton of fresh biomass was worked out for each crop. Penning de Vries *et al* (1989) have provided standard values of carbohydrate content for various crops. It was assumed that all carbohydrates were retained as polymers and that their hydrolysis to monomers would yield 10% more glucose (Garcha *et al*, 1987). The substrate energy from the biomass is used by the enzymes catalysing the conversion. It was assumed on the basis of earlier reports that energy would also be lost during the process of conversion through inefficiency of the industrial process. The total losses were thus assumed as 5% for sugarcane (sugar-based conversion), 10% for starchy cereals and tubers, and 20% for cellulose-/hemicellulose-based straw products. Considering the density of ethanol as 0.785 g/cc at 25°C and a concentration of 95% (by weight), the ethanol potential was calculated for each product as follows:

> ethanol productivity (litres ton^{-1} fresh biomass) = 1,000 kg fresh biomass * dry weight fraction * carbohydrate fraction * 1.1 (polymers to monomers) * 0.511 (carbon fraction of biomass in ethanol)/0.785 (density of ethanol)/0.95 (concentration) * (1-conversion losses).

Cost of biomass for ethanol production

In order to control the food supply and prices, the Government of India regularly procures many commodities at a regulated price from farmers. The cost of biomass required for producing one litre of ethanol was calculated using the minimum support price for different years and the calculated ethanol production potential per

Table 1. Area cultivated and biomass yield of economic components of the important carbohydrate crops in India, 2005–06.

Crop	Area, million ha	Irrigated area, %	Biomass yield, kg ha^{-1}	Production million tons
Sorghum	8.7	7.5	880	7.3
Pearl millet	9.7	6.3	802	7.7
Rice	43.7	52.6	2,102	91.8
Wheat	26.5	88.4	2,619	69.4
Maize	7.6	19.1	1,938	14.7
Sugarcane	4.2	90.7	66,928	281.2
Potato	1.4	*	17,058	23.9
Cassava	0.25	**	24,000	6.0

* Not available but largely irrigated; ** not available but largely unirrigated.

ton of biomass. Rice straw is not presently used as feed in north-western India and is generally burnt. Its cost, if utilized for ethanol production, was assumed to be rupees1,000 per ton (Rs45 = US$1), taking into account the estimated cost of its collection from the farm and transport to the processing plant.

Results and discussion

Biomass production

Carbohydrate crops, cereals and starchy tubers are primarily considered as the staple food in different parts of India. They have, therefore, traditionally been accorded much importance by the government as well as by farmers. The area under cultivation, biomass production and yield per unit area of most of these crops, particularly rice and wheat, have increased significantly during the last three decades. In 2005–06, carbohydrate-based crops were cultivated on 102 million hectares; cereals alone constituted 94.3% of this area (Table 1). The cassava crop occupied the smallest area, followed by potato and sugarcane. Rice biomass production (economic product – grains) was the highest (91.8 million tons) with an average yield of 2,102 kg ha^{-1}. Wheat production was 69.4 million tons, with an average yield of 2,619 kg ha^{-1}. Sorghum and pearl millet, being largely rainfed crops, had smaller biomass yields. The maize area was also 81% rainfed and its average yield was consequently lower. Sugarcane, a largely irrigated crop, produced 67 tons ha^{-1} biomass. Starchy tuber crops – potato and cassava – had modest yields of between 17 and 24 tons ha^{-1}.

India, being a large country, has considerable diversity in soils, climates and socioeconomic agro-environments, which result in widely different biomass productivity levels in different regions. National averages may not, therefore, reflect regional variations. The comparison of biomass production at national, state, district and experimental levels is shown in Table 2. Pearl millet, sorghum and corn produced the lowest biomass at all levels. Although these are C4 crops, characterized by higher photosynthesis, their cultivation in largely rainfed areas with negligible use of fertilizer, limited their biomass production. The highest biomass was produced by sugarcane, followed by cassava and potato. This was due to their higher moisture content and crop duration.

It is obvious that biomass production for all crops falls as the area under consideration increases. For example, the average biomass production of rice (economic product + crop residue) for the country as a whole was 4.17 tons ha^{-1}, compared with 7.52 tons ha^{-1} in the state of Tamil Nadu, 10.4 tons ha^{-1} in the district of Dindigul in Tamil Nadu state, and 21 tons ha^{-1} in the best experimental situations. Such large differences across scales are common in India, particularly for crops experiencing suboptimal management such as pearl millet, sorghum and corn. These scale-associated differences are relatively much smaller for sugarcane because this crop is largely irrigated, well managed, fertilized, and grown as a cash crop compared with other crops, which are mainly food crops.

Sugarcane generally matures in 330–530 days and has 75% moisture. Cassava matures in 200–270 days and has a moisture content of 70%. Potato also has a very high moisture content (80%) but matures in 100–120 days. Crops such as rice and wheat have 10–15% moisture and take only 120–140 days to mature, whereas rainfed cereals complete their life-cycle in about 100 days. Multiple cropping systems such as rice–rice–rice can thus be grown within a year in the intensive farming areas of Tamil Nadu. Similarly, rice–potato–wheat in Punjab can be grown in one year, whereas only one crop of cassava or sometimes sugarcane can be cultivated in the same period.

Ethanol productivity of biomass

The carbohydrate equivalent of a ton of fresh biomass varies with the crop because of its highly variable moisture content and carbohydrate proportions. The carbohydrate equivalent of cereals was from 690–760 kg ton^{-1} of biomass, whereas for cassava and potato, having a high moisture content, it was only 261 and 144 kg ha^{-1}. Sugarcane being rich in ligno-cellulose had only 143 kg of carbohydrates per ton of fresh biomass. By comparison, the straw of all crops had 470–500 kg of carbohydrate equivalent per ton of fresh biomass (Table 3).

The ethanol potential of carbohydrates, after considering conversion efficiency, was highest for wheat (403 litres per ton of biomass) followed by rice and corn, sorghum and pearl millet (Table 3). Potato and sugarcane, being rich in water content, had only 87–91 litres of ethanol potential per ton of fresh biomass. By comparison, cassava, with relatively less water content and high carbohydrates, had a high ethanol potential of 157 litres ton^{-1} of biomass. As against these, crop residues had a similar ethanol potential of 250–265 litres ton^{-1} of biomass.

The ethanol potential of biomass for various crops has been calculated by several authors (Mathur, 1988). The values vary in their magnitude, depending upon the assumptions and the process used for conversion. FAO (2000) compiled this information for various economic products. For comparison, these values are also included in Table 3. It is apparent that theoretical values calculated as above are very close to the FAO estimates.

Ethanol productivity of crops at different regional scales

At the current level of agronomic management and total

Table 2. Recorded biomass production at different regional scales for major carbohydrate crops in India.

Crop	Fresh biomass, tons ha^{-1}				Crop duration, days	Name of the best state
	Country[1]	*Best state*[2]	*Best district*[3]	*Best experiment*[4]		
Economic product						
Rice	1.99	3.58	4.95	10.00	120	Tamil Nadu
Wheat	2.68	4.70	4.72	7.50	135	Punjab
Sorghum	0.96	1.20	2.03	5.00	100	Gujarat
Pearl millet	0.79	1.35	2.61	5.00	100	Uttar Pradesh
Corn	1.76	3.18	4.84	8.00	110	Andhra Pradesh
Potato	18.64	23.75	27.62	80.00	120	W Bengal
Cassava	22.50	46.32	55.00	80.00	260	Tamil Nadu
Sugarcane	71.13	110.30	107.09	150.00	450	Tamil Nadu
Crop residues						
Rice	2.18	3.94	5.44	11.00	120	Tamil Nadu
Wheat	2.95	5.17	5.19	8.25	135	Punjab
Sorghum	1.05	1.32	2.24	5.50	100	Gujarat
Pearl millet	0.87	1.48	2.87	5.50	100	Uttar Pradesh
Corn	1.93	3.50	5.32	8.80	110	Andhra Pradesh

[1]Best of1997–98, 1998–99, 1999–2000.
[2]Best of 1998–99 and 1999–2000.
[3]Best of 1997–98 and 1998–99.
[4]Based on crop yields in experimental trials carried out in various places during 1995–2000.

Table 3. Ethanol productivity of important crops and their by-products.

Crop	Dry weight fraction (t)	Carbo-hydrate fraction (t)	Carbo-hydrate equiv-alent kg ton^{-1} fresh biomass	Ethanol potential (95%) litres ton^{-1} biomass	Ethanol potential, FAO values litres ton^{-1} fresh biomass
Rice (paddy)	0.86	0.76	654	394	346–372
Wheat (grain)	0.88	0.76	669	403	346–373
Sorghum (grain)	0.88	0.72	634	382	346–374
Pearl millet (grain)	0.88	0.69	607	366	346–375
Corn (grain)	0.87	0.75	653	394	346–376
Potato	0.185	0.78	144	87	
Cassava	0.3	0.87	261	157	
Sugarcane	0.25	0.57	143	91	92
Rice straw	0.86	0.55	473	250	
Residues of other crops	0.88	0.57	502	265	

biomass production (economic + residues), sugarcane has the highest ethanol potential (8,379 litres per hectare) when examined at the aggregated national level (Table 4). The ethanol potential was almost half of that for cassava, and 25% for potato. The potential of cereals varied between 520 litres ha^{-1} (pearl millet) and 1,860 litres ha^{-1} (wheat). The ethanol yield improved at the lower scale due to relatively higher biomass production by all crops. At the best state level, ethanol yields increased for all crops by 30–50%, but the ranking of crops in terms of ethanol yields remained similar. The relative differences among crops became still smaller in areas such as districts and experimental stations, but the superiority of sugarcane and cassava over other crops was maintained due to their longer duration. At these levels, the highest ethanol yields were 14,690 and 17,640 litres ha^{-1} for cassava and sugarcane respectively. Most of the ethanol yield at all scales was from the economic product.

The ethanol potential per day of different crops according to time spent in the field, however, showed widely differing results. At the country level, sugarcane, being a well managed cash crop, remained the highest ethanol yielder (18.6 litres ha^{-1} day^{-1} including 4.2 litres ha^{-1} in the crop residues), followed by potato, wheat and cassava (13.8–17.6 litres ha^{-1} day^{-1}). Rice and corn had yields of 10.9–11.1 litres ha^{-1} day^{-1} (Figure 1). Sorghum and pearl millet, although short-duration crops, had the lowest yields of 5.1–6.4 litres ha^{-1} day^{-1}, because these were grown in rainfed regions. At the best state level, the ethanol potential of cassava and sugarcane was highest (28–31 litres ha^{-1} day^{-1}), followed by wheat (24.2 litres ha^{-1} day^{-1}) and rice, corn and potato (18.9–19.9 litres ha^{-1} day^{-1}). Sorghum and pearl millet still remained at the lowest level. At the best district level, the highest ethanol productivity was obtained from cassava, followed by corn, sugarcane, rice and wheat (in decreasing order). Even at this level, sorghum and pearl millet had the lowest ethanol productivity.

The productivity of most crops is likely to rise in future due to continuously improving management practices characterized by the use of greater acreages of improved varieties and higher inputs of fertilizer, irrigation and pesticides. The experimental yields being obtained today, although much higher than in even the

Table 4. Ethanol production potential of major crops in India at different regional scales, with values calculated from Tables 2 and 3.

Crop	Ethanol potential, litres ha^{-1}			
	Country	*Best state*	*Best district*	*Best experiment*
Economic product				
Rice	780	1,416	1,944	3,948
Wheat	1,080	1,890	1,903	3,024
Sorghum	370	460	780	1,910
Pearl millet	290	490	940	1,810
Corn	693	1,254	1,903	3,146
Potato	1,620	2,064	2,400	6,960
Cassava	3,536	7,280	8,658	12,584
Sugarcane	6,480	10,080	9,765	13,680
Crop residues				
Rice	540	984	1,356	2,748
Wheat	783	1,363	1,377	2,187
Sorghum	280	350	590	1,460
Pearl millet	230	390	750	1,440
Corn	506	924	1,408	2,332
Potato	492	624	732	2,112
Cassava	598	1,222	1,456	2,106
Sugarcane	1,890	2,925	2,835	3,960
Total				
Rice	1,320	2,400	3,300	6,696
Wheat	1,863	3,253	3,280	5,211
Sorghum	650	810	1,370	3,370
Pearl millet	520	880	1,690	3,250
Corn	1,199	2,178	3,311	5,478
Potato	2,112	2,688	3,132	9,072
Cassava	4,134	8,502	10,114	14,690
Sugarcane	8,370	13,005	12,600	17,640

best district; could be realized in farm practice in future. Therefore, the current best experiments could be taken as an index of likely future improvement in district-level productivity. Comparisons at this level show that the ethanol productivity of potato is very high (> 70 litres ha^{-1} day^{-1}), with cassava, rice and corn next highest (50–57 litres ha^{-1} day^{-1}). Sugarcane and wheat were similar in ethanol productivity at this level (38–40 litres ha^{-1} day^{-1}). Sorghum and pearl millet had fairly high productivity, but were still the lowest among all crops. Straw also constituted an important source of ethanol in all cereals (almost 70% of the economic product), whereas in other crops the economic product was the main source.

Ethanol potential of surplus food grains

Indian government policy is to maintain at least 20 million tons of stock of cereals to meet the demands of public distribution systems and other sponsored schemes, as well as to manage any shortfalls in future production. Table 5 shows the position of such stocks and the surpluses in different years. It is evident that in many years there is a build-up of surpluses in the country, which reached 38 million tons in 2002. The surpluses are due to government policies of providing minimum support prices for these cereals to the farmers, consistently good weather resulting in higher yields, and limited alternative cropping options for farmers. The management of these surpluses is expensive, and many of them become unfit for consumption during storage. A fraction of these surplus cereals could possibly be utilized for producing a large quantity of ethanol (Table 5). For three consecutive years from 2001, the ethanol potential of these surplus grains was far more than that required for 10% blending with petrol across the whole country. Utilizing food stocks for ethanol production may, however, pose socio-political and ethical problems when there is still a large inadequately fed population. The utilization of grains declared unfit or from old stock could, nevertheless, be considered a possible option. The quantity of damaged food grains that are unfit for human consumption is not easily established. Since storage conditions in tropical, developing countries are generally suboptimal, a 5% portion can be considered as unfit for human consumption. If this were utilized for the production of ethanol, then more than 350 million litres of ethanol could be produced, which could meet a large part of the current requirement for fuel ethanol.

Table 5. Stocks (million tons) of cereals, surpluses, and their ethanol potential for different years.

Stock as on 1 January of year	Total stock, million tons	Surplus stock (>20.0 million tons minimum stock policy)	Ethanol potential of surplus stock, million litres @ 400 litres ton^{-1}	Ethanol potential of damaged food grain stock, million litres
1992	14.73	–5.27	0	295
1993	13.13	–6.87	0	263
1994	23.52	3.52	1,408	470
1995	30.30	10.30	4,120	606
1996	28.56	8.56	3,424	571
1997	20.02	0.02	8	400
1998	18.25	–1.75	0	365
1999	24.38	4.38	1,752	488
2000	31.89	11.89	4,756	638
2001	45.77	25.77	10,308	915
2002	58.11	38.11	15,244	1,162
2003	48.20	28.20	11,280	964
2004	25.02	5.02	2,008	500
2005	21.70	1.70	680	434
2006	19.26	–0.74	0	385
2007	17.49	–2.51	0	350

In addition to these stocks of cereals, there are frequent gluts in the production of potatoes, cassava and sugarcane. Every three to five years, there is likely to be a glut of potatoes leading to distress sales. As a consequence, some farmers will occasionally plough potatoes back into the field. Lack of adequate cold-storage facilities and transportation add to this unfortunate situation. If such surplus biomass could be processed for ethanol production, many affected farmers would be able to benefit.

Cost of biomass per litre of fuel ethanol

The Government of India has announced a minimum support price for certain crops, at which government agencies will procure them. This is a good index for comparing the value of the economic product of crops in terms of their ethanol productivity. The analysis showed

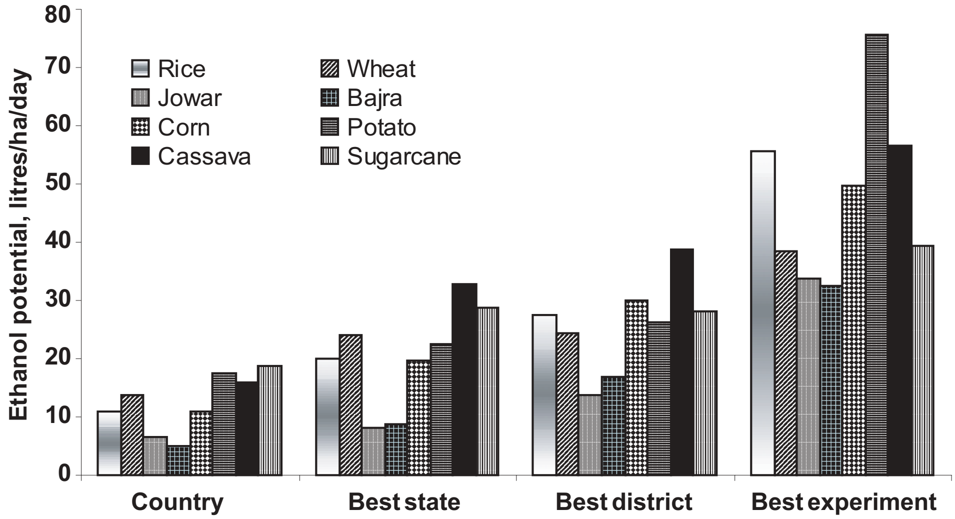

Figure 1. Ethanol potential of different crops per hectare of land per day of crop growth period at different spatial levels.

Table 6. Cost of biomass from different agri-sources for ethanol (prices are for 1999–2000).

Resource	Price of biomass (rupees ton^{-1})	Ethanol (litres ton^{-1} biomass)	Cost of biomass for ethanol (rupees litre^{-1})	Rank
Paddy	4,900	394	12.44	11
Wheat	5,800	403	14.39	12
Sorghum	4,150	382	10.86	9
Pearl millet	4,150	366	11.34	10
Maize	4,150	394	10.53	8
Potato[1]	3,010	87	34.60	14
Cassava[2]	3,030	157	19.30	13
Sugarcane	560	91	6.15	6
Damaged food grain – feed I	2,760	400	6.90	7
Damaged food grain – feed II	2,070	400	5.17	5
Damaged food grain – feed III	1,380	400	3.45	3
Damaged food grains – industrial use	690	380	1.81	2
Damaged food grains – manure	340	360	0.96	1
Straw[3]	1,000	250	4.00	4

[1]Price of biomass is mean of UP and West Bengal.
[2] Price of biomass is for Kerala only.
[3] Rice straw @ Rs1.0 per kg (including estimated cost of collection from farm and transport to briquette plants in Punjab).

that the cost of biomass production per litre of ethanol varied from as low as Rs0.96 to Rs34.60, depending upon the source of biomass (Table 6). The cheapest biomass was damaged food grains having less than 30% sound grains, which were only suitable for manure use or dumping. Rice straw and other crop residues are also cheap sources of biomass for ethanol. The cost of biomass varies between Rs10 and 14 per litre of ethanol for food grain crops. Sugarcane was comparatively much cheaper than any of the food grains. Potato and cassava, the tuber crops, were the most expensive in terms of their cost for ethanol production. These are two crops that do not have a government-prescribed minimum support price, as is available for rice, wheat and sugarcane.

The minimum support price of all commodities has been continuously rising over the last few years due to increased costs of cultivation and for policy reasons. Against this, biomass yields per unit of land have, in general, shown only small increases or stagnation, especially in intensive farming areas (Aggarwal *et al*, 2000). As a consequence, the cost of biomass per litre of ethanol, irrespective of source, has shown a considerable increase in the last decade (Figure 2). The price of sugarcane biomass per litre of ethanol, based on 1990 prices, was Rs2.41, with Rs4.3 to 4.7 for all cereals except wheat, which was priced at Rs5.33 per litre of ethanol. These have increased for all crops at an average rate of 14% per year, resulting in the cost of biomass varying from Rs6.2 in sugarcane to 16.0 in wheat in 2006.

Resources needed for producing biomass for ethanol

The ethanol required for meeting the 10% blending target for 2003–04 was about 1,600 million litres, with 2,540–3,192 million litres required for 2010–11 (Gokaran *et al*, 2002). Our results indicate that 3 million tons of various cereal grains, or about 4.5 million tons of straw alone could have met the ethanol requirement for gasohol for 2003–04, with about 7–12 million tons for 2010–11 (Figure 3). Alternatively, 13.5 million tons of potato, or 7.5 million tons of cassava tubers, or 13 million tons of sugarcane can meet the current requirement of ethanol for 10% blending in gasohol. These are relatively small amounts compared with our current agricultural production (210 million tons of food grains).

Rice straw has no significant use in north-west India, and farmers generally burn much of it for timely wheat planting. This straw could be an ideal and cheap substrate

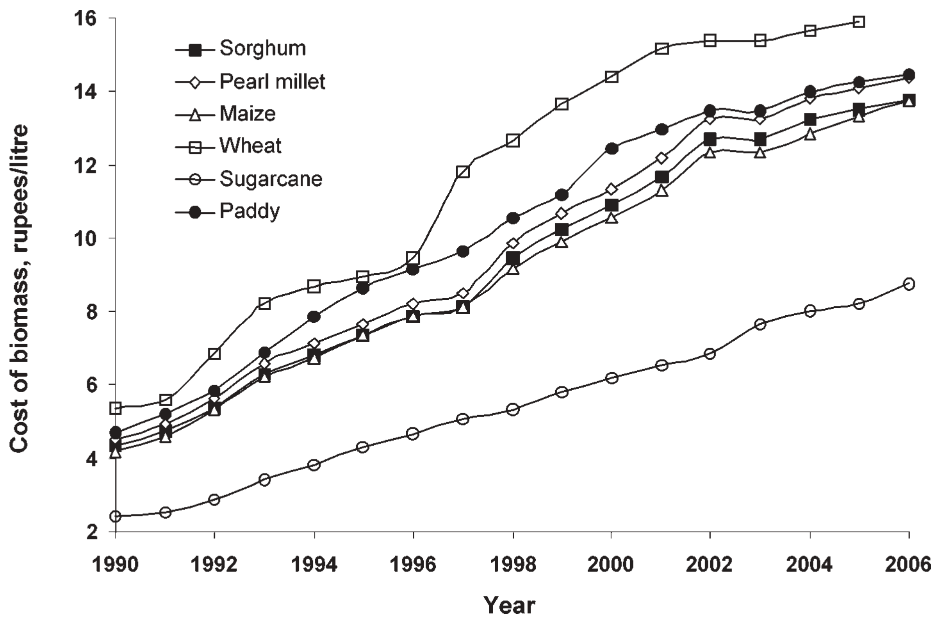

Figure 2. Change in cost of biomass for ethanol from different agricultural sources over time.

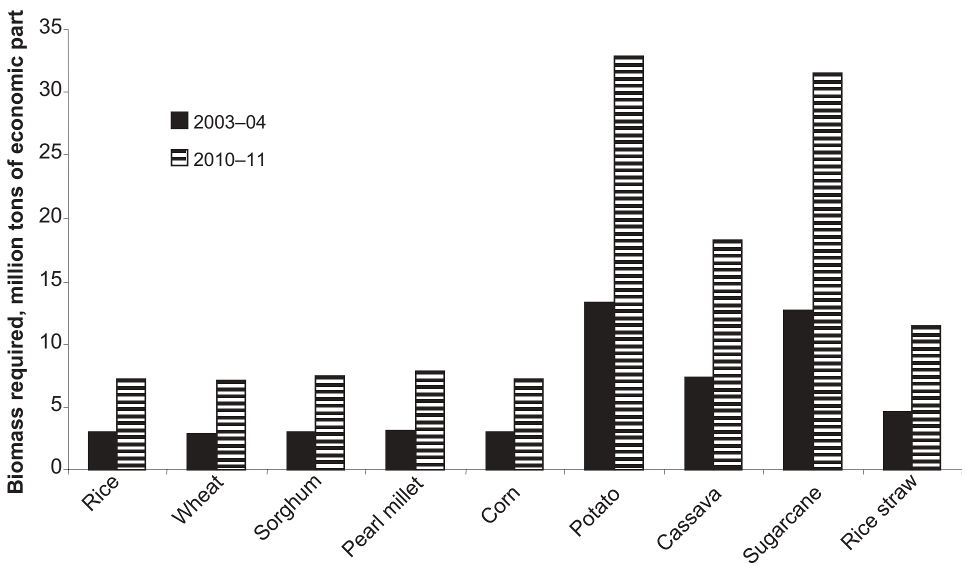

Figure 3. Biomass required from different crops, assuming they alone were to meet the fuel ethanol demand of the country (10% blend) for 2003–04 and 2010–11.

for ethanol production, provided the industrial conversion process is cost-effective. A rough estimate indicates that there are more than five million tons of such rice straw in Punjab and Haryana alone. The ethanol potential of this straw is 1,250 million litres, which would meet a large fraction of the present 10% blending requirement for gasohol for the whole country.

Intensive cropping systems such as the maize–potato–wheat system in northern India could produce the desired biomass for the current ethanol requirement of 10% blending in gasohol in a year's time on 0.12 million ha of land using only current agricultural technology. Similarly, sugarcane alone could produce enough biomass from 0.128 million ha of land in Tamil Nadu. An intensive rice–rice–rice system or cassava in Tamil Nadu could do so by using only 0.12 million ha of land. Rainfed systems such as pearl millet–fallow in Haryana would need 0.68 million ha of land (Table 7). This requirement of land from diverse cropping systems is a negligible fraction of the land currently utilized in agriculture (145 million hectares).

Rainfed systems, although requiring more land, do not

Table 7. Land required (million ha) for producing biomass from some typical cropping systems to meet the fuel ethanol requirement of the whole country for 10% blending. It may be noted that any one cropping system in different parts of India could meet the entire demand.

Cropping system	2001–01	2010–11
Cassava in Tamil Nadu	0.114	0.283
Rice–rice–rice in Tamil Nadu	0.117	0.289
Maize–potato–wheat in Punjab	0.119	0.295
Sugarcane in Tamil Nadu	0.128	0.318
Maize–wheat in Punjab	0.304	0.753
Pearl millet–fallow in Haryana	0.675	1.674

need any significant input of fertilizers, pesticides, or irrigation, a precious resource that increasingly needs to be conserved. In India, although the productivity of cassava is low, the majority of land is under coconut and other plantation crops. Thus the land and other resources required for cassava are minimal. Intensive rice- and potato-based cropping systems may need less area, but require great amounts of irrigation water and other inputs. The key limitation with sugarcane-based systems, which take 12–18 months to mature in Tamil Nadu, would be the varying supply of biomass at different times of the year. Other crops, maturing in much shorter times, permit more than one harvest per year and a more regular supply of biomass to utilize the capacity of industry throughout the year.

Conclusions

Our study has shown that producing biomass to meet the ethanol requirement for gasohol in India would not constitute a large drain on land and other resources. Thus this may be a worthwhile goal for further costing and policy analysis in view of the surplus production in recent times, the physical and economic constraints of storing large food stocks, inevitable damage during storage, environmental goals, and the need to provide additional sources of revenue to farmers. The biomass can be made available on a continuous basis from several crops and in different regions. Once agri-biomass is utilized for the ethanol industry, it is, however, likely that the cost:benefit ratio of farm production may also undergo considerable changes. Also, the policy of reducing subsidies currently provided to agriculture and the consequent prices of agri-biomass used in the present study may change significantly in the light of this. A proper auditing of the environmental costs of producing biomass for gasohol *versus* the use of petrol in terms of carbon mitigation and improved local air quality also need to be considered in any policy decision.

Utilization of food grains for fuel has several other social, ethical, political and economic dimensions. India still has more than 200 million people who are underfed due to their limited purchasing power. One hectare of intensively cultivated land produces more than 25 tons of biomass, which is sufficient to meet the food requirements of 40 or so human beings for a whole year. The land currently needed for producing biomass for 10% blending with petrol could produce food for almost 4.67 million human beings, and the by-products could feed a few million livestock. Processing rice straw that is currently burnt, plus damaged food grains used for manure, could ease these pressures, provided their industrial conversion was cost-effective.

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References

Aggarwal, P. K., Bandyopadhyay, S. K., Pathak, H., Kalra, N., Chander, S., and Sujith Kumar, S. (2000), 'Analysis of yield trends of the rice–wheat system in north-western India', *Outlook on Agriculture*, Vol 29, No 4, pp 259–268.

FAO (2000), *The Energy and Agriculture Nexus*, FAO, Rome.

Garcha, H. S., Sedha, R. K., and Singh, R. (1987), 'Production of liquid fuels (ethanol) from biomass', *Proceedings of Bioenergy Society 4th Convention & Symposium '87, Bioenergy Society India, New Delhi*, pp 121–131.

Gokaran, S., Bedi, J. S., and Pandey, M. (2002), 'An economic assessment of the feasibility of introducing ethanol as a motor vehicle fuel in India', report submitted to the Ministry of Non-Conventional Energy Resources, Government of India, National Council of Applied Economic Research, New Delhi.

IPCC (2007), *Climate Change 2007: The Physical Science Basis. Summary for Policymakers* (in press), Inter-Governmental Panel on Climate Change, Cambridge.

Mathur, H. B. (1988), *Ethanols – the Biosolar Fuels (Their Production and Utilisation for Energy Needs)*, Mahaluxmi Offset Printers, New Delhi.

Penning de Vries, F. W. T., Jansen, D. M., Ten Berg, H. F. M., and Bakema, A. H. (1989), *Simulation of Ecophysiological Processes in Several Annual Crops*, Simulation Monograph, PUDOC, Wageningen.

Pimentel, D. (2003), 'Ethanol fuels: energy balance, economics and environmental impacts are negative', *Natural Resource Economics*, Vol 12, pp 127–134.

Pimentel, D. and Patzek, T. W. (2005), 'Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower', Natural Resources Research, Vol 14, pp 65–76.

Shapouri, H., Duffield, J. A., and Wang, M. (2003), 'The energy balance of corn ethanol: an update', *Agricultural Economic Report No 813*, USDA, Washington, DC.

Sinha, S. K. (1986), 'Energy balance in agriculture: the developing world', in Swaminathan, M. S., and Sinha, S. K., eds, *Global Aspects of Food Production*, Tycooly International, London, pp 57–84.