

Viable feedstock options and technological challenges for ethanol production in India

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Though improvements in processing and technology are important, the fluctuating price of inputs such as molasses, corn, sugar beet, sugarcane, sweet sorghum, starch, etc. and their seasonal availability play an important role in ethanol industry. As a matter of fact, the ethanol industry based on conventional resources has reached its saturation point. Technologies for ethanol production from lignocellulosics are being developed by scientists world over with the objective of exploiting the potential of a resource, which is otherwise considered a waste, to generate energy. The focus has been to produce ethanol in a cost-effective manner, besides aiming to find use of its by-products as food supplements for cattles, etc. Recent developments like adoption of technologies such as dry grind fractionation, which is now commercially viable, would reduce the cost of milling; wet milling being cost-intensive and dry milling requiring smaller plants.

Keywords: Ethanol, feedstock, lignocellulosics, molasses, sugarcane.

URBANIZATION and rapid population growth are responsible for increasing consumption of energy in the world. The worldwide consumption of energy has increased 17-fold in the last century¹. On the other hand, conventional energy sources (non-renewable) such as fossil fuels are limited and thus cannot meet the demand in the long term. Moreover, uses of fossil fuels also have a negative environmental impact, e.g. increased greenhouse gas emissions. Thus, the major challenge for sustainability world over is to find renewable, efficient, cost-effective and environment-friendly sources of energy that can meet the demand of the transport, energy and industrial sector. Bioethanol, manufactured by fermenting any biomass rich in carbohydrate content (starch, sugar and cellulose), is considered to be one of the alternatives to fossil fuels. The transport sector itself is considered as one of the largest consumer of fuels contributing significantly to environmental pollution². According to the International Energy Agency statistics, the transport sector accounts for about 60% of total global oil consumption. About 20% of CO₂ emission on a global scale is due to transport fuels²⁻⁴.

Bioethanol is emerging as a fuel for cars, which can be used in its anhydrous form. Bioethanol from different renewable sources has already been introduced on a large scale in Brazil, Europe, USA, China and India⁵⁻¹¹. In 2006, out of the total world production of 48,652 million liters, USA and Brazil together contributed around 70%. The production of ethanol needs a variety of feedstock that can meet the huge demand. At present, major ethanol-producing countries in the world are Brazil, USA, China and India, which produce ethanol from sugarcane, corn, grains and molasses respectively. It is expected that around 33% of the energy needs of Europe and USA for different transportation purposes will be satisfied by converting biomass to biofuels by 2030 (refs 10-13).

Bioethanol production

Feedstock options

The material biomass comes from plants, which utilize solar energy for converting CO₂ and H₂O into sugar. Some plants store the energy in the form of simple sugars, while others store it as complex sugars (starches)¹⁴. Both of these sugars can be fermented into bioethanol. Another type of resource, i.e. cellulosic biomass is composed of complex sugar polymers, which cannot be directly fermented into bioethanol and need pretreatment and hydrolysis to fermentable sugars. Various categories of feedstock used worldwide for ethanol production are mainly the source of sugars that can be directly fermented. For example, molasses, cane sugar, sweet sorghum, sugar beet and other fruits consisting of sugars and different grains (wheat, corn, rice, sorghum, barley, etc.) and other tubers (sweet potato, cassava, etc.) consisting of starches. Both these types of feedstock are derived from agricultural crops and hence their production would always be a topic of debate on 'food versus fuel'. The other renewable feedstocks with potential to be the source of fermentable sugars are cellulose and lignocellulosics derived from plant waste materials such as straw, wood, bagasse, etc. Such feedstocks have yet to be exploited for the production of ethanol¹⁵⁻¹⁷.

The feedstocks used for bioethanol production vary throughout the world (Table 1)¹⁸. In Brazil, sugarcane is preferred; in USA corn is the major crop; across Europe it

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is predominantly wheat and barley, and in India, it is sugarcane molasses – a by-product of sugar manufacturing industry³.

Sugarcane juice: In India, majority of ethanol is obtained from sugarcane molasses. In the future it may also be produced directly from sugarcane juice¹⁹. Shetimal Sahakari Sanstha Ltd, Kolhapur, Maharashtra is the first plant of 30 kilo litre per day (KLPD) fuel ethanol production directly from sugarcane juice²⁰⁻²².

Sweet sorghum: A high-yielding variety, namely Madhura, mainly for ethanol production has been developed²³. One manufacturing unit of 40 KLPD capacity for ethanol was set-up in 2006, based on sweet sorghum in Medak district, Andhra Pradesh. Depending on the success of this unit, another one with 200 KLPD capacity of biofuels from sweet sorghum is expected soon. It is apparent that in future, sweet sorghum may become the major feedstock for ethanol in India²⁴.

Tropical sugar beet: This is another high-yielding variety of sugar, which is being tested in thousands of farms in Maharashtra²⁵. If successful, the faster growth rate of tropical beet compared to sugarcane may motivate farmers to switch over to the former.

Fruits: These are being used only for production of wine. It will not be viable to use fruits for production of transport fuel.

Grains: These are used only for potable ethanol. It will be a non-viable feedstock of ethanol for transport sector.

Damaged grains: Among these, sorghum is the most frequently used grain for ethanol production, but again for potable liquor.

Tuber: Cassava has been used in South India for potable ethanol production, but this cannot become the major feedstock.

Cellulosics and lignocellulosics: Technology for ethanol production from cellulosics is still under development stage²⁶. Among the various feedstocks available,

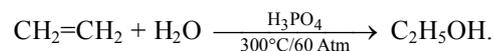
by-products of sugarcane processing industry, i.e. molasses from sugar industry are mainly used for ethanol production in India.

As the ‘food versus fuel’ issue will not allow utilizing food produce as a source of bioethanol production, alternatives like lignocellulosics need to be exploited. Specific feedstocks of cellulosic biomass under consideration include: Different residues from agriculture; dead trees, tree branches, forestry wastes, chips and sawdust from lumber mills; household garbage, solid waste from municipal and other paper products; wastes from different food processing industries (black liquor, by-product from paper and textile industry); energy crops such as fast-growing grasses and trees being developed for the production of ethanol.

Technology options

Presently, there are two main processes through which commercial ethanol is being manufactured.

Synthetic process: Conventional method for production of industrial ethanol is acid catalysed hydration of ethylene produced from petroleum resources. The reaction of ethylene with phosphoric acid is



The use of acids as a catalyst alters the manufacturing process due to corrosion, safety and other environmental issues. Advanced technology permits ethanol to be manufactured by the use of zeolite or silica aerogel saturated with phosphoric or tungstic acid. The advantages of the present process are that the reaction can be completed in one stage, the used catalyst can be regenerated, and also concerns (associated with sulphuric acid) about environment, corrosion and safety are diminished. The relative low cost of ethylene from petroleum resource makes this route preferable compared to the fermentation route.

Since ethylene is produced from hydrocarbons, which are also used as fuel, making ethanol as an alternative fuel by this process would not be a good option. But if ethanol can be produced by renewable resources in a cost-effective manner, this can be an alternative fuel for the future. This has become feasible and viable after the experiences of bioethanol in countries like Brazil.

Fermentation process: This process of ethanol (bioethanol) production involves conversion of fermentable sugars into ethanol followed by distillation of ethanol. During fermentation, carbon dioxide is evolved as a by-product. Feedstock that can be used in the fermentation process are: Sugar crops like sugarcane, beetroot, switch grass, etc.; By-products from sugar industry like molasses; grains like wheat, corn, etc.; lignocellulosic biomass.

Table 1. Country-wise feedstock used for bioethanol production

Type	Feedstock	Country
Carbohydrate	Sugarcane	India, Brazil, Thailand, Philippines
	Sweet sorghum	China
	Sugar beet	France
Starchy	Corn	USA, UK, China
	Wheat	Germany, Spain, France, UK, China
	Cassava	China, Thailand

is in agreement with the theoretical values. The heat produced from a fermentation involving 67,950 kg of sugar is 39,000,000 Btu (ref. 34).

Fermentation begins after the fermentor is filled and is active after 2–4 h; it typically takes 48–80 h for completion. After fermentation is complete, the resulting broth contains ethanol (6–8%). Yeast culture obtained from cell free broth is taken for distillation once fermentation is completed.

For ethanol distillation system by Indian distilleries, generally 6–9 fermenters are used for ensuring continuous feed³⁵. Over 100 distilleries in India are producing ethanol by continuous process, due to its higher efficiency, i.e. 89–90% (80–84% for batch process), less water consumption and ease of operation^{3,13,36}.

Distillation: Preheated (90°C) cell-free fermented broth is sent to the de-gasifying chamber of the analyser section. Any trapped gases are removed by bubble-cap fractionating column from the liquor. To the rectifying column, ethanol vapours from the analyser chamber are further taken, 94–96% rectified ethanol is trapped, cooled and collected by reflux action.

Besides molasses, other feedstocks such as sugar beet, sugarcane and sweet sorghum can also be used as sources of sugar for ethanol production^{30,31,37–42}.

Dehydration: As a fuel, water must be removed completely from the bioethanol. From distillation, the purity is limited to 95–96%, due to the formation of low-boiling water–ethanol azeotrope. The 96% ethanol v/v (95% w/w) and 4% v/v water (5% w/w) mixture may be used as a fuel only in FLEXI-FUEL vehicles and it is called hydrated ethanol^{30,42–44}.

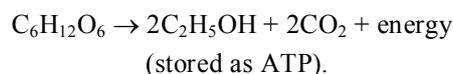
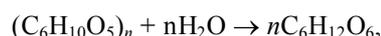
For ethanol to be used as fuel in conventional vehicles, it is necessary to remove water from it, i.e. to make ethanol anhydrous to a minimum of 99.7% w/w purity level. Currently, the most widely used technique for the production of anhydrous ethanol is the physical adsorption (of water) process using molecular sieves. A molecular sieve contains a series of small beads that adsorb all the remaining water from hydrated ethanol. Ethanol molecules are too large to enter the sieves; thus the dehydration step produces pure ethanol^{14,16,29,31}.

Another method by which dehydration of ethanol is achieved uses hydrocarbon benzene (entrainer) in azeotropic distillation. Addition of benzene breaks the water–ethanol azeotrope and ethanol off with benzene leaving water. A third method involves the use of calcium oxide as desiccant. Prior to shipping ethanol to the gasoline distribution centre for blending, a small amount of gasoline (~5%) is added to denature the ethanol, making it unfit for drinking^{3,12,30,42,45}.

Ethanol production from indirectly fermentable feedstocks: All grains like wheat, rice, corn and barley are

good sources of starch. The conversion of corn and other food/feed crops into ethanol by fermentation is a well-known and established technology which involves three steps: Pretreatment – milling, extraction and hydrolysis to form a solution of fermentable sugars; Fermentation of sugars to ethanol; Separation and purification of ethanol to anhydrous ethanol.

Production of ethanol from grain sources includes grain milling, starch hydrolysis and inoculation of yeast cell. The remaining spillage from ethanol production is processed to produce distiller's dried grains and solubles (DDGS), a good ingredient for animal feed.



In USA, corn is the principal feedstock for ethanol production. The ethanol yield from a large production plant is about 1 litre from 2.69 kg of corn grain⁴⁶.

On the basis of methodology of milling, the process can be divided into two types, i.e. dry and wet milling.

Dry milling: This includes the following processes:

Grinding: Whole grain is utilized in this method. It is ground into flour and referred to as meal, which is processed out without separation into the various component parts of the grain⁴⁷.

Cooking: Meal is converted into slurries with water to form mash and enzymes are mixed for converting starch to dextrose. For pH control, NH₃ is added which also acts as a nutrient to the yeast. The mash is finally processed under certain temperature and pressure called cooking, which makes mash suitable for fermentation.

Fermentation: After cooling, the mash is transferred to the fermentor where yeast culture is added and the conversion of sugar to ethanol and CO₂ takes place. The fermentation process generally takes about 40–50 h.

Distillation: The resulting beer is transferred to the distillation chamber after fermentation, where ethanol is concentrated to 190 proof by removing water and impurities of aldehyde, ketone and other higher alcohols. To obtain 200 proof ethanol, the purified ethanol is passed through a molecular sieve system.

Wet milling: This includes the following processes.

Steeping: The grains are soaked in wet milling for 24–48 h in a mixture of dilute sulphurous acid (H₂SO₃) and water. This steeping facilitates breakdown of the grains into separable components^{47–49}.

Table 2. Technological challenges involved in bioethanol production

Production process	Process type/step	Challenge
Synthetic alcohol	Hydration of ethylene	Ethanol from synthetic route cannot be the alternative to fossil fuels.
Directly fermentable feedstock (molasses, sugarcane, sugar beet and sweet sorghum)	Batch	Need frequent cleaning and sterilization. Poor efficiency (80–84%) as against 89–90% in continuous. Needs a separate inoculum vessel. More controls are required
	Continuous	High risk of contamination and mutation due to long cultivation period.
	Semi-continuous	Higher investment costs for larger reactor.
Indirectly fermentable feedstock (starchy and industrial waste)	Milling and hydrolysis	Need costly pretreatment, steeping, milling and hydrolysis to convert starchy material into fermentable substrates.
Ethanol from lignocellulosic biomass	Pretreatment	Extensive energy, chemical/enzyme demand. Reduction in cost of pretreatment reactor. To curtail pollutants such as black liquor of lignin.
	Dilute acid hydrolysis	Toxic degradation products like furan from sugars, aliphatic acids from hemicellulose acetyl groups, and phenolics from lignin that interfere with fermentation.
Ethanol from lignocellulosic biomass	Concentrated acid hydrolysis	Cost-effective acid recovery.
	Microbial fermentation of hexoses and pentoses to ethanol	Microorganisms capable of fermenting both hexoses and pentoses with effective rate of conversion.
	Direct conversion of cellulose into ethanol	To minimize by-products like acetate and lactate that lower the efficiency of the process.
Ethanol from gasification of lignocellulosic biomass	Gasification	Extensive energy demand. Combustion needs sophisticated controls to obtain the desired composition of syngas.
	Fermentation	Needs special kind of fermenter that can support bacteria, <i>Clostridium ljungdahlii</i> .
	Catalytic conversion	To arrest the formation of by-products like methanol, butanol and propanol.

Grinding and separation: Steeped corn is ground in wet condition through a series of grinders and four products are separated: (i) corn germ (embryo portion of seed), (ii) fibre (outer tough covering of corn seed), (iii) gluten (protein part of corn seed) and (iv) starch (carbohydrate part of corn seed).

Product (i) is used for corn oil production. Products (ii) and (iii) are segregated using centrifugal, screen and hydrocyclonic separators, both constitute a good feed for livestock industry. Heavy steep water left after extraction of the above four components is generally used in feed preparation and melting ice on roads; hence, it is also known as ice bran^{50,51}.

The last product, i.e. (iv) starch, can be processed in one of the three ways: processed into corn syrup, dried and sold as corn starch or fermented into ethanol^{12,13,29,31,42,50}. The processes of cooking, fermenting and distillation are same as mentioned earlier in the process of dry milling.

Comparative studies between wet and dry milling showed that ~5% more ethanol yields with wet milling

process, dry milling process and the average oil content of germ was 10% more^{17,18,42}.

Pretreatment cost of directly fermentable sugar containing materials is less, whereas indirectly fermentable starchy materials need costly pretreatment to convert them into fermentable substrates⁵². Besides this, such resources cannot be considered as sustainable because they would be used as food first and not for fuel.

However, it may be noted that the lignocellulosics can also be converted into fermentable form similar to the manner in which starchy products can be processed. Moreover, this would involve certain technological challenges related to extracting and processing of the fermentable sugar that can then be converted into bio-ethanol^{53–65}.

Technological challenges

Based on the various technological options discussed in this article for the production of ethanol, Table 2 provides

a summary of the challenges that need to be addressed by technologists^{66,67}.

Challenges involved in large-scale bio-ethanol production

Socio-economic challenges: These include the following:

Food prices: The role of biofuels in increasing the price of food has already been debated earlier. It is estimated that ~30% increase in food prices can be attributed to the increased production of bioethanol in place of food, as more grains are required for more ethanol production causing increased price of grains. The prices of raw materials are expected to grow further by 30–40% by 2020 (refs 68–82).

Tenure and conflicts: The production of more ethanol requires more land and water. Such type of agricultural shift can reduce the production of other grains causing scarcity of food. The marginal lands that are being targetted are often inhabited and used by rural farmers for various subsistence purposes^{83–92}.

Lower fuel economy: The energy content of ethanol is less than gasoline; so increasing the percentage of ethanol in gasoline, most likely results in lower fuel economy. However, using 5–10% ethanol in the blend will have little or no impact on fuel economy^{93–104}. Further increasing the ethanol by ~20% reduces fuel economy ~1–3% (refs 105–114).

Environmental challenges: These includes the following:

Soil and water: It has been observed that mostly crops related to biofuel are highly water-intensive. Crops like tropical sugar beet and sweet sorghum can grow on soil containing less water content, but may require fertilizers and irrigation to become commercially profitable crops. In Brazil, sugarcane cultivation is a big consumer of agricultural pesticides, causing pollution of water ecosystems¹¹⁵.

Deforestation, climate change and ecosystem services: Deforestation often takes place due to large-scale monoculture biofuel production, which is a major threat to biodiversity. Intact savannas, forest and wetlands provide ecosystem benefits to people such as protection against extreme weather events, carbon storage, erosion and pollination needed for the production of other crops¹¹⁵.

Conclusion

Considering the multi-feed approach of bioethanol production as adopted worldwide depending upon the avail-

ability of a particular feedstock in a country or even a region, no universal process can be adopted. The seasonal nature of the renewable feedstock also forces one to adopt the multi-feed approach for ethanol production throughout the year. Irrespective of the technological and feedstock options available, a cost-effective and environment-friendly process is needed for the industry as well as society. Above all, an immediate priority of research in the field of ethanol production is to develop processes for the conversion of lignocellulosics into bioethanol with tenfold reduction in the cost by identifying microorganisms that can ferment both five- and six-carbon sugars and enzymes that break down cellulose directly into ethanol.

It is apparent that for the conversion of biomass to ethanol, the first step may be radiation processing of the biomass. So as far as the other steps of manufacturing ethanol from the residue biomass are concerned, the process seems well established. The emphasis would be on the improvement in the efficiency of the fermentation technology. The research efforts would therefore be directed towards realizing the expertise acquired so far in all the above-mentioned challenging areas.

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