

## ***New Generation Biofuels – Technology & Economic Perspectives***

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### **Abstract**

Biomass is unique among the entire renewable energy spectrum as it is the only source of carbon that can be converted into convenient solid, liquid, and gaseous fuels. The technologies for biofuels and bioenergy are developing rapidly and are fast becoming an important business area.

The use of biomass crops in producing fuels has many advantages viz. non-food crop of renewable nature, reduced green house gas production, recyclability of nutrients (lower inputs required), longer growing season (more carbon fixed) in some cases etc. As compared to fossil fuel, most of the biofuels are environmentally benign with the emission of very little sulfur and non-toxic chemicals. However, the development of bio-fuels from lignocellulosic biomass is a major step towards harnessing one of the world's most prevalent, yet least-utilized renewable energy resources.

Generally, second generation biofuels have the potential to improve land use and provide greenhouse gas savings compared to current, first generation technologies. The major drivers for promotion of such advanced biofuel technologies are rising energy prices, adverse impact on climate caused by the fossil fuels and their declining supplies in tandem with economic development & business growth. Biofuel also contributes significantly to energy security of a country. While the first generation biofuel processes such as conversion of sugar/starch to ethanol & oil seeds to fatty acid methyl ester (FAME) through transesterification processes are well established across the world, the industry remains in its infancy in case of second-generation biofuels.

Of the advanced biofuel processes, majority of the global R&D work is focused on the production of ethanol from lignocellulosic biomass. Various factors that affect successful emergence of biofuels industry include the extent of sustainable biomass supply, the kinds of products that can be produced, the nature of the conversion processes employed, the ability to efficiently extract the energy content of biomass, and the economics of large-scale plants to be built. Second-generation biofuel could be produced using a variety of non-food crops. The surplus biomass available in India viz. the stalks of wheat, rice, corn, pine needles, bamboo, sugarcane tops, cotton & chilli plant stalks, food-processing wastes etc. have been identified as potential non-food, non-feed bio-resources for their conversion into biofuels. The paper would discuss in detail the technology potentials for next generation biofuels such as thermo-chemical (pyrolysis & gasification) & bio-chemical (ligno-cellulosic ethanol) conversions, algal biodiesel etc. Towards improved process economics for biofuel production, synthesis of some value-added products from byproducts generated would also be covered in the paper. Indicative data on costs & prices of biofuel economics would be discussed.

The development of the advanced technologies for production of biofuels along with bio-chemical derivatives and integrating them with the existing biofuel production facilities could significantly enhance the viability of biomass processing industries. The success of the biofuel industry depends on having a large & sustainable supply of low cost, high quality ligno-cellulosic biomass and its complete utilization in an efficient manner.

Identifying this crucial need, Technology Information, Forecasting & Assessment Council (TIFAC), New Delhi and the National Institute for Interdisciplinary Studies on Science & Technology (NIIST), Thiruvananthapuram have conducted an in-depth nationwide study on current generation, consumption and availability patterns of surplus biomass from select agro & forest residues for their effective exploitation. The paper would also cover storage & transportation logistics for procurement of biomass.

## **Introduction**

Biomass refers to plant-derived organic matter generated through photosynthesis and other biological processes. It is a cost-effective energy source with the potential to greatly reduce greenhouse gas emissions. Agricultural & forestry residues and dedicated energy crops are among the major bio-resources available to the mankind. India has a large untapped biomass resources, which could offer sustainable solutions to many of the problems faced today. While use of residues would improve the local environment, plantation of energy crops on land not suitable for food crop production could improve rural economies. The most efficient utilization of these resources is conversion of biomass to energy by appropriate technologies. Biomass can directly be converted to energy or liquid & gaseous fuels such as ethanol, methanol, methane, and hydrogen. Biofuel production offers a solution to waste management as well, by converting waste into usable form of energy. In addition to three distinct perspectives of biofuels in the international context viz. energy security, GHG mitigation & business opportunities, the fourth dimension of augmentation of rural income & employment generation assumes importance particularly for developing countries like India.

India is the world's sixth largest consumer of energy. The demand of energy is estimated to grow by eight times by the year 2030 at the present growth rate of ~4.8% per annum. Every year India is losing substantial amount of foreign exchanges through import of crude fossil fuel, which caters to about 70% of the country's requirement. Biofuel is considered to be one of the potential alternative sources of energy that has caught attention of the world today. The sector has witnessed a continuous growth and developments over the last few years. The fluctuations in oil prices and production levels have heightened the need for further development of the sector. As the demand for biofuels continues to grow, more emphasis would be placed on producing a cost-competitive liquid transportation biofuel. The major issues concerning the technology development challenges include the utilization of multiple feedstock and optimization of process parameters, exploitation of by-products generated during the conversion processes, environmental & social impacts and economic feasibility.

Besides generating heat and electricity, biofuels are mainly used to supplement the traditional petroleum-based transportation fuels. The major products of the biofuels industry are ethanol and biodiesel. Biomass-based liquid fuels have good potential to succeed for transportation energy as it is relatively easy to introduce biofuels, independently or as a mixture with a fossil-based liquid fuel into existing internal combustion engines and distribution infrastructures.

Biomass utilization for generating biofuel can be of different types viz. biomass wastes from the food processing industry, agricultural & forestry residues such as straw, firewood, saw dust, rice husks, coconut shell, groundnut shell, pine needles, bamboo, sugarcane tops, cotton & chilli stalks etc., which can be either directly used as fuels for catering to the rural energy needs or gasified into producer gas. Besides this the biomass like biodegradable wastes from households, municipal sewage, and industrial refuse, etc. could be excellent sources for producing bio-gas (methane) for meeting the local energy needs. Gasification of the biomass into syn-gas ( $\text{CO} + \text{H}_2$ ) and its further conversion by Fischer-Tropsch process into synthetic fuels has been an established technology. Efforts are also underway for selective fermentation of the syn-gas into value-added biopolymers in the form of Poly-hydroxyalkanoates (PHAs).

Many developed countries have identified biomass as an ideal resource for partly substituting the fossil fuels especially for generating power. The energy crops such as miscanthus & willow (in UK), switch grass & poplar (in USA) have been good candidates for replacing coal to some extent in the thermal power stations. Specifically grown agricultural products for use as biofuels include corn & soybeans (in USA) and sugarcane (in Brazil) for their fermentation into ethanol. In the similar lines, flax & rapeseed (in Europe), palm oil (in South-East Asia) and non-edible oil seeds like jatropha, karanja (in India) are cultivated for conversion into bio-diesel by transesterification process.

The potential of first generation biofuels as oil product substitution, climate change mitigation and contribution to economic growth is limited. There are concerns over their sustainable production and the possibility of an undesirable competition for land and water used for food and fibre production. Due to competition with food crops, first generation biofuels are often considered to be contributing to higher food prices. These concerns have led to the efforts for technologies for new generation biofuels that can be produced from non-food biomass.

In 2007, the global biofuels market was estimated at USD46 billion and is projected to reach USD247 billion by 2020. The bioethanol segment represented nearly 85% of the total biofuels market. Global ethanol production is forecast to grow at a CAGR of 6% in the period 2009- 2018 to reach 33,895 million gallons. However, the technology is presently in the nascent stage with a total production capacity of 57.37 million liters, mostly in the 'pilot' or 'demonstration' stages. However, there are close to thirty plants globally which are either at the planning or construction phases; of these some are expected to be operational in 2010. India's first biorefinery based on sugarcane bagasse has been set up in Karnataka by Godavari Sugar Mills Ltd (GSML), Mumbai with technology support from National Chemical Laboratories (NCL), Pune.

Bio-based fuels are very susceptible to destabilization from low level metal contamination and such low levels are difficult to control through the supply chain. Metal deactivators can inhibit the catalytic effects of such ions. Fuel additives can impact the rate of reaction and when used properly will result in a very stable fuel. The Fischer-Tropsch technology and other advanced processes hold the potential to increase biofuels production. Global biodiesel production increased from 2 billion litres in 2004 to more than 12 billion litres in 2008 (six fold). Top producer in EU were Germany, France, Italy & Spain & other leaders were USA, Brazil & Thailand etc. EU had 185 biodiesel plants with a capacity of 10 million MTPA. Feedstock used included rapeseed (84%) & sunflower (13%). In USA, biodiesel production has been recorded as 2.8 billion litres in 2008. The biodiesel market is estimated to grow substantially over the years assuming development of & investment in synthetic biofuel production technologies.

## **2.0 New Generation Biofuels**

Many of the problems associated with first generation biofuels can be addressed by the production of biofuels manufactured from agricultural and forest residues, and from non-food crop feedstocks.

The new generation biofuels include *biomass to cellulosic ethanol*, *Bio-DME/methanol*, *Biosynthetic Natural gas (BioSNG)*, *Bio-oil/biocrude*, *algal biofuels*, *hydrocarbons from catalysis of plant sugars*, *biohydrogen*, *biobutanol* etc.

The ligno-cellulosic biomass has been identified as important feedstock for next generation biofuels. The advanced technology interventions dealing with the biomass conversions involve mechanical, thermal, chemical or biochemical processes. Two most promising pathways for biomass conversion are thermo-chemical & biochemical conversions. Biomass can be pyrolysed into bio-oil that can be fired into existing fossil fuel boilers, furnaces etc. with minimum modifications. The current research interest in the developed as well as in developing countries focuses on the pre-treatment & enzymatic hydrolysis of ligno-cellulosic biomass into sugars followed by their fermentation into ethanol. However, the development of bio-fuels from lignocellulosic biomass is a major step towards harnessing one of the world's most prevalent, yet least-utilized renewable energy resources.

The production of other value-added products would further enhance the economics of the process. The following section discusses in detail the second-generation bio-fuels conversion processes:

## **2.1 Biochemical Conversion Process**

The biochemical conversion process is an integration of pretreatment, enzymatic hydrolysis and fermentation. Pretreatment process is necessary to open up the structure of biomass to allow hydrolysis of cellulose to glucose. The process deals with the agricultural residues, energy crops and to some extent pulp & paper mill residues thus presenting a good potential for producing biofuels on large scales.

Biochemical conversion processes operate at lower temperatures and lower reaction rates and the pathway varies depending on the type of biomass feedstock. While the first generation feedstock viz. sugarcane, corn etc. has easily accessible sugars in the form of starch, the second generation feedstock i.e. ligno-cellulosic biomass must be pretreated before enzymes can break down the cellulose into fermentable sugars. The breakdown or hydrolysis of the cellulose is a complex step in the conversion process because of the cell wall, which is composed of matrix polysaccharides in order to minimize the accessibility of hydrolytic enzymes to the plant. This poses a challenge in the enzymatic hydrolysis and fermentation step during ethanol production. Biomass contains five-carbon sugars (usually D-xylose and L-arabinose) and six-carbon sugars (D-galactose, D-glucose and D-mannose) and uronic acid. Hemicellulose (C<sub>5</sub> sugars) consists of short, highly branched chains of sugars, which is difficult to hydrolyze into fermentable sugars. The major focus of today's research is improving ligno-cellulose (C<sub>6</sub> & C<sub>5</sub>) conversion into sugar by enzymatic hydrolysis. Further, metabolic engineering techniques are being used to develop the microorganisms that can more effectively ferment the variety of sugars derived from biomass to improve the ethanol production economics. Lignin, a polymer constructed of non-carbohydrate units, need to be separated from the cellulose and hemicellulose by chemical & other means and the separated lignin is used as binder in pulp & paper industries, road construction etc.

### **2.1.1 Pretreatment & Hydrolysis**

Pretreatment is carried out in order to weaken biomass recalcitrance either by breaking into the structure and increasing the surface area of exposed cellulose or by removing lignin and hemicellulose and exposing the cellulose. It is required to change the chemical composition of the cellulosic biomass to make it more accessible for further break down into its constituent sugars by use of acids, alkali, enzymes, etc. with higher yield. Pretreatment of biomass can be performed in a number of ways. The process involves breaking down of biomass into three components viz. cellulose, hemicellulose & lignin, which can be fermented or otherwise converted to fuels & value-added products.

The presence of lignin in lignocelluloses leads to a protective barrier that prevents plant cell destruction by microorganisms for conversion to fuel. In the production of biofuels, pretreatment assumes importance as it depends on the structure of the biomass substrate and the hydrolysis agent to be used at later stage. However, the selection of suitable pretreatment method must supplement the formation of sugars, avoiding the degradation or loss of carbohydrate & the formation of byproducts that are inhibitory to the subsequent hydrolysis and fermentation processes. The method should be cost-effective in order to improve the overall economics of the process.

The pretreatment methods are divided into different categories viz., physical pretreatment of biomass involving milling & grinding; physico-chemical involving steam explosion, auto-hydrolysis, hydro-thermolysis, wet oxidation; chemical method involving concentrated & dilute acid, alkali, oxidizing agents & organic solvents; biological; electrical; or a combination of these processes. Some of the major pretreatment methods commonly used are described below:

The physical pretreatment involves a combination of chipping (~10–30 mm), grinding(~0.2–2 mm) and/or milling to reduce cellulose crystallinity. The energy consumption is higher than the theoretical energy content available in the biomass in most of the cases and hence, the method is too expensive to be used in a full-scale process.

The physico-chemical pretreatment involves steam explosion, wherein the biomass is treated with high-pressure saturated steam, and then the pressure is suddenly reduced, wherein the materials undergo an explosive decompression. Steam explosion is typically initiated at a temperature of 160–260 °C (corresponding pressure, 0.69–4.83 MPa) for several seconds to a few minutes before the material is exposed to atmospheric pressure. The biomass/steam mixture is held for a period of time to promote hemicellulose hydrolysis, and the process is terminated by an explosive decompression. The process causes hemicellulose degradation and lignin transformation due to high temperature, thus increasing the potential of cellulose hydrolysis. The factors affecting the steam-explosion pretreatment are residence time, temperature, chip size, and moisture content. This method is recognized as cost-effective for hardwoods & agricultural residues, but it is less effective for softwoods. The limitations of the method include destruction of a portion of the xylan fraction, incomplete disruption of the lignin-carbohydrate matrix, and generation of compounds that might be inhibitory to microorganisms used in downstream processes.

In Ammonia fiber explosion (AFEX) process for pretreatment, lignocellulosic biomass is exposed to liquid ammonia at high temperature and pressure for a period of time, and then the pressure is suddenly reduced. The AFEX process is very similar to steam explosion. The operating conditions in typical AFEX process are the dosage of liquid ammonia is 1–2 kg of ammonia/kg of dry biomass, the temperature 60-90 °C, and the residence time is 30 min. The ammonia used in the process can be recovered and reused and washing step is not required during the process, which facilitates high solid loading hydrolysis. However, the AFEX process is not efficient for lignocellulosic biomass with relatively high lignin content.

In case of hydrothermal pre-treatment process, biomass is brought into contact with water at elevated temperature and pressure. The process could be auto-catalysed by the formation of acetic acid from the carboxylic acid groups present in hemicellulose.

In the organosolv pretreatment process, the biomass is treated with a mixture of an organic solvent and water at typically 150-200 °C and under pressure. Thus, the hemicellulose fraction of the biomass can be hydrolysed and the lignin is extracted from the matrix.

The chemical pretreatment method involves treatment with concentrated acids (such as H<sub>2</sub>SO<sub>4</sub> and HCl) to treat lignocellulosic materials. The acid concentration used in the process is ~ 10-30%, operating temperatures (~<50 °C) and atmospheric pressures are required during the concentrated-acid hydrolysis process. The process results in improvement of enzymatic hydrolysis of lignocellulosic biomasses to release fermentable sugars. However, the concentrated acids are toxic, corrosive, hazardous, and thus require reactors that are resistant to corrosion, which makes the pretreatment process very expensive. In addition, the concentrated acid must be recovered after hydrolysis to make the process economically feasible.

Dilute acid hydrolysis has been successfully developed for effective pretreatment of lignocellulosic materials. It uses high temperatures (160-230 °C) and pressures (~10 atm) because of the low yields of sugar from cellulose. The concentration of sulfuric acid ~ 2-5 %, has been used. Dilute acid effectively removes and recovers most of the hemicellulose as dissolved sugars, and glucose yields from cellulose increase with hemicellulose removal to almost 100% for complete hemicellulose hydrolysis. The disadvantages of the acid-pretreatment method are equipment corrosion and the formation of toxic substances in the process.

Alkali pretreatment processes utilize lower temperatures and pressures than other pretreatment technologies and the effect of alkaline pretreatment depends on the lignin content of the materials. Compared with acid processes, alkaline processes cause less sugar degradation, and many of the caustic salts can be recovered and/or regenerated. The limitations of the method are long residence times and formation of the irrecoverable salts in the process.

Biological treatment involves use of microorganisms to degrade lignin and hemicellulose in waste materials. The method is a safe and environmentally friendly and is increasingly being used that does not require high energy for lignin removal from a lignocellulosic biomass, despite extensive lignin degradation. However, the rate of hydrolysis is quite low.

## **2.2 Thermo-chemical Conversion Process**

In thermo-chemical conversion, biomass is converted into gas & liquid intermediates that can be used for fuels and chemical synthesis. The term Biomass to Liquid (BtL) is applied to synthetic fuels produced from biomass via thermo-chemical route. The objective is to produce fuel components that are similar to those of current fossil-derived petrol (gasoline) and diesel fuels and hence can be used in existing fuel distribution systems and with standard engines. They are also known as synfuels. Although the processes for production of BtL are well known and have been applied using fossil-feedstocks, such as methane (GtL) or coal, commercial biofuels based on these technologies are not currently available in the market.

The processing technologies can be categorized as gasification, pyrolysis, or hydrothermal processing. Intermediate products include clean syngas ( $\text{CO} + \text{H}_2$ ), bio-oil (pyrolysis or hydrothermal product), and gases rich in methane or hydrogen. These intermediates can further be synthesized to gasoline, diesel, alcohols, ethers, synthetic natural gas etc. and also high-purity hydrogen, which can be used as fuels and electric power generation.

### **2.2.1 Gasification**

If the gasification of biomass takes place at a relatively low temperature ( $\sim 700^\circ\text{C}$  to  $1000^\circ\text{C}$ ), the product gas will have a relatively high level of hydrocarbons which could be burnt directly for heat or electricity generation via a steam turbine or, with suitable gas clean up, to run an internal combustion engine for electricity generation.

### **2.2.2 Fischer-Tropsch Process for Liquid Fuels**

In case of high temperature gasification ( $1200^\circ\text{C}$  to  $1600^\circ\text{C}$ ), it leads to few hydrocarbons in the product gas, and a higher proportion of  $\text{CO}$  &  $\text{H}_2$ . If the ratio of  $\text{H}_2$  to  $\text{CO}$  (syngas or biosyngas) is 2:1, Fischer-Tropsch (FT) synthesis could be an option to convert syngas into high quality synthetic biofuels which are fully compatible with conventional fossil fuel engines. FTL processes use catalysts based on Iron, Cobalt, Ruthenium, and Potassium, and have been extensively characterized, operate at high pressures (2.50 - 4.50 Mpa) and temperatures (between  $220^\circ\text{C}$  and  $450^\circ\text{C}$ ). The process can co-produce electricity, heat, and a liquid fuel. However, the multistage process requires high capital cost resulting in considerably high cost of biofuels thus making the process economically unviable.

### **2.2.3 Pyrolysis**

Biomass pyrolysis is the thermal depolymerization of biomass at modest temperatures in the absence of added oxygen. The steps in pyrolysis process include feedstock preparation and introduction into the reactor, carrying out the reaction by application of heat or addition of other reactants such as air, oxygen, steam, hydrogen, post combustion or processing of the gases produced during the reaction step, and the management of the resulting liquids, char, and ash.

### **2.2.4 Fast Pyrolysis**

The products from the fast pyrolysis process include gases, bio-oil, and char. The products of the process depend on the process temperature, pressure, and residence time of the liberated pyrolysis vapors. The production of bio-products is maximized by fast pyrolysis, typically performed at temperatures (~450 - 500°C) at atmospheric pressure, high heating rates (i.e., 500°C/sec) and short residence times (1-2 sec) produce substantial yields of bio-oils that retain upto 70% of the energy present in the biomass feedstock prior to processing. The major limitations for use of fast pyrolysis bio-oil for production of liquid transportation fuels is its high oxygen content & high acid number, which cause corrosion in standard refinery units. Hence to make the oil more compatible and to address the aforesaid problems, the oxygen needs to be removed & the bio-oil needs to be efficiently pre-processed.

### **2.3 Bio-Hydrofined Diesel (BHD)**

BHD, a hydrocarbon produced by hydrogenation of palm oil, is nearly identical to conventional diesel. The initial problems associated with poor cold flow properties have been improved by Nippon Oil Corporation using hydroisomerization technologies through isomering BHD into iso-paraffin, having branched chain in its molecular structure, at elevated temperature. It has superior oxidation stability compared to Fatty Acid Methyl Ester (bio-diesel) due to hydrogenation of the unsaturated carbon bonds. In recent years, the industrial practicality of BHD technology has been demonstrated and the technology is approaching the commercialization stage faster than the second generation lignocellulose-to-ethanol technology. Due to higher resistant to than conventional biodiesel oxidation, Bio-hydrofined diesel could have higher concentrations in diesel blends. Moreover, in BHD production, process allows the raw materials viz. vegetable oil, animal fat and used cooking oil to be processed together.

### **2.4 Biohydrogen**

Hydrogen, used mainly as transportation fuel and for decentralized power generation, can be produced from fossil fuels as well as renewable sources e.g. biomass. This promising clean fuel when used in fuel cells can yield high-electrical efficiencies with zero emissions. Methane, produced by anaerobic digestion of organic wastes, could be converted into hydrogen through steam reforming process. Bio-hydrogen can be produced through fermentation of biomass by microorganisms either in presence of light (photo fermentation) or in absence of light (dark fermentation). Currently research is underway to increase yields of hydrogen from various strains of bacteria. Bio-hydrogen can also be produced by algae (e.g. *Chlamydomonas reinhardtii*) under anaerobic conditions.

### **2.5 Biodiesel**

The production of biodiesel from non-edible vegetable oil & animal fats involves mainly three steps i.e. raw material preparation, oil extraction and processing of oil. Transesterification of vegetable oil has been the commercially proven technology for the production of biodiesel. The process commonly uses methanol to produce bio-diesel (methyl esters) in presence of alkali catalyst. However, higher molecular weight alcohols

such as iso-propanol and butanol have also been used for improving the cold flow properties of the resulting ester. Unlike straight vegetable oil, transesterified bio-diesel has combustion properties very similar to those of petro-diesel and can be blended up to 20% with petro-diesel in the existing vehicles without any major modifications.

To promote the conversion of non-edible vegetable oil to bio-diesel, Govt. of India has identified oils from *Jatropha Curcas* or *Karanja* seeds as the feedstock. In recent years, great hopes have been pinned on *Jatropha* as a source of bio-energy which can be grown in sub-humid to semi-arid climates in India. Extensive work had been carried out in the country to demonstrate *Jatropha* plantation, extraction of oil from *Jatropha* seeds, its transesterification, application of bio-diesel in automobiles & locomotives blended with petro-diesel etc.

India's biodiesel processing capacity is estimated at 200,000 MTPA but the majority of biodiesel units is not operational most of the year. Commercial production & marketing of biodiesel is negligible due to lack of availability of *jatropha* and other non-edible oilseeds. Reliance Life Sciences plans an integrated biorefinery primarily for R&D purpose with an end-to-end process from growing *jatropha* to biodiesel manufacturing to byproduct utilization.

## **2.6 Green Diesel**

The green diesel can be synthesized from the lignocellulosic biomass by controlled catalytic depolymerization at a temperature of  $>300^{\circ}\text{C}$ , which is much lower than that required for conventional pyrolysis process at  $700^{\circ}\text{C}$ . The said catalytic process of cellulosic biomass conversion would result into 30-40% diesel, 40% water, 20% carbon dioxide and 3% ash. Technologies such as biomass reforming can be used to provide hydrogen for reduction of components of cellulosic biomass, such as sugars, as well as lignin fractions of biomass, into gasoline or diesel range hydrocarbons. In some cases, the small biomass fragments need to be coupled for higher molecular weights. Green diesel can also be prepared via the catalytic deoxygenation of fatty acids derived from virgin or waste vegetable or animal oils. The same oils can be transformed into biodiesel by a transesterification reaction with methanol. Germany based Alphakat GmbH has developed a new kind of FCC reactor and a catalyst (based on zeolite) for controlled cracking of biomass to obtain diesel. The company has set up its first green diesel plant based on the aforesaid technology using waste oil feedstock in Mexico in 2004. A pilot plant of 50 liter / hour capacity, which would be scaled up further in future, is being set up by Nandan Biomatrix Ltd. in partnership with Alphakat at Zaheerabad near Hyderabad. The proposed plant would use lignocellulosic feedstock (pruned *jatropha* woods, branches, leaves etc.). The cost of green diesel is quite competitive with the cost of petro-diesel. During the controlled catalytic cracking, 90% of the biomass would be realized as diesel whereas balance 10% would be converted to lighter gases, such as  $\text{CO} + \text{H}_2$ . These lighter gases would be used for running DG set to generate power for the reactor. The amount of carbon dioxide and water produced as by-products could also be a good source for cultivating algae by capturing the emitted carbon dioxide. The ashes obtained in amorphous state (as conversion temperature is low) can be used as fertilizer.

## 2.7 Biobutanol

Biobutanol, an advanced biofuel, offers a number of advantages over ethanol and can help accelerate biofuel adoption in countries around the world. It has a higher calorific value, it is less hydrophilic than ethanol less corrosive and can be transported via pipeline integrated in the existing petroleum fuels infrastructure and it can be added to gasoline at higher levels without engine modification. The biobutanol can be used directly as a fuel component or further processed into renewable gasoline, diesel, jet fuel or chemicals.

Biobutanol is produced by a microbial fermentation and can be made from sugar, starch or cellulosic feedstocks. Historically it has been produced through acetone-butanol-ethanol (ABE) fermentation process. There have been modifications undertaken by researchers worldwide to improve the yield of biobutanol from the ABE process. One such modification has been developed by the *University of Illinois* and licensed to US based Co., *Tetravita*. It incorporates an improved microorganism (*Clostridium beijerincki* BA101) and a gas stripping system for in situ product removal. Another such process is based on a combination of patents from Gevo and DuPont. It incorporates a novel pathway for the production of isobutanol by a solvent-tolerant microorganism developed by Gevo and a recovery process based on a DuPont patent application. Neither process is commercial but in the demonstration phase.

Cobalt Biofuels expects to build a 10,000-35,000 gal/year pilot plant by 2010. Between 2010 and 2011, the company hopes to build a demo-scale plant with a capacity between 2m and 10m gallons/year, and to proceed to a commercial plant by 2012. Cobalt uses non-food feedstock, such as forest waste and mill residues, and the company claims that its technology reduces greenhouse gas emissions by 85 percent compared to gasoline.

Reliance Life Sciences, division of Reliance Industries Ltd., Mumbai has been working on producing biobutanol using renewable feedstocks. They have developed a solvent tolerant strain producing 20 gms/lit of butanol in a single batch process without solvent stripping.

n-Butanol consumption amounted to 2.8 million tons in 2006. Primary current uses of n-butanol are butyl acrylate and methacrylate esters, accounting for about 46 percent of the total n-butanol demand. Consumption of n-butanol is forecast to grow @ 2.1 % PA between 2006 and 2020. Growth is relatively moderate in all regions except Asia, where consumption continues to grow and outpaces local supply.

## 2.8 Algal Biofuels

Algae and aquatic biomass have the potential to provide a new range of third generation biofuels, including jet fuels. Their high biomass and oil yields, widespread availability, negligible competition with agricultural land, high quality and versatility of the by-products, their efficient use to capture CO<sub>2</sub> and their suitability for wastewater treatments and other industrial plants make algae and aquatic biomass most promising and attractive renewable sources for a fully sustainable and low-carbon economy

portfolio. In 2008, the US Department of Energy noted that algae could produce 30 times more energy per acre than land crops such as soybeans.

Microalgae use non-arable land, water, carbon dioxide (CO<sub>2</sub>), nutrients, sunlight and do not compete with food or other crops resulting in economic & social benefits to mankind. Most importantly, CO<sub>2</sub> is fixed by the microalgae as it grows, thus helping recycle its carbon emissions. Carbon dioxide is absorbed to the tune of 50% of the weight of micro-algae. The biofuels plants from algae may be developed on land adjacent to thermal power stations & cement plants for converting the CO<sub>2</sub> trapped from exhausts into fuel. Productivity of microalgae is higher in the controlled & contained environment of a photobioreactor, but the investment in terms of capital equipment & operational cost is both substantially higher compared to open pond systems. Hence, significant research work is needed for establishing high levels of guaranteed productivity on a commercial scale.

Indian Oil Corporation has signed an MoU with Florida based green fuel company, PetroAlgae to license the latter's proprietary technology for producing and harvesting algae. PetroAlgae has developed bioreactors & harvesting methods for converting algae grown in open-pond fresh water farms into biodiesel. On successful completion of building test facility in the first phase, Indian Oil plans to build a commercial production facility for 200,000 MTPA of biodiesel as well as to produce a protein byproduct for use in animal feed.

### 3.0 Biofuel Economics

#### 3.1 Biodiesel

One litre of jatropha biodiesel priced at USD0.53 in India is comparable with the current prices in Germany (one litre of rapeseed based biodiesel priced at EUR 0.55). The price would compare more favorably considering use of fallow land and absence of any subsidy to Indian farmers. The selling of by-products i.e. glycerin for industrial use and seed cake as manure can bring in additional profits for the producers. Technology development challenges exist for detoxification to use the seed cake as animal feed and also for extracting more oil out of it for better yield. All these efforts can result into reduction of price for biodiesel.

**Table – 1.0 : Final selling price of bio-diesel after factoring in returns from selling by-products**

Item	Value	Remarks
Factory cost of one litre of bio-diesel (USD)	0.53	
By-product glycerol (USD)	0.08	(0.095 l per l of bio-diesel, USD 0.08 per l)
By-product seed cake (USD)	0.05	(2.1 kg per litre of bio-diesel at USD 0.05 per kg)
Net cost per litre of bio-diesel (USD)	0.40	(0.53–0.08–0.05)

*(Source: A concept for simultaneous wasteland reclamation, fuel production, and socio-economic development in degraded areas in India: Need potential and perspectives of jatropha plantations by George Francis, Raphael Edinger & Klaus Becker, Natural Resources Forum 29 (2005) Pg.12-24)*

An indicative capital investment required for biodiesel plant based on Jatropha oil is as follows:

- Optimum plant size : 10,000 MTPA
- ROI : 15% (pretax) on capital cost employed
- Feedstock cost : 80% of operating cost of biodiesel
- Capital cost : @Rs.15,000-20,000/- per MT of biodiesel

Assuming the following yields of Jatropha:

- Yield of seeds per tree: 12 kg (from 30 kg fruits)
- No. of trees per hectare: 400 Nos.
- Seeds per hectare of land: 4800 kg

The following indicative cost & pricing would broadly show the economics of Jatropha based biodiesel (basis 100 kg seeds of Jatropha):

Assuming 100 kg seeds @Rs.5/- per kg:	Rs.500/-
Cost of oil extraction @Rs.1.50 per kg:	Rs.150/-
Transesterification cost @Rs.8/- kg oil: (Assuming 30 kg oil / 100 kg of seeds)	Rs.240/-
TOTAL Cost:	Rs.890/-
Assuming price of biodiesel @Rs.25/- per lit.: (assuming 30 kg oil gives 30 kg or 33 lt. biodiesel)	Rs.825/-
Price of glycerin @Rs.20/- per kg: (assuming 3 kg glycerin produced from 30 kg oil)	Rs.60/-
70 kg oilseed cake @Rs.2/- per kg:	Rs.140/-
TOTAL Price:	Rs.1025/-
Margin:	Rs.135/-

### 3.2 Bio-ethanol

Comparing the cost of biofuels from different sources and processes is very complicated. Production costs are uncertain and vary with the feedstock available. Rarely same bases of economic evaluations are considered in different studies. Differences in assumed plant size, biomass costs, method of project financing, and even the year in which analysis were performed can skew comparison.

**Table – 2.0 : Indicative biofuels yield from biochemical & thermo-chemical conversion routes**

Process	Biofuel yield (litres/dry ton of biomass)		Energy content (MJ/l)	Energy yield (GJ/ton)	
	Low	High	Low heat value	Low	High
Enzymatic hydrolysis ethanol	110	300	21.1	2.3	6.3
Thermo-chemical Syngas-to-Fischer Tropsch diesel	75	200	34.4	2.6	6.9
Syngas –to-ethanol	120	160	21.1	2.5	3.5

Source: Mabee et al. 2006, ORNL,2006, Putsche, 1999

Enzyme hydrolysis could be expected to produce up to 300 l ethanol/dry tonne of biomass feedstock whereas the Biomass to Liquid (BtL) route could yield 200 l of synthetic diesel per tonne. Similarly, the overall yield in energy term (~6.5 GJ/ton) is because synthetic diesel has a higher energy density by volume than ethanol.

A study conducted at the Iowa State University showed that capital costs for plant with 150 million litres of gasoline equivalent capacity range from around USD111 million for a conventional grain ethanol plant to USD854 million for an advanced Fischer Tropsch plant. However, the differences in the final cost of the fuel was less severe, being USD1.74 for grain ethanol (with corn cost USD3.00 per bushel) and USD1.80 for cellulosic biofuel (with biomass cost USD50 per ton).

The commercial scale production costs of second generation biofuels have been estimated by the IEA in the range of USD 0.80 –1.00/litre of gasoline equivalent (lge) for ethanol and at least USD 1.00/litre of diesel equivalent for synthetic diesel (when the crude oil price is between USD 100-130/bbl). Given that second generation biofuels are still at the pre-commercial stage, widespread deployment would be expected to lead to the improvement in technologies, reduced costs from plant construction and operation experience etc. The potential for cost reductions is likely to be greater for ethanol produced via the biochemical route than for liquid fuels produced by the thermo-chemical route, because much of the technology for BtL plants (based on Fischer-Tropsch process) is mature and the process mainly involves linking several proven components together. Hence, there would be limited scope for further cost reductions. However, if the commercialization succeeds in the 2012-2015 time frame and rapid deployment occurs worldwide beyond 2020, then costs could decline to between USD 0.55 and 0.60/lge for both ethanol and synthetic diesel by 2030. Ethanol would then be competitive at ~70/bbl

**Table 3.0 –Feedstock production, costs, and emissions data for bioethanol and biodiesel production**

<b>Performance</b>	<b>Bioethanol</b>		<b>Biodiesel</b>
Feedstocks	Sugar cane	Ligno-cellulosic	Vegetable oils
Fossil energy input (%)	10-12	(a)	30-40
Co-products	Heat and power	Heat and power	
Production cost (USD/lge)	0.3-0.5	1.0 (b)	0.7-1.0 (USD/lde)
<b>Environmental Impact</b>			
CO <sub>2</sub> reduction (%c)	90	70	40-60
Pollutant abatement	CO	CO, NO <sub>x</sub>	SO <sub>x</sub> , particulates
Land use (lge/ha)	3000-6000	Na	700-1300 lde/ha (3000 palm)

a) Energy input may be higher than final ethanol energy, but most such energy comes from the biomass itself. (b) Twice gasoline cost at \$ 60/bbl. (c) Compared with gasoline (2.8 kg CO<sub>2</sub>/l) or conventional diesel.

Source : <http://www.iea.org/techno/essentials2.pdf>

Currently ligno-cellulosic ethanol costs around USD1.00/lge at the pilot scale, assuming a basic feedstock price of USD3.60/GJ for delivered biomass. The cost is projected to halve in the next decade with process improvement, scaling up of plants, low-cost waste feedstock and co-production of other by-products (bio-refineries). Biodiesel production

depends on feedstock and land availability even more than bioethanol production. The Fischer-Tropsch BTL technology and other advanced processes hold the potential to increase biofuels production basis.

Costs of biofuels are highly dependent on feedstock, process, land and labour costs, crop yield, credits for byproducts, agricultural subsidies, food (sugar) and oil market. Ethanol energy content by volume is two-thirds that of gasoline, so costs refer to litre of gasoline equivalent (lge).

**Table 4.0 : Cost comparison of biofuels from various sources**  
(figures only indicative)

Sugar-cane ethanol (Brazil)	USD0.25-0.35/litre of gasoline equivalent (lge), competitive with gasoline at USD40-50/bbl oil prices
Ethanol from corn (US) and sugar-beet (EU)	USD0.60- 0.80/lge
Ligno-cellulosic ethanol	Presently over USD1.00/lge (feedstock price USD3.60/GJ) with potential reduction to USD0.50/lge in the next decade
Biodiesel from animal fat	USD0.40-0.50/lde
Biodiesel from vegetable oil	USD0.60-0.80/lde
Biodiesel from BTL	> USD0.90/lde.

#### 4.0 Future Perspectives

Production costs for biofuels are uncertain and vary with the feedstock available. There is no clear candidate for “best technology pathway” between the competing biochemical and thermo-chemical routes. For biochemical route, the technology agenda includes improvement in feedstock characteristics, cost reduction in pretreatment process, improvement in efficiency of the enzymes and cost lowering in their production and improvement in the overall process integration. On the other hand, there are much less technical hurdles to the thermo-chemical route since much of the technology is already proven. But perfecting the gasification of biomass reliability at reasonable cost is yet to be achieved, although good progress is being made. Additionally, there are perhaps fewer opportunities for cost reductions.

A large commercial scale plant needs secured quantity of feedstock supply at a reasonable delivered cost at the plant site in order to become economically successful. Considerably more investment in R&D and technology demonstration & deployment is needed to ensure that in future the sustainable production of various biomass feedstocks can be undertaken by choosing the preferred conversion technologies which are at more advanced R&D stage and proven to be viable.

New developments in the production processes of the new generation biofuels are taking place, and hence they should have good potential for cost reductions and increased production efficiency levels as more experience is gained. Making biofuels economically viable would require the optimum utilization of the biomass, not only for production of fuel, but along with it value -added bioproducts or energy that may be derived from the

process. This has led to the concept of biorefineries. Biorefineries can make a significant contribution to sustainable development by adding value to the sustainable use of biomass. They can produce a spectrum of bio-based products (food, feed, materials, chemicals) and bioenergy (fuels, power and/or heat) feeding the full Bio-based Economy. This should be realized by maximizing biomass conversion efficiency, so minimizing raw material requirements, while at the same time the economic positions of various market sectors (e.g. agriculture, forestry, chemical and energy) are strengthened.

## 5.0 Conclusion

Biofuels are increasingly being regarded as an important source of energy with potential to address several aspects such as environmental degradation & climate change, energy security, rural development and business opportunities.

In the backdrop of food vs. fuel debate for existing grain based ethanol, cellulosic biofuels is considered to be the ultimate solution. However, it would need to overcome the major technological barriers towards lower capital investment for cellulosic plants to make it cost competitive with the conventional biofuel systems for wide scale commercialization.

TIFAC under its Bioprocess & Bioproducts Programme has supported National Institute for Interdisciplinary Science & Technology (NIIST), Trivandrum to establish a dedicated **Centre for Biofuels** to carry out advanced research in ligno-cellulosic ethanol production along with the development of other bio-chemicals for improved process economics to address some of the critical technology issues in the sector. For assessing the feasibility and sustainability of producing biofuels and other bio-chemicals from biomass in India, a clear understanding of the current generation of biomass, consumption and availability patterns of surplus biomass from select agro & forest residues was needed. Further, the storage, transportation and procurement practices of such biomass resources also needed to be understood.

With this background TIFAC & NIIST commissioned the nationwide study on '**Availability of Indian Biomass Resources for Exploitation**'. Keeping in mind the shortage of cattle fodder in India, it is unlikely that the biomass would be available in large amounts for biofuel production unless specifically grown for that purpose. Hence, the aforesaid study focused on non-fodder crops like *sugarcane tops*, *cotton crop residue*, *chilli crop residue*, *pulses crop residue*, *oilseeds crop residue (select)* and *bamboo residue*. These residues are typically burnt in the fields or used to meet household energy needs by farmers. An interesting findings emerged from the study as, **sugarcane tops** is the most surplus residue as it is mostly burnt in the fields itself. Other fuel crops like **cotton, chilli, pulses and oilseeds** generate surplus because they do not have much other use apart from fuel. An estimated **164.5 MMT** of surplus crop residue was available in 2007-08. This is 26.4% of overall generation. Sugarcane tops are by far the highest available surplus crop residue followed by oilseed residue, cotton stalk, rice straw and wheat straw. An additional 4 MMT of main bamboo plant would be available as potential biomass. Based on the study finding, it was observed that Uttar Pradesh, Haryana and Tamil Nadu are leading states based on per sq. km availability of biomass.

Biofuels carbon emissions can be offset by the carbon uptake of their feedstocks. As plants grow, they absorb carbon dioxide from the atmosphere whereas fossil fuel production and utilization removes carbon from the Earth's crust and introduces it to the atmosphere, where it will contribute to global warming for centuries. However, a detailed Life Cycle Assessment (LCA) would need to be studied for biodiesel and ethanol systems in Indian context to establish the carbon neutrality, energy balance and impact on land & water use.

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