Biomass to fuel: the uncertain path

The diversity of materials that can be used as sources of energy, the variety of energy-rich end products that can be obtained through different methods of processing biomass and the vast array of scientific, social, economic and other challenges that need to be addressed[1] make working with biofuels formidably complex. Biofuels research is especially important for a country like India, which ranks sixth in the world in terms of energy demand[2], and satisfies almost 80% of its energy needs by importing fossil fuels[1]. The large rural population in the country adds to the gravity of the situation: 'While the energy demand is expected to grow at 4.8% a year, a large part of India's population, mostly in the rural areas, doesn't have even access to it', say Linoj Kumar and Ram Mohan of The Energy and Resources Institute (TERI), New Delhi[2].

A quick look at history tells us that using materials other than fossil fuels as energy sources is not new. For centuries, women in countries like India have been burning wood, charcoal and cow dung for cooking. It is said that Rudolf Diesel used groundnut oil to power his engine, in the late 19th century (http://www.cyberlipid.org/glycer/biodiesel.htm), and Henry Ford designed a car powered by ethanol around the same time[3]. S. Dasappa (Indian Institute of Science (IISc), Bangalore), who works on biomass gasification, says that the technology for gasification existed even during the Second World War, but people 'forgot' it after petroleum oil became available. The possibility of using biomass for energy production was revisited during the fuel crisis in the 1970s (ref. 4). After repeated 'relapses' into the habit of depending on petroleum products and coal for everything from transport to agriculture and industry, the world is now again awakening to the possibility of using biomass, and organisms ranging from fungi and algae to angiosperms to generate fuels (Figure 1). Biofuels also seem to have advantages when compared to other renewable sources of energy, such as solar and wind power. As Andrew Carroll (Stanford University, California, USA) says, 'Solar power and wind power are both difficult to scale up and both produce electricity but neither can produce liquid fuel. It is very easy to scale biofuels – a single plant can process material from a 60 km radius, and far more people know how to grow crops on those 60 km than know how to build and install solar plants or wind turbines on them. Wind and solar are both very promising, but there are limits on how quickly they can be deployed' (pers. commun.).

One of the most widely used biofuels today is ethanol – it constituted 94% of all biofuels used in the world in 2006. Brazil has shot into prominence in the last few years thanks to its success in bioethanol production – till 2006 it remained the world's largest producer of ethanol for fuel (USA overtook Brazil that year)[5]. In 2009, USA produced 10,600 million gallons of fuel ethanol, and Brazil produced 6,578 million gallons – together they accounted for 88% of the fuel ethanol produced that year. The Indian bioethanol production in 2009 was about 92 million gallons (http://cta.ornl.gov/bedb/biofuels.shtml).

The feedstock for ethanol production is different in different regions of the world. While in Brazil sugarcane is the main crop used for the purpose, in USA, it is mainly corn (in 2009, more than 98% bioethanol production in the US depended on corn, either alone or in conjunction with other cereals such as wheat (http://cta.ornl.gov/bedb/biofuels.shtml)). The dependence of the US on corn for ethanol production has invited a lot of criticism, with concerns being raised about crops meant for food being diverted into fuel production, and the increasing demand for resources such as land, water and fertilizer; a recent article in *Nature* complains that 'The use of corn grain for ethanol in the United States more than tripled from 2005 to 2010, and more than a third of the US corn crop now goes to ethanol facilities' and that 'In the United States, the production of corn ethanol is polluting surface water and groundwater, while undermining existing efforts to ensure long-term agricultural productivity'[6]. Further, as Ramesh Maheshwari has mentioned[3], 70% more energy is required to process corn into ethanol (for processes such as harvesting, transportation, refining, etc.) than what is ultimately obtained from it. But cultivation and transport costs are not problems limited to corn alone. That is why, 'It is ideal to produce all the biomass required for biofuel production within as small a radius as possible' (Andrew Carroll, pers. commun.).

Interestingly, the food versus fuel problem does not seem to have affected Brazil much. Marcos Buckeridge, a researcher at the University of Sao Paulo, Brazil, working on the response of sugarcane to climate change, describes the situation there: '... the current pro-

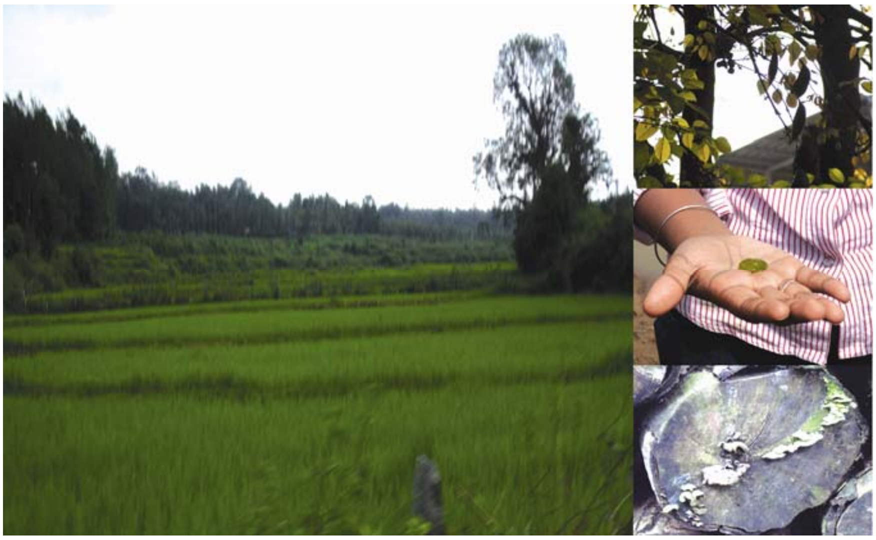

Figure 1. Scientists are trying to harness a wide range of organisms in their endeavour to produce biofuels – ranging from angiosperms such as crop plants rich in sugars and trees such as *Pongamia* that bear oil-rich seeds, to algae and cellulose decomposing fungi.

duction of bioethanol does not compromise food production at all, as we are using less than 1% of the agriculturally usable land area in the whole country. Furthermore ... the exports of ethanol needed for 2017 will be ca. 8.3 billion litres. Considering the actual internal demand ... the impact on land area expansion in Brazil due to sugarcane is likely to be very mild. Furthermore, one has to remember that we are constantly producing new varieties and there are several initiatives in Brazil ... focused on improving productivity of sugarcane[7].' David Lapola (University of Kassel, Germany) summarizes the differences between Brazil, USA and India: 'In Brazil it is less likely that the production of biofuels would affect the production and prices of food because the country still has large tracts of under-used land (like poorly managed pastures) which could support the biofuel expansion. On the other hand, India is a country that uses almost all its agricultural land (with almost no pasture). Therefore any expansion of the production of biofuels would certainly affect food availability and/or prices. The US situation resembles India's case because it seems like the diversion of corn to produce biofuel instead of food or feed causes changes (in some occasions, depending also on external factors like the world corn market prices) in food and feed corn' (pers. commun.).

Many scientists like P. T. Vasudevan (University of New Hampshire, USA) believe that it is unwise to produce biofuels from edible sources (pers. commun.). At present, Indian ethanol production depends on sugarcane molasses[8], though there have been attempts to use other crops like sweet sorghum, that are much more economical and much less draining on the country's land and water resources[9]. Researching alternate sources for ethanol production is important since, as David Lapola who has studied the biofuel scenario in India[10] says, 'Increasing the production of sugarcane ethanol in India is nearly unfeasible, because the country has a huge demand for sugar, and therefore, the sugarcane plantations are all used for sugar production. And increase in cropland in India would get stuck due to the lack of good land for plantations' (pers. commun.). Andrew Carroll also feels that food crops must not be used for biofuel production: 'The main risk, I feel, is to be certain that production of biofuel crops does not compete with production of food crops. This means that biofuels should be made either with waste products (and care must be taken that their use does not degrade the land), or must be produced from lands that are too degraded to have reasonable yields of food crops. Ideally, an expansion of the use of biofuel crops will be accompanied by an intensification of agricultural production', he says (pers. commun.).

Harnessing agricultural wastes, wood shavings and other such cellulosic materials for ethanol production may be a good solution[11], but one needs to exercise caution while using agricultural wastes for biofuel production. As Deepak Rajagopal (Institute of Environment and Sustainability, University of California, Los Angeles, USA) says, 'One has to be careful with agricultural residues since their current uses for soil replenishment, for producing heat, for fodder, etc. may be affected. A better approach may be investigating the potential of waste vegetable oil from restaurants and municipal solid waste in urban areas. Given the poor separation and recycling rates of waste, the landfill concerns, and the high density of waste in Indian urban areas, these alternative sources could be a win–win approach in terms of providing energy, creating jobs in collection and management, reducing soil and water contamination and improving public health' (pers. commun.). 'There is a weed called *Prosopis juniflora* in Tamil Nadu; it is a rampant problem in Ramanathapuram district and various other places. Many of the municipalities pay to eradicate it. But it can become an input for power generation,' suggests Dasappa[4], indicating another 'win–win' situation. Mere usage of the cellulosic waste generated in India might go a long way in ensuring energy security of the country. As Linoj Kumar and Ram Mohan have pointed out, '... cellulose residues in the country come to around 800 million tonnes... . If 10% of this potential can be exploited, around 15 billion litres of ethanol can be produced with 60% conversion efficiency'[2].

Carroll and Somerville[12] suggest using sugarcane bagasse and the cultivation of *Mischanthus* spp., switchgrass (*Panicum virgatum*), *Leucaena leucocephala* and other plants for obtaining cellulose for ethanol production. Grasses such as some of those mentioned above are not only considered better sources of cellulose than agri-residues[13], but have other advantages too – many of them have deep root systems that trap fertilizers applied to agricultural fields and thus help reduce water pollution, the roots also sequester carbon and thus help in the fight against climate change[6]. Talking about the sustainability of such sources of cellulose, Carroll says, 'The grasses we discuss in our paper[12] are quite sustainable over the long term, requiring minimal inputs and increasing carbon content in the soil (if harvested properly). Using industrial wastes from paper milling is obviously sustainable. Using agricultural wastes needs to be looked at closely. If agricultural wastes are used, care must be taken to return the nutrients to the land that were removed when the waste was taken for processing. For syngassing this means returning at least some of the char to the land, for cellulosic plants this might mean separating as much NPK from the biomass as possible. In addition, some use of fertilizers may be necessary to offset the removal of agricultural material' (pers. commun.).

Lignocellulosic biomass has proved to be exceptionally difficult to be converted to ethanol[14]. Some researchers have explored the possibility of exploiting fungi, with their amazingly diverse enzyme arsenal, to tackle the problem. Cellulase producing fungi such as *Trichoderma reesei*, *Chrysosporium lucknowense*, *Penicillium funiculosum* and *Sporotrichum thermophile* have been studied with the hope that some of them might be used for releasing sugars from the obstinately tough cell walls of plants for fermentation into ethanol[3]. There have also been reports of hydrolysing lignocellulose biomass before subjecting it to microbial fermentation to obtain ethanol[15]. Genetic engineering methods are being used to produce plants with lower lignin content, to allow more efficient conversion of cellulose into ethanol, and to modify metabolic pathways in microorganisms to ensure better ethanol production[16,17].

Apart from ethanol, biodiesel, which is 'a clean-burning fuel produced from grease, vegetable oils, or animal fats... by transesterification of oils with short-chain alcohols or by the esterification of fatty acids'[18], is another viable option for satisfying our energy needs. In fact, biodiesel may even be better than ethanol in

Box 1. Biofuels and the Government of India

The Government of India (GoI) has taken up a number of initiatives over the years to promote biofuels. This note attempts to give a brief overview of some of these initiatives[2].

- In 1948, the India Power Alcohol Act was passed[39], which made blending of petrol with alcohol mandatory (http://www.indiankanoon.org/doc/1603427/). The Act was repealed in 2000.
- In 2002, India started the Gasohol Programme, which made 5% doping of petrol with ethanol mandatory in several states and union territories, including Uttar Pradesh, Punjab, Haryana, Gujarat, Maharashtra, Goa, Karnataka, Andhra Pradesh, Tamil Nadu, Chandiagarh, Daman & Diu, Dadra & Nagar Haveli and Pondicherry (http://www.indianexpress.com/oldStory/7604/).
- In 2003, the National Mission on Biodiesel was proposed, and it was officially launched in 2006 (http://www.thehindubusinessline.in/2006/01/19/stories/2006011901170300.htm, http://wwwa.vito.be/bioses/pdf/D2c_biofuels_India_Dec2005.pdf). The mission was supposed to comprise 'six micro missions covering all aspects of plantation, procurement of seed, oil extraction, trans-esterification, blending and trade, and research and development'. Further, the document on the Mission says, 'The financial requirement of the Demonstration Project is estimated at little over Rs 1496 crores during the Tenth Plan. The proposed plantation in 4 lakh hectares in phases will generate 127.6 million person days of work in the Tenth Plan.' The target of the Mission was to 'gradually raise biodiesel production to 20% in the year 2011–2012, beginning with 5% in 2006–2007.' (http://planningcommission.nic.in/reports/ genrep/cmtt_bio.pdf) Unfortunately, the Mission was abandoned in 2008. (http://articles.economictimes.indiatimes.com/2008-08-04/news/27723860_1_jatropha-plantation-farm-land-biodiesel)
- In 2009, the National Policy on Biofuels was passed (http://pib.nic.in/newsite/erelease.aspx? relid=56469, http://www.mnre.gov.in/policy/biofuel-policy.pdf). The importance of producing oil from non-edible plants grown on marginal lands was recognized, and a goal of 20% blending of biofuels, both for bio-diesel and bio-ethanol, by 2017 was set.
- In 2011, the Ministry of New and Renewable Energy (MNRE), GoI, proposed a 'Strategic Plan for New and Renewable Energy Sector for the Period 2011–2017' (http://www.mnre.gov.in/policy/strategic-plan-mnre-2011-17.pdf). It states that the mission of the MNRE is to 'Develop, demonstrate and commercialize technologies for harnessing new and renewable energy sources in close concert with corporate, scientific and technical institutions; to replace use of different fossil fuels wherever possible, and increase access to electricity/lighting in remote and rural areas, through renewable energy systems; and to increase the contribution of renewable energy in the total energy mix of the country to 6% by 2022, with about 10% contribution to total electricity mix'.
- Other projects such as the Biomass Energy for Rural India (BERI) project (http://bioenergyindia.kar.nic.in/aboutus.htm), the Integrated Rural Energy Programme (http://india.gov.in/citizen/agriculture/viewscheme.php?schemeid=1269), and the Village Energy Security Programme (http://neda.up.nic.in/PROGRAMMES/VESP.pdf) have been taken up by the State and Central governments in the country.

many ways; Jason Hill *et al.*[19] enumerate some of the advantages: 'Ethanol yields 25% more energy than the energy invested in its production, whereas biodiesel yields 93% more. Compared with ethanol, biodiesel releases just 1.0%, 8.3% and 13% of the agricultural nitrogen, phosphorus, and pesticide pollutants respectively, per net energy gain. Relative to the fossil fuels they displace, greenhouse gas emissions are reduced 12% by the production and combustion of ethanol and 41% by biodiesel. Biodiesel also releases less air pollutants per net energy gain than ethanol.' In India, since diesel consumption is said to be much higher than petrol consumption, biodiesel may come as a blessing[20].

Jatropha curcas is considered to be one of the best sources of biodiesel in countries such as India, followed by other plants such as *Pongamia pinnata*, *Ricinus sativus*, *Argemone* sp. and *Camelina sativa*[21–25]. In fact, *J. curcas* was seen as a major source of biodiesel when the National Mission on Biofuels, that sought to achieve 20% replacement of diesel with biodiesel by 2011–2012, was proposed (see Box 1). *Jatropha* is a perennial shrub that can be grown on wastelands and on lands with limited water availability, its numerous seeds have high oil content and it is largely non-susceptibile to insects and pests – wonderful characters for a potential biodiesel crop to have[26]. *Jatropha*'s popularity fuelled the development of the biodiesel industry in India to some extent – by 2006, there were two firms that had embarked on biodiesel production projects, the Naturol Bioenergy Limited and the Southern Online Biotechnologies, both in Andhra Pradesh[26]. Two years later, the number of companies who were interested in starting biodiesel production projects had gone up to 150 (http://www.business-standard.com/india/story-page.php?autono=335423). In 2010, there were reports that the Indian Oil Corporation had offered to purchase 50,000 hectares of land in Uttar Pradesh to cultivate *Jatropha* (the Corporation had already acquired about 32,000 hectares for the purpose, in Chhattisgarh and Madhya Pradesh by then) (http://www.business-standard.com/india/news/ioc-wants-50000-acres-for-biofuel-cultivation-in-up/381690/).

Though the Indian Government and corporate bodies, and many scientists are apparently convinced about *Jatropha*'s suitability as the biofuel crop of India, some scientists like Deepak Rajagopal are a little doubtful, since the 'wastelands' that have been earmarked for the cultivation of *Jatropha* are actually part of 'common property resources' of rural populations who depend on such lands for their firewood, roofing, fodder and other requirements; *Jatropha* itself does not provide much wood and its leaves cannot be consumed by animals; and its long maturation period (3–4 years) makes it an economically unattractive option for potential cultivators[27]. Furthermore, reports from regions where *Jatropha* plantations have already come up do not paint a very optimistic picture. For instance in Chhattisgarh where 400 million *Jatropha* seedlings were planted, after three years, some of the saplings were dead, many of those that survived had not borne fruits, and even in areas where there was fruit production, the farmers were still 'waiting for guidelines on collection and sale of seeds'[1].

Given the disadvantages of *Jatropha*, some scientists see *Pongamia* as a better option for biodiesel production: while sharing some of *Jatropha*'s advantages like the high oil content of its seeds and its ability to grow on wastelands, *Pongamia* unlike *Jatropha* also promotes the growth of other plants around it, it lacks allelochemicals and thus does not discourage animals from feeding on its leaves, and it adds to the fertility of the land on which it grows since its roots are associated with symbiotic Rhizobia that fix atmospheric nitrogen[28]. In India, apart from development of better varieties of *Jatropha*[22] and harnessing *Pongamia* to augment biodiesel production, other plants like *Camelina*[25] are also being considered as supplementary sources.

Apart from cellulosic ethanol and oil from plants that can be converted to biodiesel, algae are gaining importance as another source of 'second generation' biofuels. In fact, algae are considered superior to many of the higher plants producing oil since they have a higher photosynthetic efficiency, they produce 15–300 times as much oil as conventional energy crops, they can be grown throughout the year, they have a much shorter turnover time when compared to angiosperms, and they can be grown in much lesser space using media such as waste water, and hence do not compete with food crops for resources[29,30]. Apart from using cyanobacteria[31] and unicellular algae like *Chlorella*, recent efforts have tried to harness other algae such as diatoms for the production of biofuels[32]. Genetic engineering has found many applications in this area of biofuel research too, with scientists trying to make algae secrete their stored oil (so that cumbersome extraction processes are bypassed), to make them synthesize hydrocarbon molecules that closely resemble molecules in petroleum products, and for inducing algae to synthesize greater amounts of oil while growing under more challenging environments than what they are naturally capable of. However, large scale cultivation of algae is said to be beset with problems. The US Department of Energy undertook a project from 1978 to 1996 to research methods of using algae for biodiesel production. A report[33] noted that 'Algal species that looked very promising when tested in the laboratory were not robust under conditions encountered in the field.' Some researchers feel that using algae for biofuel production is not a viable option after all, unless it is coupled with other processes such as wastewater treatment[34].

While liquid biofuels (ethanol, biodiesel, and also compounds such as dimethylfuran and butanol[35]) have been studied in great detail, converting biomass into gaseous fuel has also received a lot of attention. An advantage with gaseous fuel is that biomass of any kind can be channelized into syngas production. As Dasappa says, 'When you crush seeds to generate oil, there is a lot of pith that is left behind and this can go into either combustion or gasification-based power generation. So if you have oil-bearing plants, there are multiple applications – one is oil for transportation, another is fuel for stationary applications[4].' An advantage with gasification of biomass is that it can be conveniently used for small scale power generation in rural settings. Gasification has been used in rural bioenergy projects undertaken in China[36]; there are examples of such experiments done in India as well[37,38]. Talking about the importance of village electrification using biomass gasification, especially for agricultural economies like India, Dasappa says, 'Biomass-based systems can be of grid quality in the distributive power generation model. You can have a system that can generate electricity, right from few kilowatts to megawatt level. It is especially useful to meet the needs of isolated communities. A farmer earning a certain amount of money by cultivating a patch of land, depending on rains for his water needs, could generate 16 times the same value the moment we provided him with water (for irrigation). And this was possible due to the gasification system[4].' Andrew Carroll too feels that gasification systems may be excellently suited to Indian conditions. He says, 'I think syngas production would be promising for India. There are various scales at which it could potentially be implemented, with smaller scale plants focused on taking local inputs and producing oil for competition with kerosene or heating oil, while larger plants would focus on production of more valuable products. A key determinant of success for syngas would be how much biomass it could get from the surrounding area... On the rural scale, I understand that India has implemented this more than most other countries already'[37,38] (pers. commun.).

Despite the feasibility of small scale power generation projects, there are many challenges that need to be addressed. Dasappa gives an example: 'Operating with a grid is very easy, since what you produce is only a small fraction of the total power generation, and fluctuations are easily addressed. But when you are trying to electrify a small village, the load could vary with the time of the day, and the usage pattern; you need to regulate this[4].'

Gaseous fuel generated from biomass can also be used for running engines, and thus has applications in the area of transportation too. A group at IISc has been working on this for the last few decades. Dasappa, who belongs to this group, talks about the challenges that they had to address: 'When you take producer gas as a fuel into an engine, there are a few issues to be addressed. One is the cleanliness of the gas. When you look at slightly higher capacity engines, about 1000 kilowatts, you get an intermediate component called a turbocharger, which is used as a device to improve the output of a given engine. Since the turbochargers run at several tens of thousands of rpm, even a small particulate impurity may become a major issue when it comes to operation. That ultimately depends on the quality of the gas. Then, since the properties of biomass gas are very different from natural gas properties, you also need to look at how to regulate the air : fuel ratio in the engine, to meet various operating conditions.[4]' Gaseous fuel generated from biomass has other applications too – for instance, the gasification technique developed at IISc can be used for substituting oil in industrial applications, such as in metallurgical processes, chemical processes, or for running boilers, drying systems, etc. Dasappa estimates that roughly a kilogram of oil can be replaced by 3.5–4 kg of biomass[4].

The path towards making biofuels a viable alternative to fossil fuels still has many unresolved problems. Deepak Rajagopal feels that it might still be premature to consider biofuels as a cost-effective strategy for either reducing oil dependence or to mitigate climate change, though their contribution might be significant in the long run. He says, 'We should be patient and invest in R&D that can improve the seed quality, productivity and other beneficial characteristics in biofuel crops and try to create domestic industries that can be world leaders in these technologies in the coming decades' (pers. commun.). Further, biofuels might not be a panacea for all energy problems everywhere. 'It may become necessary to produce fuels from algae, *Jatropha*, cellulosics, etc. But as you can imagine, this cannot replace diesel or gasoline from petroleum. There is no unique solution to solving the energy problem. Depending upon the logistics, you will have to propose different solutions for different areas in India,' (P. T. Vasudevan, pers. commun.). Economic viability of using biofuels is another factor that needs to be considered. Dasappa feels that though options like biomass gasification might be an economical solution for urban institutions or industries that typically spend about Rs 4.5–5 per kilowatt-h, they may not yet be viable solutions to meet the energy needs of people in the peri-urban or rural setup[4]. There are also social factors that need to be addressed if biomass-generated energy is to become widely accepted[36,37]. The complexity and diversity of the scientific and other hurdles that need to be crossed before biofuels can come to popular usage would make us tend to agree with Arthur Mol, when he says, 'Biofuels represent the first serious challenge to petroleum-based fuel for a century, but it will take at least two more decades before biofuels will seriously challenge the oil economy'[5]. India had already spent Rs 410 million on biofuels research by 2008 (http://in.reuters.com/article/2008/04/25/idINIndia-33239520080425). Would two more decades, and undoubtedly a lot more research, see us fossil-fuel independent? Only time can tell.

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