WORKING PAPER

Technologies to produce liquid biofuels for transportation

An overview

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Working Paper 72

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This report has been produced with the financial assistance of the European Union, under a project titled, 'Bioenergy, sustainability and trade-offs: Can we avoid deforestation while promoting bioenergy?' The objective of the project is to contribute to sustainable bioenergy development that benefits local people in developing countries, minimises negative impacts on local environments and rural livelihoods, and contributes to global climate change mitigation. The project will achieve this by producing and communicating policy relevant analyses that can inform government, corporate and civil society decision-making related to bioenergy development and its effects on forests and livelihoods. The project is managed by CIFOR and implemented in collaboration with the Council on Scientific and Industrial Research (South Africa), Joanneum Research (Austria), the Universidad Nacional Autónoma de México and the Stockholm Environment Institute. The views expressed herein can in no way be taken to reflect the official opinion of the European Union.

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1. Introduction

Mandates and incentives to drive greater use of biofuels for transportation are being adopted in both developed and developing nations. Greater production and use of biofuels is being promoted to improve rural living conditions, reduce reliance on imported petroleum and mitigate climate change. For developing countries, increased income from exports and accompanying opportunities to improve social and employment opportunities are also important goals.

These mandates and incentives are needed to drive biofuel production because, with the exception of Brazilian sugarcane-based ethanol, all biofuel production pathways currently result in fuels whose costs are higher than those of petroleum-based fuels (at prevailing oil prices). In response to the new drivers, use of proven crops, conversion technologies and fuels (first generation pathways) is increasing and research into and testing of new crops, conversion technologies and fuels (second generation elements) is accelerating.

This paper provides an overview of the state of the art of primary biofuel production options. After these descriptions, selected assessments of how pathways rate against criteria are presented. Biofuel pathways tend to be evaluated against a number of criteria, including: cost; technological readiness, for which cost relative to commercial-scale pathways provides an indication; and environmental footprint, including greenhouse gas (GHG) emissions and efficiency of land use. GHG profiles are important because reduction of GHG emissions is a major reason that developed countries – key potential importers – are interested in biofuels. Efficiency of land use is important because arable land is a limited resource and use of crops in first generation biofuel pathways competes for land with food and feed production.

Evaluations of alternative biofuel pathways by developing countries should also take national objectives into account. For example, some pathways are more suitable for exploiting export opportunities or reducing GHG emissions, while others may be more suitable for improving rural conditions through local production and use. While important, these considerations are beyond the scope of this paper.

2. Overview of liquid biofuel pathways

This overview, focuses primarily on first generation means to produce biofuels: ethanol through fermentation of plant sugars and sugars derived from starches, and biodiesel through transesterification of oils from seeds. While no classification scheme is universally accepted, in general, second generation avenues are characterised by higher costs, greater risks, and technological hurdles. Thus, with a few exceptions, second generation avenues are less likely to be suitable for developing country investment.

2.1 Current production

Ethanol is the leading biofuel used today. In the United States it is primarily produced by fermenting sugars in corn starch and in Brazil primarily from sugarcane. In 2009, the US produced over 40 billion litre of ethanol and Brazil just under 25 billion litre, 10 times more than the next highest producer, China. Production from the other main producer countries and the European Union is shown in Table 1.

As can be seen in Table 2, production of both biodiesel and ethanol has grown strongly since 2000. Biodiesel has grown from approximately 6% of total biofuels in 2001 to 23% in 2009.

The EU is the leading producer of biodiesel, producing 235 of the total 308 thousand barrels in 2009. Some 50% of this was produced from soya and 40% from rapeseed. The next highest producers were the United States, Brazil, and Argentina, with production primarily from soya (S&T)^2 Consultants 2009). In many developing countries oil palm is the primary source of oil for biodiesel.

2.2 Biofuel pathways

Biofuels can, at least potentially, be produced from any type of biomass. Considering vegetation only, different plant materials are converted to biofuels using different processes. The variety of biofuel pathways are illustrated in Figure 1. As indicated, a biofuel pathway consists of a feedstock, a conversion process and an end product.

Distinctions are often made between first and second generation pathways, and some schemes classify some pathways as third generation. No classification scheme is universally accepted and authors differ as to the stage of feedstocks, conversion technologies and end products. This paper distinguishes at the element level rather than at the pathway level. A pathway element is considered as being first generation if it is widely used at commercial scale for biofuel production. A second generation element is still at the pilot or demonstration stage or is being tested at commercial scale in only a few locations.

As used here, the primary purpose of distinction is to assist stakeholders in deciding where to focus efforts.

Table 1. Ethanol production in primary producer countries (excluding the US and Brazil) (millions of litre)

	Canada	Colombia	China	India	Thailand	Australia	EU	Other	Total
2009	1.102	314	2.048	348	1.647	216	3.933	935	73.944

Source: RFA (2010)

Table 2. Production of liquid biofuels in thousands of barrels per day

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Ethanol	299	323	378	466	512	584	712	924	1,219	1,327
Biodiesel	NA	21	27	36	44	77	142	203	271	308

Source: US EIA (2010)

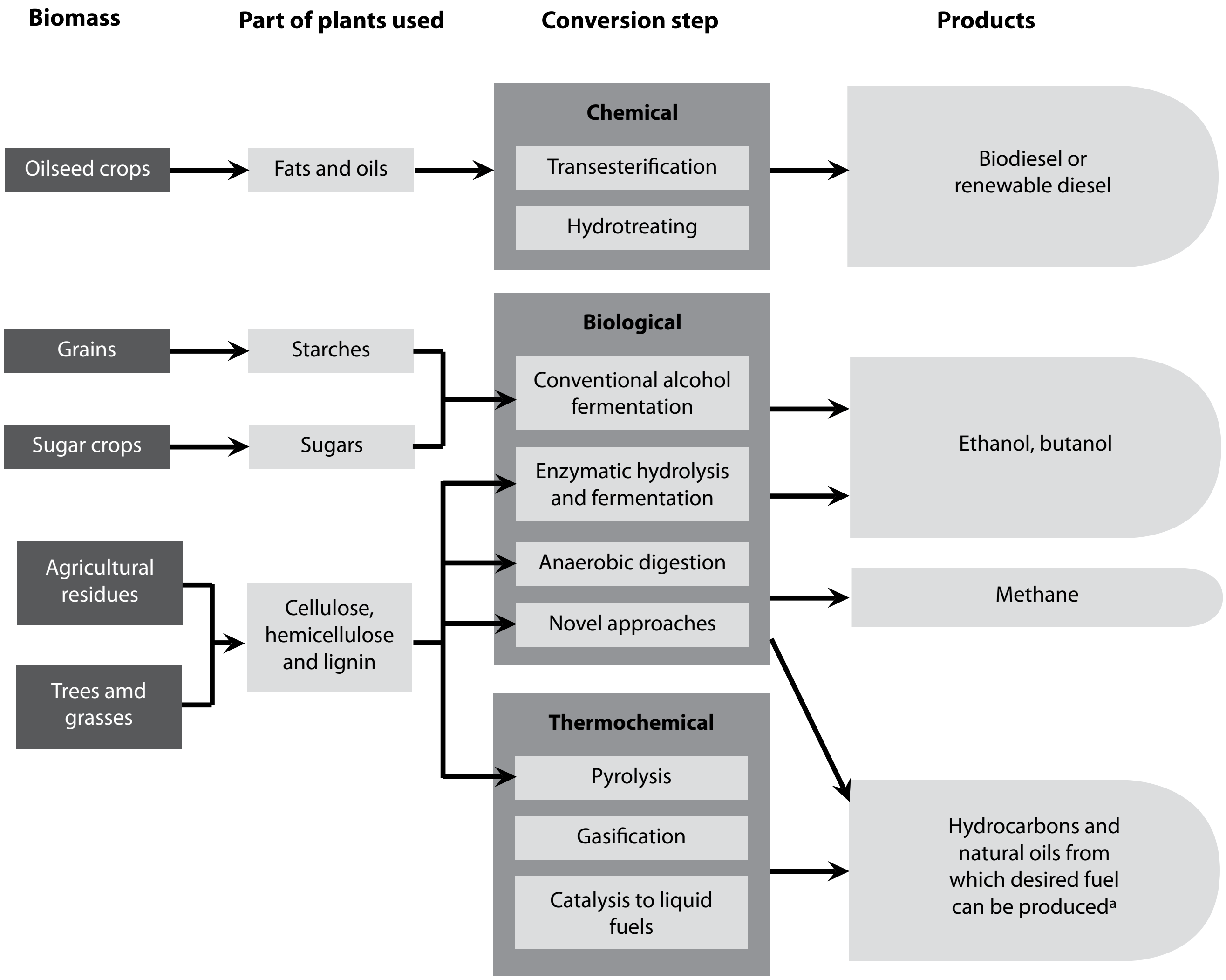


Figure 1. Overview of biofuel pathways

a These include gasoline or diesel equivalents, syngas and hydrogen.

Source: Pena (2008)

If a country has considerable experience with a particular feedstock or conversion process, these may be considered first generation in that nation; while in other countries they remain second generation due to greater costs, risks or technological challenges. Thus, although the below discussions utilise these distinctions to provide a general orientation to the state of the art, we recognise that views and circumstances differ.

Of the combinations shown in Figure 1, there are two primary pathways s in which all elements are widely considered first generation: 1) production of ethanol by fermenting grains and sugar crops; 2) production of biodiesel via transesterification or hydrotreatment of oilseed crops or waste oils. Thus, a pathway which consists entirely of first generation elements produces a specific product: either ethanol or biodiesel. One advantage of this is that it simplifies market evaluation.

All other pathways include at least one second generation element. In some cases, the feedstocks are considered second generation because commercial-scale experience with their cultivation for biofuels is limited. In other cases, conversion technologies are still at research and demonstration stages. In the case of algae, both production of the feedstock and the conversion technologies are at the research stage. Examples of crops that, in general, should be considered second generation feedstocks are sweet sorghum and jatropha. These crops can be converted via conventional fermentation or transesterification, to produce ethanol or biodiesel, respectively. On the other hand, grasses and trees can be considered first generation plants that require second generation conversion technologies. While the object of considerable research and being tested in some demonstration plants, the conversion processes needed for these feedstocks are considerably more expensive than first generation conversion technologies. In addition, processing these feedstocks requires advanced combinations of enzymes (in the case of enzymatic hydrolysis), or technologies that have not been widely applied for the purpose of making biofuels (thermochemical processes). Another feedstock that can be considered first generation is black liquor. Black liquors are produced in the course of pulp and paper production, but their use to produce biofuels is still in the early demonstration stage.

3. Feedstock origins, quantities and yields

Countries around the world are producing feedstocks for biofuels. Preferred feedstocks depend on country circumstances, including climate and soils, trading opportunities, traditional and current crops, and land uses. The following subsections provide an indication of the feedstocks being produced in various countries and the variation in yields, both per hectare and per litre of fuel.

3.1 Feedstock origin and quantities

As shown in Table 3 and Table 4, the primary feedstocks for ethanol are corn and sugarcane; and for biodiesel are soya, rapeseed and oil palm. With the exception of China, developing countries are using sugarcane as a feedstock for ethanol. Oil palm is the primary feedstock being produced for biodiesel in developing countries, except in Brazil and Argentina (which rely on soya), the Philippines (coconut), and China (waste oils).

Figure 2 and Figure 3 show current and planned feedstocks for ethanol and biodiesel, by country.

3.2 Feedstock yields

Given that first generation biofuel feedstocks compete for land with food and feed products, and that arable land is limited, the amount of biofuel that can be produced per hectare is an important issue. The per hectare biofuel yield is a function of the efficiency of the conversion process and the per hectare production of usable plant materials. A general indication of the relative land efficiency of first generation pathways can be garnered from Figure 4. From this figure it is clear that production of ethanol from sugarcane is the most land-efficient source of biofuels, with biodiesel from oil palm the most land-efficient biodiesel option.

While Figure 4 provides an indication of biofuel yields per hectare, it is important to bear in mind that per hectare productivity of the crops themselves plays an important role in biofuel yield per hectare. Figure 5 and Figure 6 illustrate the spread in per hectare yields for corn and oil palm across nations. Crop yields also vary by species, variety, soil and climate conditions, and farming practice.

Table 3. Global fuel ethanol production by feedstock

Country or region	2008	2009	Primary feedstock
	Million litres		
USA	34 968	39 700	Corn
Brazil	24 200	24 900	Sugarcane
EU	2 803	3 935	Beet/grain
China	1 900	2 050	Corn
Canada	950	1 100	Corn
Other	436	936	Sugarcane
Thailand	322	450	Sugarcane
Colomboia	258	315	Sugarcane
Australia	131	215	Sugarcane/grain
Idia	60	150	Sugarcane
Total	**66 028**	**73 751**	

Source: (S&T)^2 Consultants (2009)

Table 4. World biodiesel production by feedstock, 2009

Region	Million litres	Feedstocks
EU	9 848	Rapeseed (50%), soyoil (40%), oil palm (5%) and tallow (5%)
USA	1 682	Soya (40%), tallow (20%), canola (20%), oil palm (20%)
Brazil	1 386	Soya (80%), tallow (10%), other vegetable oils (10%)
Argentina	1 250	Soya
Thailand	614	Oil palm
Malaysia	284	Oil palm
Colombia	205	Oil palm
China	191	Waste vegetable oils
Republic of Korea	182	Oil palm (33%), soya (33%), Waste vegetable oils (33%)
Indonesia	170	Oil palm
Singapore	124	Oil palm
Philippines	108	Coconut
Canada	102	Tallow
O.S. America	63	Oil palm
O. Europe	58	Rapeseed
Australia	57	Tallow
Taiwan	43	Oil palm (33%), soy (33%), waste vegetable oils (33%)
O.N & C Am	38	Oil palm
India	23	Waste vegetable oils
O. Oceania	6	Waste vegetable oils
O. Asia	5	Waste vegetable oils
World	**16 436**	

Source: (S&T)² Consultants (2009)

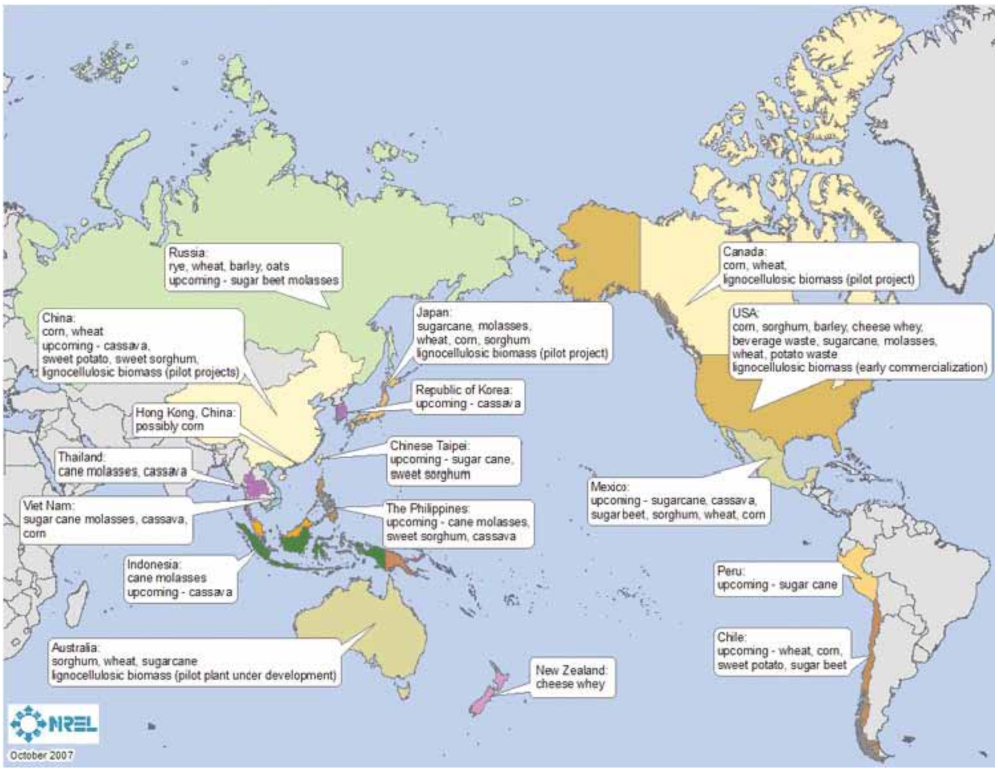


Figure 2. Ethanol feedstocks by country

Source: APEC (2007)

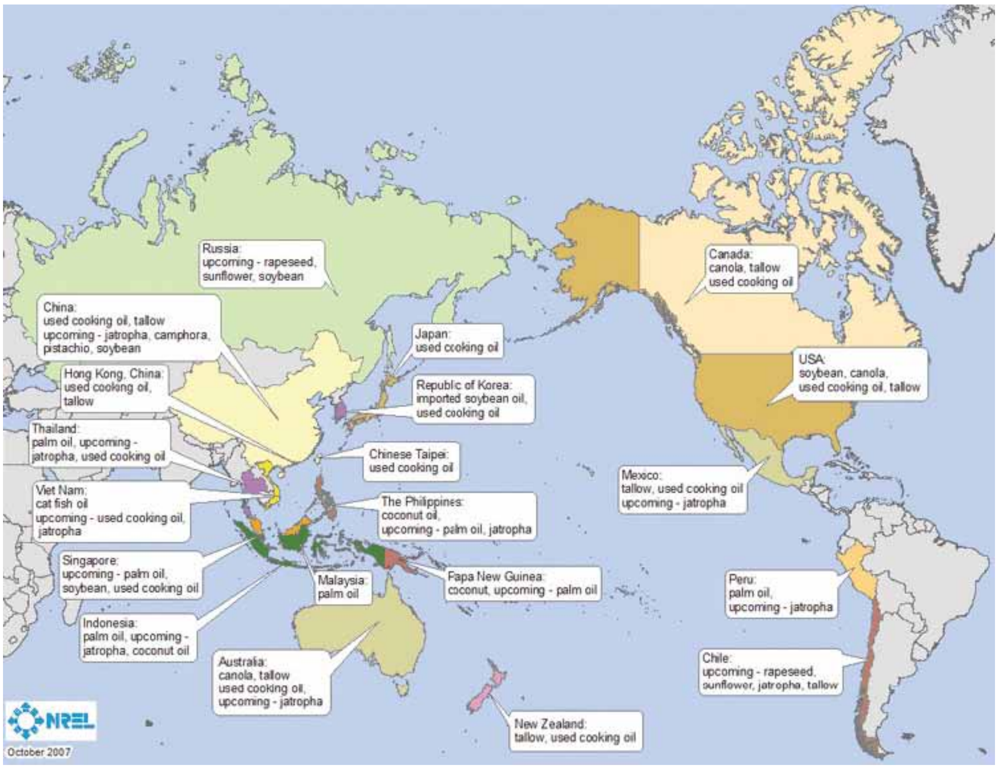


Figure 3. Biodiesel feedstocks by country

Source: APEC (2007)

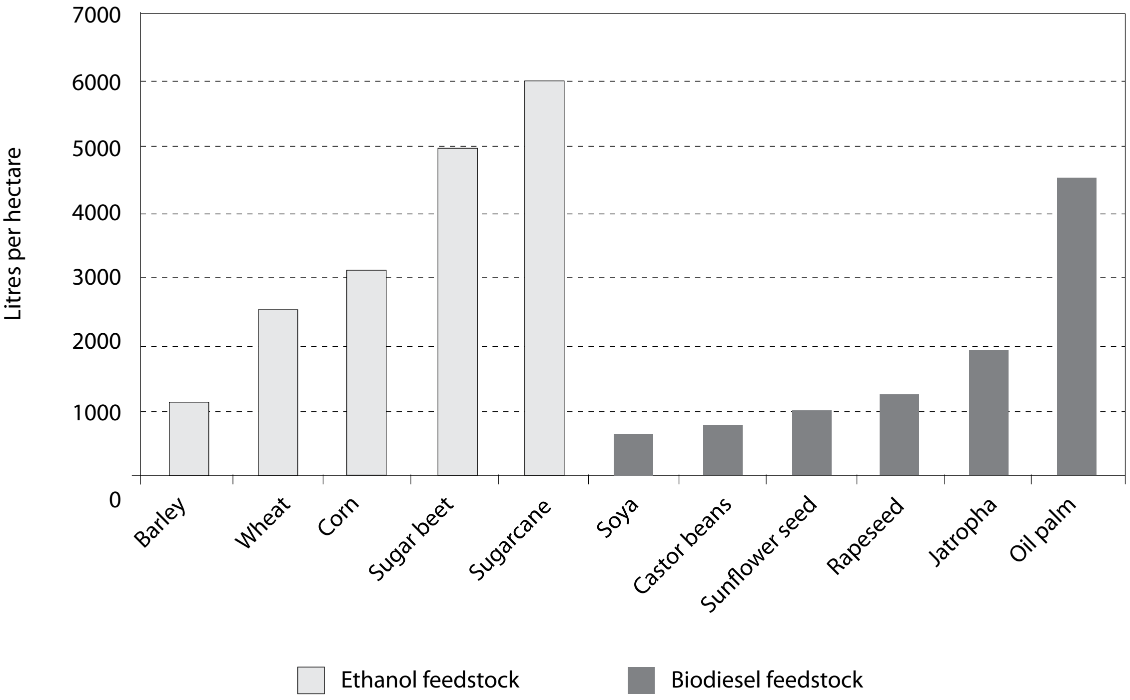


Figure 4. Biofuel yields of selected ethanol and biodiesel feedstocks

Source: Fulton *et al*., cited in Davis (2007)

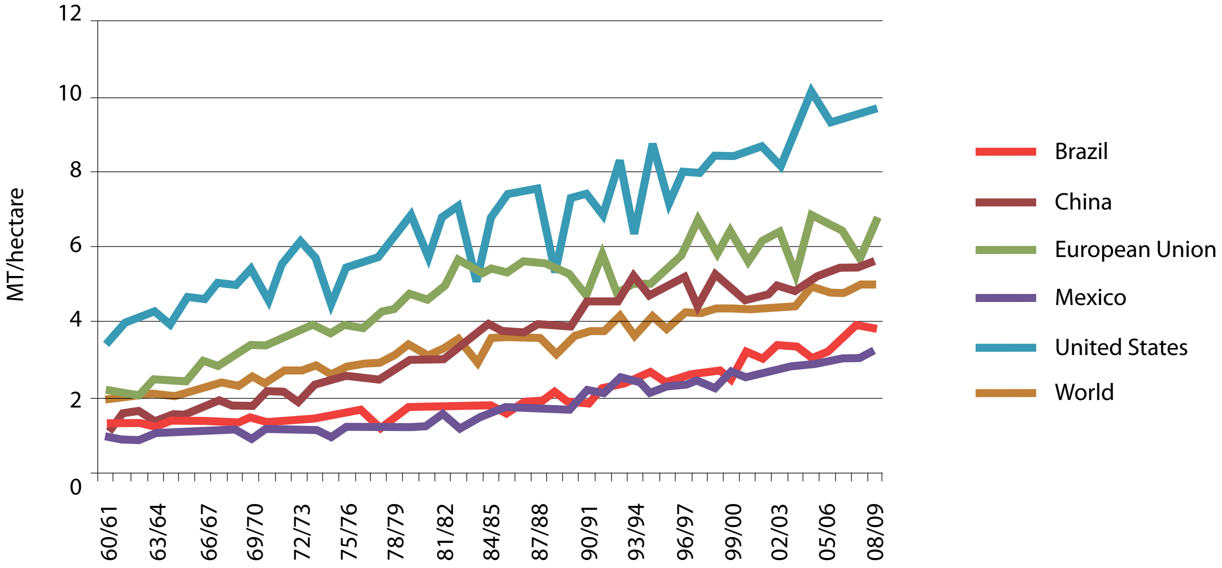


Figure 5. Countries ranked according to corn yields in 2007

Sources: http://www.fedepalma.org/statistics.shtm; http://www.fas.usda.gov/psdonline/; 2008-2009 projected

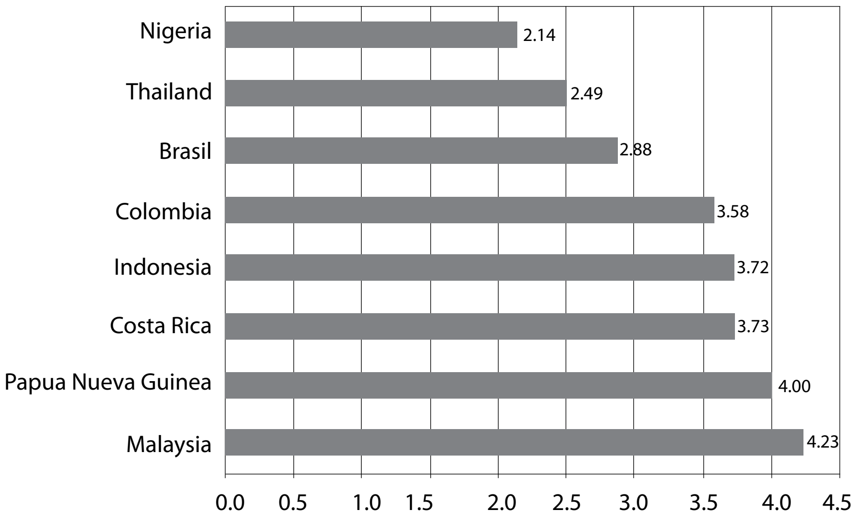


Figure 6. Countries ranked according to crude palm oil yields in 2007 (tonnes per hectare)

Source: Fulton *et al*., cited in Davis (2007)

4. Crops

Brief descriptions of key crop materials used, or foreseen, as biofuel feedstocks are provided below. The descriptions start with first generation plant materials, divided into those used for ethanol (sugars and starches) and those used for biodiesel (oils). Plants that are second generation but convertible with first generation technologies are covered next, followed by materials that require second generation technologies.

4.1 First generation crops and materials

All first generation feedstocks have both the advantage and disadvantage of being used for food and biofuel. The primary disadvantage is that use of these crops for biofuels competes with food demand. The advantage is that farmers gain some protection against market price and demand swings by having the option of selling into alternative markets.

4.1.1 Sugar and starch crops

There is extensive experience with use of sugarcane to produce ethanol. Much of this comes from Brazil where decades of research and experience have resulted in considerable improvement in crop yields, with average yields of 82 tonnes per hectare (WWI 2007). Plant wastes from the sugar extraction process (bagasse) can be used for the energy needed in the conversion process, avoiding the need to use fossil fuels (Coelho 2005, Wang 2006).

Sugarcane. Sugarcane requires a long, warm growing season, and needs substantial nitrogen, potassium and water supply (1500–2500 mm over the growing season) (FAO undated). Most of the potential growing area thus lies in the tropics. The area under sugarcane cultivation has grown at an annual average rate of 1.4% over the past decade. Expansion rates have been greatest in Thailand (2.7% per year), followed by Brazil (2.5%), China (1.9%) and India (1.8 %). Sugarcane can be harvested either mechanically or with manual labour.

Corn. As in the case of sugarcane, there is extensive experience in use of corn for ethanol. Corn yields have also increased over the past decades and breeds have been specially designed for the ethanol market. An average acre of corn in the United States currently yields roughly 440 gallons of ethanol (4110 litres per ha) but high crop yields require substantial amounts of fertiliser.

Sugar beets. Sugar beets can be used to produce ethanol. Yields per hectare are lower than for sugarcane, although in general higher than for corn. Worldwide, the area cultivated in sugar beets is decreasing. Due to survival of pests in the soil, beets cannot be cultivated more than once every three years on the same field. In general, harvesting and processing sugar beets is a heavily mechanised operation.

Wheat. As with corn, only the kernel containing the starch is used to produce ethanol. The ethanol yield per hectare of wheat is lower than for corn and sugar crops, but wheat can also be grown in drier and colder conditions than either corn or sugarcane. Wheat straw residues can be used for energy where not needed for other purposes, such as soil conditioning.

4.1.2 Oilseed crops

Oil palm. In general, oil palm has the highest yields per hectare of feedstocks currently used to produce biodiesel (see Figure 4). As a tropical plant, it is the feedstock of choice for a wide range of developing countries. Oil palm is grown either in small plots or in large plantations. Oil palm production has grown rapidly in Malaysia and Indonesia, the two countries with the largest amount of land in oil palm production (4.5 million ha in Malaysia and 3.7 million ha in Indonesia) (Fedepalma).

A substantial proportion of the land devoted to oil palm production, including new areas, is drained peatlands. While estimates of GHG emissions from peatlands vary widely, it is known that these emissions are substantial. Thus, while there is controversy over the climate mitigation benefits of all biofuels, resolving the issue in the case of palm oil from drained peatlands may be particularly difficult.

Soya. Soya has low yields per hectare compared to other oilseed crops. However, as a nitrogen-fixing crop, it can be used to improve fertility and has low fertiliser requirements. Soya has to date evoked little interest in developing countries other than Brazil and Argentina. In these countries, as well as in the United States, soya cultivation and harvest is highly mechanised. Soya is grown in rotation with corn in the US and in rotation with sugarcane in Brazil.

Rapeseed. Rapeseed can be grown in rotation with cereal crops but in the EU, the primary producer of biodiesel from rapeseed, it is frequently grown on set-aside land (WWI 2007). The global cultivated area is expanding by 2% annually. Australia is experiencing a rapid increase in the area under cultivation, while only minimal expansion is occurring in China, the world´s largest rapeseed producer.

4.1.3 Second generation feedstocks amenable to first generation conversion

Feedstocks in this group are generally of interest because they can be grown on lands that have little potential for primary first generation feedstocks. While these crops can be grown in poor soil or where water availability is low, yields are likely to be lower than when they are grown in more suitable situations. There is frequently considerable experience with growing these crops, but little experience in growing or using them for biofuels, particularly in commercial-scale operations.

Jatropha. Jatropha produces oil-rich seeds and can be grown on marginal and semi-arid land. However, as is the case for most crops, yields are considerably lower than when it is grown on fertile land with good water availability. Advantages include: 1) it is a bush that can be harvested twice annually; 2) it is poisonous and therefore not disturbed by livestock; and 3) it remains productive for decades.

Jatropha has been identified as a promising feedstock for both large and small-scale biodiesel production, and countries in both Asia and Africa are starting jatropha programmes. Figure 7 illustrates the latitudes considered promising for jatropha cultivation although to date productivity has often proved less than hoped for in some of these regions.

Sweet sorghum. Sorghum is native to tropical and subtropical regions in all continents as well as islands in the South West Pacific. Sweet sorghum can tolerate hotter and drier conditions than corn. Consequently, large areas across Africa and Asia that may not be suitable for corn or sugarcane may be suitable for sorghum production. The genus *Sorghum* contains numerous species of grasses, some of which can be grown for grain, while others can be used to produce other foods (sorghum syrup) or fodder. Sorghum can be cultivated separately in dedicated fields or grown as part of pastures.

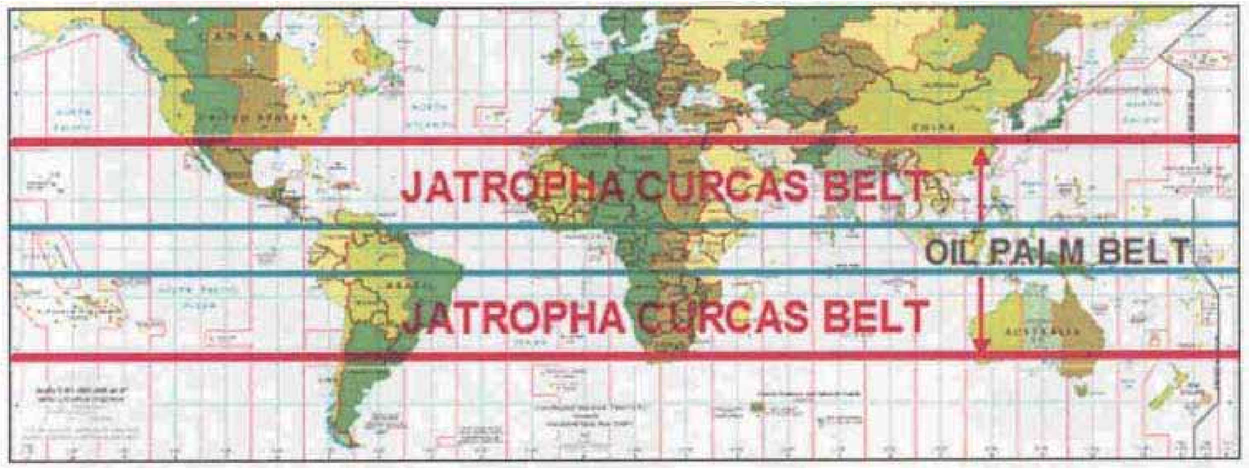


Figure 7. The global jatropha belt

Source: www.jatropha.de/news/jcl-new.htm

Recent researchers have found water requirements of between 25% and 70% of sugarcane water needs (Layaoen *et al.*, Praj) and fertiliser requirements 40% of sugarcane and 60% of corn requirements (Nimbkar *et al.* 2006, Stevens *et al.* undated). Earlier researchers found the fertilizer requirements similar to that of corn (Carter *et al.* 1989).

Cassava. Cassava, or tapioca, is the most commonly cultivated crop in sub-Saharan Africa and the second most commonly cultivated crop in Africa as a whole. While more than 60% of cassava is grown in Africa, the highest yields are achieved in Asia. Cassava is typically cultivated in areas with poor soils and high risk of drought. Cassava's high concentration of starch in its roots – about 30% in fresh roots – renders it a potential feedstock for ethanol, sharing the food and fuel market options of corn and sugarcane. Thailand has begun using it for its ethanol programme and Nigeria is also planning to use it for its ethanol programme (WWI 2007).

4.1.4 Plants and materials requiring second generation conversion technologies

Two major sources of feedstocks for biofuels fall into in this group: lignocellulosic materials (grasses, trees and crop residues) and materials derived from algae. While there is no lack of experience in growing, harvesting, and collecting grasses, trees and crop residues, there is little – or no successful – experience in these procedures for algae.

Lignocellulosic materials. Lignocellulose, which is made up of cellulose, hemicellulose and lignin, is resistant to biodegradation. The cellulose – the most common organic compound on earth – must be separated from the lignin and then hydrolised to produce simple sugars. Hemicellulose contains a high percentage of 5-carbon sugars – including xylose – which are difficult to ferment. Due to these challenges, second generation technologies such as enzymatic hydrolysis and thermochemical treatment are required to convert much of the sugar content of lignocellulosic materials to ethanol.

Black liquor, a by-product of producing pulp and paper via the Kraft process, consists of a mixture of lignin, hemicellulose, cellulose and carbohydrates. In the Kraft process, debarked wood is cooked in the presence of sulphides to dissolve the lignin while minimizing dissolution of carbohydrates. The proportion of carbohydrates in the resulting black liquor depends on the initial feedstock and the cooking conditions (Niemelä *et al.* 2007). Where pine trees are the feedstock, the black liquor also contains tall oil. Thus, black liquor contains some carbohydrates that, at least potentially, can be fermented with conventional technologies, as well as materials that require sophisticated conversion technologies.

Algae. Algae can be grown in fresh or saline water and in either open pounds or – at least potentially – in closed loop systems. Due to the great variety of algae, they can be used to produce virtually any biofuel through some production and conversion pathways. Algae can be cultivated to produce lipids, sugars and starches, or cellulosic materials. The pathways to biofuels, however, require technologies that are not yet operating at commercial scale. Moreover, due to high water, energy, and fertiliser demands across the production, harvesting and concentration processes in open ponds – as well as the lack of success to date with closed-loop systems – all algae pathways must be considered second generation at this time.

5. Conversion technologies

5.1 First generation: ethanol from sugars and starches

Conventional ethanol processes convert sugars to ethanol (C_2H_5OH), through yeast-based fermentation. Fermentation with yeast has been used for centuries if not millennia all around the world. In the case of starches, enzymes are used to break the starches down to simple sugars in a process called hydrolysis to enable the fermentation process. Once the ethanol is produced it must be distilled.

Both fermentation and distillation require heat. In the case of sugarcane-based ethanol, cane residues (bagasse) supply the heat. Since bagasse is a biomass energy source sugarcane- based ethanol has very low GHG emissions. In the case of corn-based ethanol, the heat is usually supplied by a fossil fuel such as natural gas. While this results in higher GHG emissions, corn-based processes result in co-products which reduce costs and to which some of the GHG emissions are attributed. Figure 8 illustrates ethanol production from sugar and starch feedstocks.

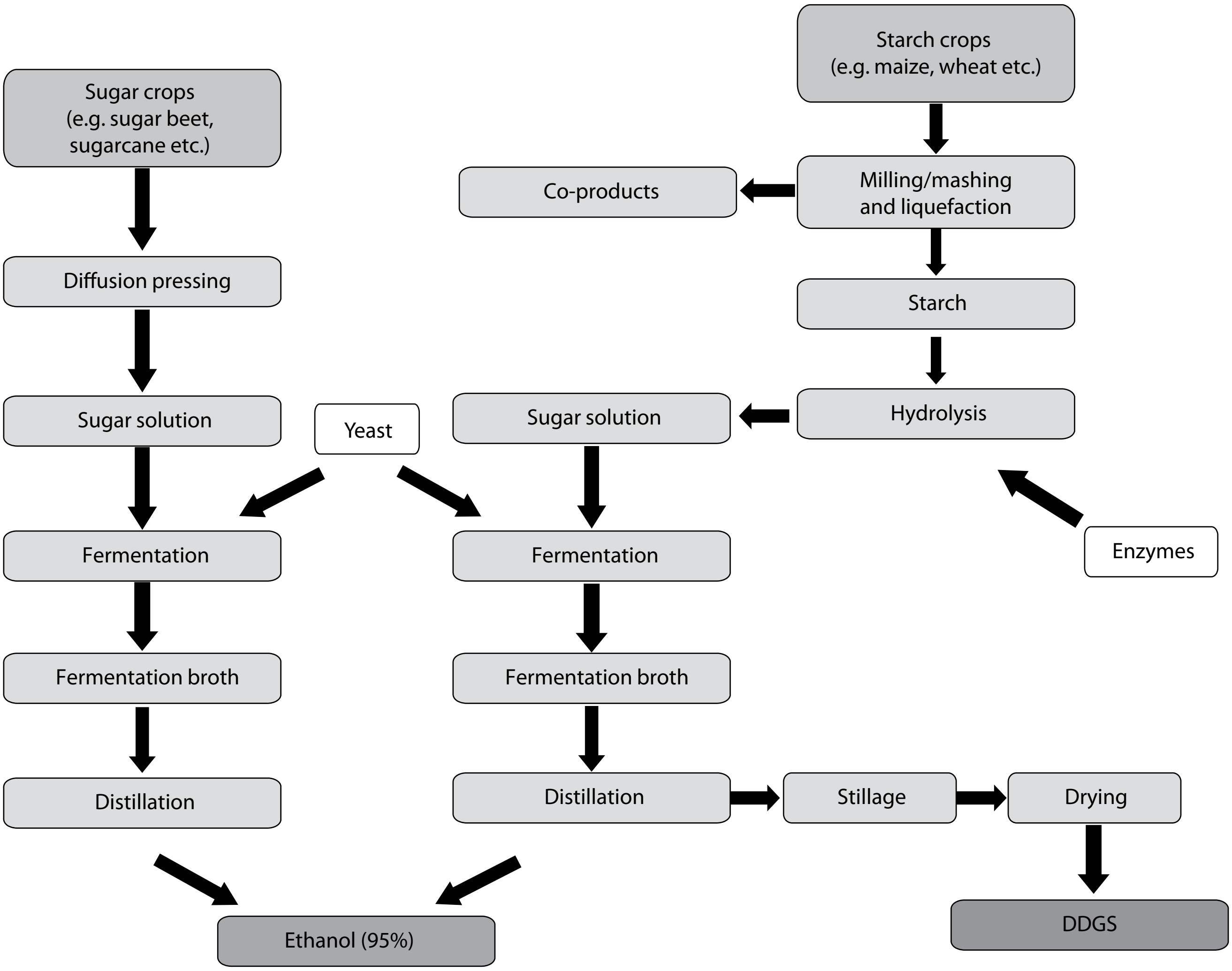


Figure 8. Ethanol from sugar and starch

Note: DDGS=dried distiller grains with solubles

5.1.1 Conversion of sugarcane (or other directly fermentable sugar plant parts)

The simplest and least energy-intensive path to ethanol is fermentation of sugarcane. The cane is cut into small pieces and the juice is squeezed out, leaving solids referred to as 'bagasse'. The bagasse is used as fuel for the remaining steps. Non-sucrose impurities in the juice are filtered out, the juice is heated and centrifuged to separate sugars from molasses, and the sugars are fermented to alcohol. After fermentation, water is removed by distillation.

5.1.2 Conversion of corn kernels (or other starch plant parts)

Converting corn or similar starch feedstocks into ethanol is somewhat more complex than conversion of sugarcane. Starches must be converted to sugar prior fermentation, requiring both more heat and use of enzymes.

Corn can be converted to ethanol through either a dry or wet process. In dry milling, the corn kernel is ground into a flour or 'meal', the meal mixed with water, and enzymes are added to convert the starch to dextrose. The resulting mix is heated to high-temperatures to reduce bacteria levels and then cooled and fermented. After fermentation, ethanol must be separated by distillation and dehydrated. The remaining material is used to make dried distillers grains with solubles (DDGS) which is used as livestock feed.

In wet milling, the grain is soaked in water and dilute sulfurous acid for 24–48 hours to facilitate the separation of the grain into its components. Grinders separate the corn germ from which corn oil is extracted. The fiber, gluten and starch components are segregated using centrifuges with the gluten used to produce animal feeds. The starch can then be fermented into ethanol as in the dry mill process.

5.2 First generation: biodiesel from oilseeds

5.2.1 Transesterification

After pressing and extraction of the oil from seeds, plant oils are most frequently converted to biodiesel via transesterification. Esterification separates the fatty acids – hydrocarbon chains – from the glycerine molecule to which they are attached and attaches them to an alcohol. Methanol, usually of fossil fuel origin, is most frequently used to replace the glycerine molecule, with sodium or potassium hydroxide used as a catalyst. The resulting compound is referred to as FAME (fatty acid methyl ester). As in the case of corn-based ethanol, co-products can be obtained. Plant materials remaining after pressing can be used to produce animal feeds. If rapeseed is used, for example, 'rape cake' can be produced from the fibre and protein fractions. The glycerine separated during esterification can be used to make glycerol, a versatile compound used in a wide variety of industries, including food, cosmetics, medical, and coatings. Figure 9 depicts the options along to a typical biofuel process chain.

5.3 Second generation conversion technologies

With the exception of the enzymatic hydrolysis process used to produce ethanol from cellulosic materials, second generation conversion technologies can produce transportation fuels of desired characteristics, including fuels virtually indistinguishable from their fossil fuel counterparts. In particular, gasification and hydrotreating processes can produce fuels with better performance characteristics and ones more compatible with current engines and delivery systems than ethanol or FAME.

5.3.1 Conversion of black liquors to transportation fuels

Production of transportation fuels from black liquors is in early demonstration stages. Some of the sugars in black liquors are amenable to standard fermentation-to-ethanol processes, but even this is only in early trial stages. However, if experience results in favourable economics, fermentation processes may offer a relatively near-term option for developing countries with pulp and paper industries to produce biofuels.

Thermochemical treatment is likely to be used to convert remaining sugars to fuels since gasification can be integrated into the pulp and paper production process. In regard to conversion of tall oils present in some black liquors, to date only one plant in Sweden is scheduled to undertake this (Kempemo 2009).

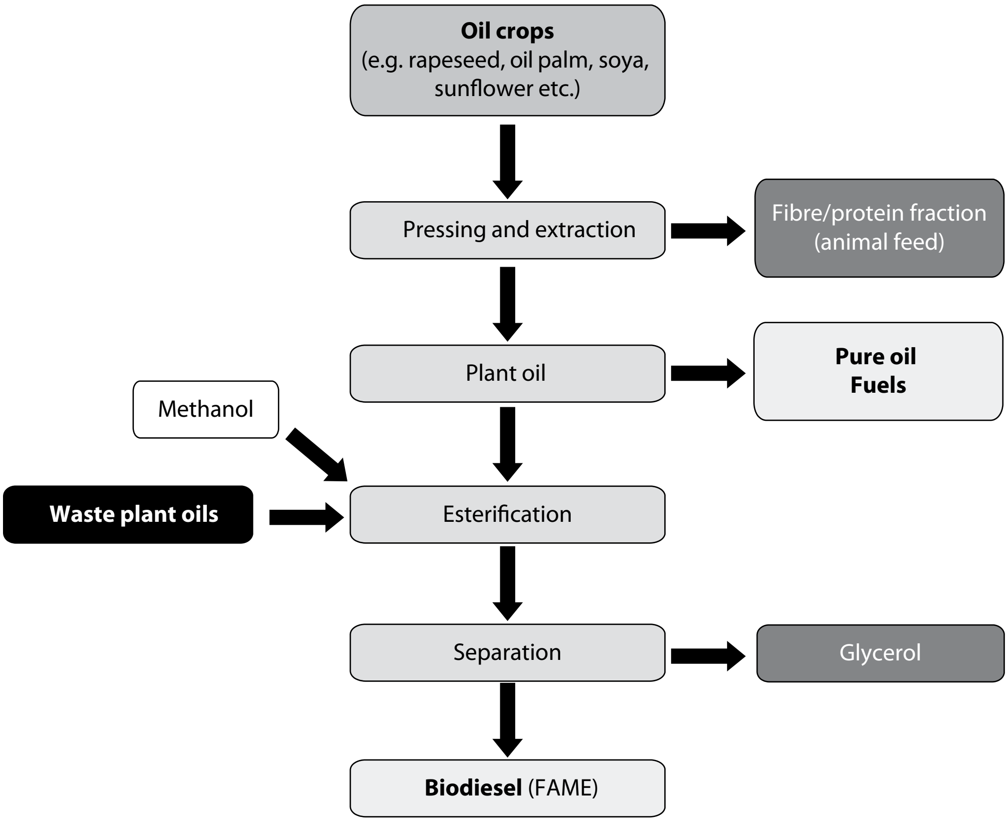


Figure 9. Biodiesel from oil seeds and waste oils and greases

5.3.2 Enzymatic hydrolysis

Lignocellulosic processes are considered second generation due to their high costs, limited production experience and challenging technologies required. Production costs for ethanol via enzymatic hydrolysis are approximately double those of ethanol from corn (Paustian *et al.* 2006). As of 2009, for example, there were no commercial cellulosic ethanol plants in the United States and total capacity of demonstration plants was less than four million gallons per year (Concentric Energies 2010). One demonstration plant was operational in the UK (Biomass Power and Thermal 2009).

To convert lignocellulosic materials, they first undergo pre-treatment to release the cellulose from the surrounding lignin and hemicellulose. While this can be accomplished with dilute acids, expensive equipment is required and sugars tend to be degraded and other processes are under investigation. Given the recalcitrance of cellulose, creating sufficiently robust, affordable enzymes capable of breaking released cellulose into sugars in desired timeframes is also a challenge. Finally, fermentation of sugars into ethanol is complicated by the presence of compounds toxic to the microbes needed for this step, including those needed to covert 5-chain sugars (NREL 2007).

Given the substantial subsidies and high capital costs, the sophisticated equipment and enzymes needed for this technology, the current very limited production capacity, and the practice of sourcing material from local wastes, neither establishment of lignocellulosic plants nor supplying cellulosic feedstocks are likely to represent an opportunity for developing countries in the near-to-medium term.

5.3.3 Thermochemical processes

Thermochemical conversion encompasses various processes in which biomass is gasified by subjecting it to heat under pressure. The Fischer-Tropsch process and fast pyrolysis are examples of gasification processes.

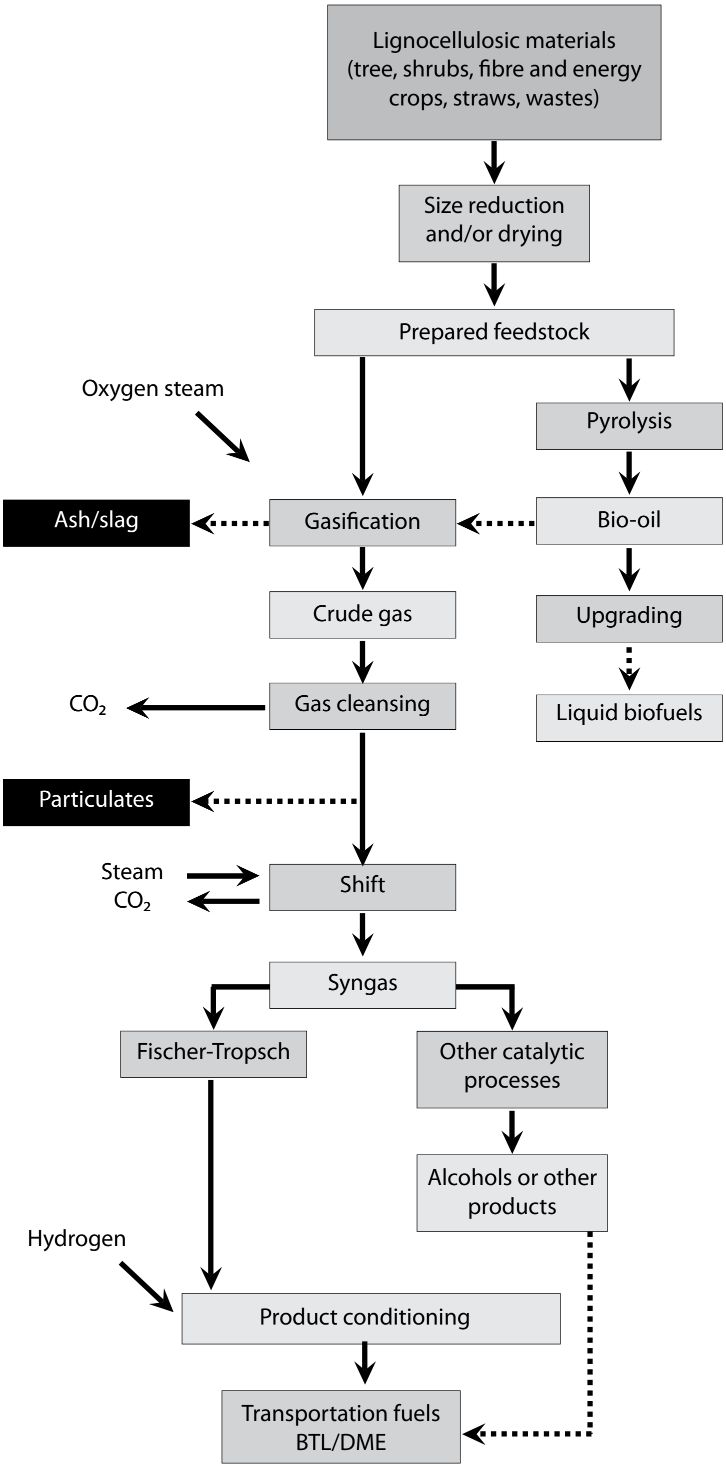


Figure 10. Thermochemical processes to produce liquid biofuels

Source: European Biofuels Technology Platform (2008)

In the Fischer-Tropsch process gasification is done in the presence of oxygen and steam, resulting in a synthesis gas (a mixture including carbon monoxide, hydrogen, carbon dioxide and methane) that can be converted into desired fuels. In pyrolysis the biomass is heated at high temperatures in the absence of oxygen. Fast pyrolysis results, after cooling of the gases, in a dark liquid with a heating value about half that of conventional fuel oil. Although the Fischer-Tropsch process has been in use since the first half of the 1900s, production of biofuel via this route is untried and is expected to be expensive. Fast pyrolysis is an advanced process requiring careful temperature control both in heating and cooling (Aatola *et al.* 2008). Figure 10 illustrates these processes.

5.3.4 Hydrotreating

Hydrotreating is an alternative process to produce biobased diesel fuels. Hydrogen is used to remove oxygen, resulting in paraffins with excellent fuel properties. Hydrotreated vegetable oils (HVO) are free of sulphur and aromatics and do not result in the stability problems, increased NOx emissions and deposits typical of biodiesel. Currently there is one plant producing HVO fuels in Finland, with others planned in Singapore and Rotterdam (Honkanen 2008).

6. Costs of biofuels

Figure 11 illustrates the costs of ethanol and biodiesel from current pathways. While other sources provide cost estimates differing from those shown, sources generally agree that the lowest cost biofuel option is sugarcane-based ethanol from Brazil. Ethanol costs in India are similar to those shown for China (i.e. around €0.4/litre) (Feller 2007). Production costs for biodiesel generally fall in the range of the higher cost sources of ethanol, except where waste vegetables oils are used as the feedstock. Johnston and Holloway (2007) estimate biodiesel costs of €0.4/litre for Malaysia and Indonesia and €0.5/litre in India and South Africa.

When considering this figure, it is important to bear in mind that feedstock costs play a major role in biofuel cost. Just as yields vary due to a variety of factors, feedstock costs vary both by nation and over time. As an example, US corn prices since 1998 have ranged from $1.50 to over $6.00 per bushel (€48/ton–€191/ton) (Good 2008). These price swings are a major problem for both ethanol and biodiesel producers, and can result in plant closures.

As can be seen from Figure 12, the only plant-based pathway that has consistently been competitive with fossil fuel-based transportation fuels is sugarcane-based ethanol. While it is projected that ethanol from lignocellulosic materials, as well as some biodiesel from plant materials, will be competitive in the range of currently prevalent oil prices by 2030, such projections are notoriously unreliable and do not provide a basis for current decisions. In sum, with the exception of sugarcane-based ethanol, primarily from Brazil, all biofuel supply and demand relies on government mandates and subsidies.

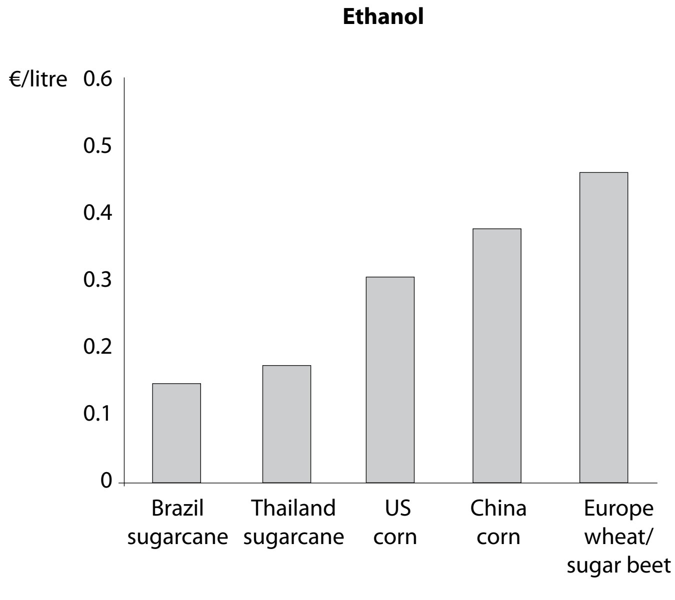


Figure 11. Illustrative costs for ethanol and biodiesel

Source: BiofuelsB2B

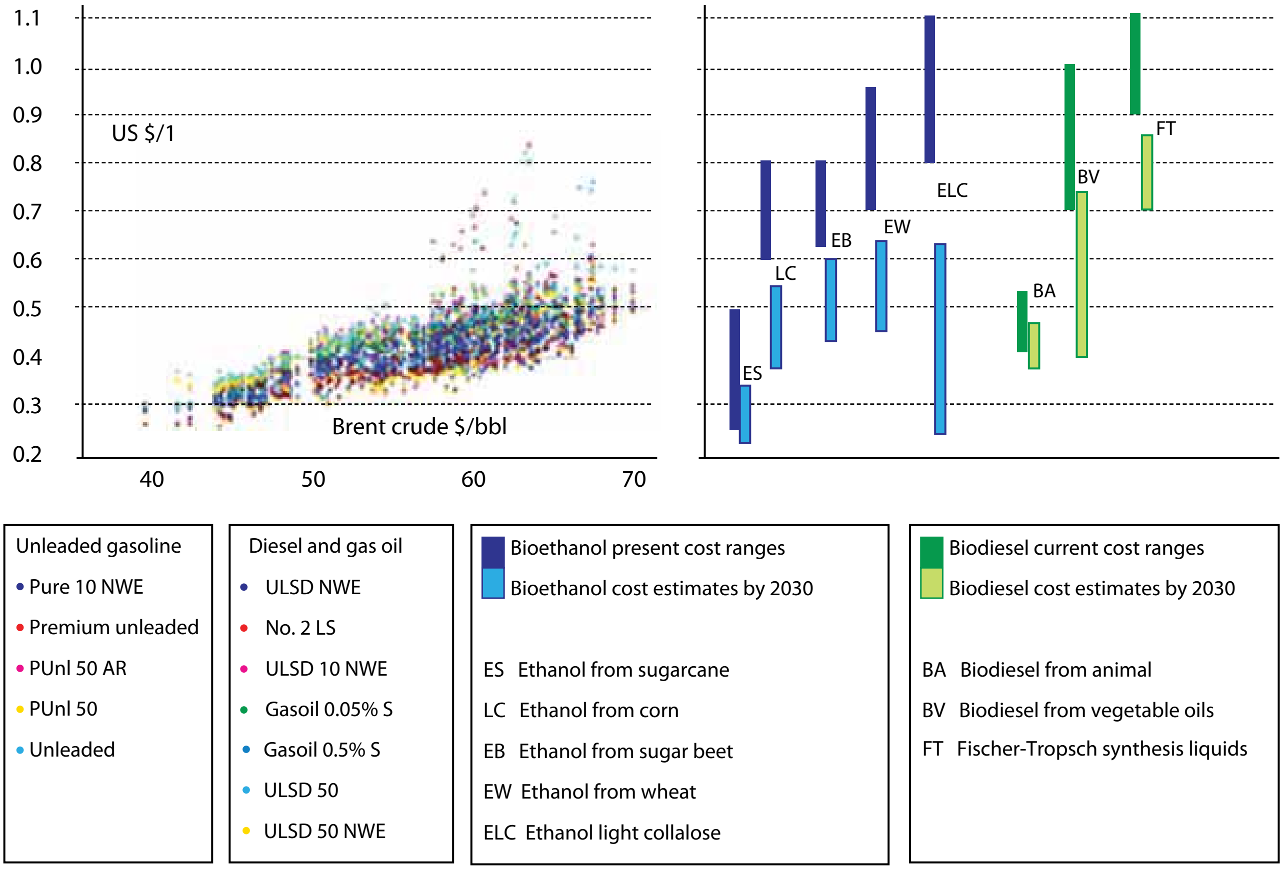


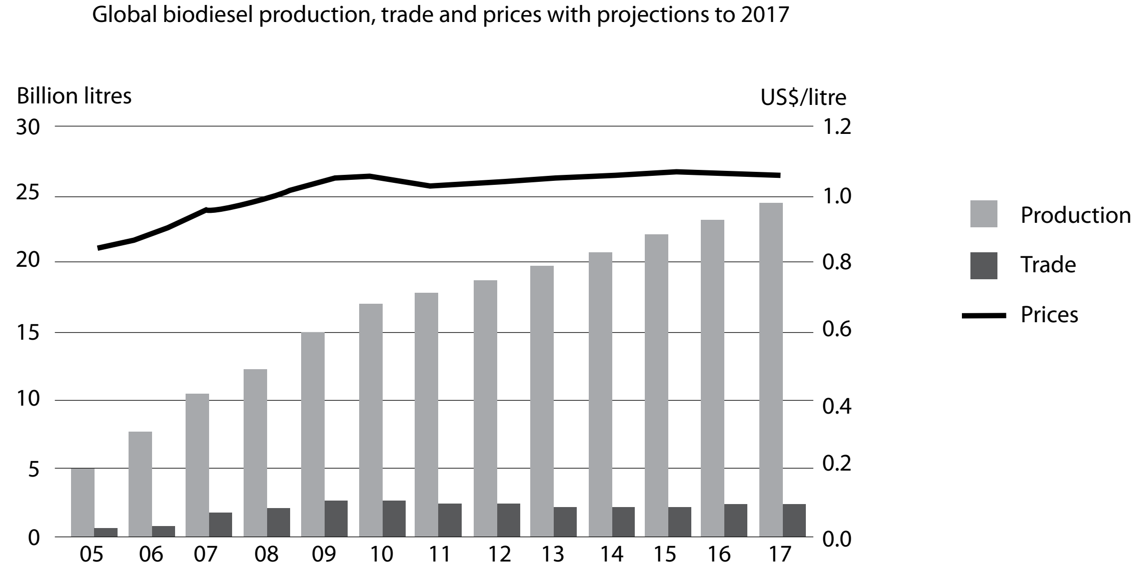
Figure 12. Current and projected costs of biofuels compared to oil prices

Source: IEA (2007)

7. Market opportunities

For developing countries interested in producing feedstocks or biofuels for export, the magnitude of fuels imported, as well as primary importing countries, will be important. As Figure 13 shows, trade in biofuels is, and is expected to remain, a small fraction of production.

Table 5 shows that Brazil, a major ethanol exporter, has been exporting more ethanol to India than to the United States, with exports to South Korea, Sweden and the Netherlands also significant.


Global biodiesel production, trade and prices with projections to 2017

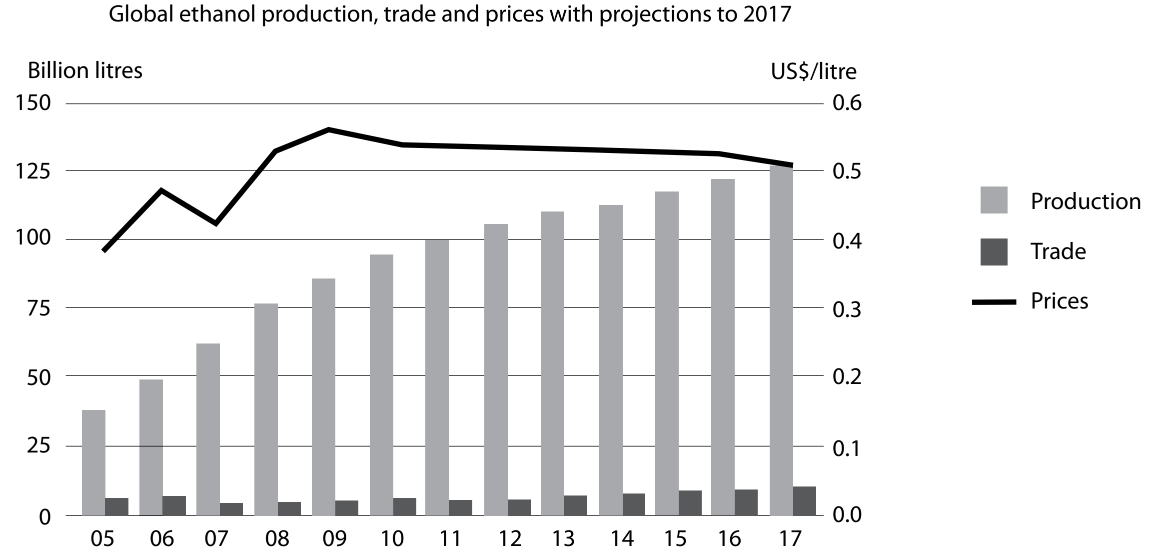

Global ethanol production, trade and prices with projections to 2017

Figure 13. Global ethanol and biodiesel production and trade 2005–2017

Source: OECD -FAO (2008)

Table 5. Major importers of Brazilian ethanol by country (in millions)

Country	2003		2004	
	US$	Litre	US$	Litre
Costa Rica	5.40	25.7	92.9	382.9
India	3.90	19.2	80.4	339.7
Jamaica	17.20	82.4	56.0	222.7
Japan	18.90	72.3	46.2	154.7
Mexico	8.70	32.4	44.3	178.5
Netherlands	18.40	67.8	36.4	133.5
Nigeria	11.40	38.2	27.2	107.5
Republic Korea	11.70	44.7	23.8	85.4
Sweden	21.40	79.5	23.2	93.4
USA	9.70	35.6	18.3	71.4
Others	31.20	106.0	49.0	155.9
Total	**157.90**	**605.9**	**497.7**	**1926.6**

Source: Lagercrantz (2006)

8. Overall greenhouse gas profiles

Since GHG reductions are important to both Europe and the United States, biofuels with low GHG profiles will be important to the extent that these are desired markets. Evaluations of the GHG savings of biofuels vary widely due to differences in assumptions regarding the multiple factors that contribute to GHG profiles. Assumptions include fertiliser use, productivity per hectare, machinery used in cultivation and harvesting, land use change, and conversion process fuel and efficiency.
An important factor in a biofuel's GHG profile is whether GHGs are split between a biofuel and its co-products, if any. If so, attributing part of a conversion process' GHG emissions to a co-product can significantly reduce the GHG profile of the biofuel. Figure 14 provides insight into the range of a product's GHG profile, in this case of corn-based ethanol.

Figure 15 shows default values proposed by the UK Department for Transport, illustrating how biofuel GHG profiles vary with feedstock and nation. Despite considerable variation in estimates of the GHG emissions from various biofuels, sugarcane-based ethanol from Brazil is generally agreed to have the lowest GHG profile among first generation pathways (Figure 15 also shows this). Sugarcane's high per-hectare productivity plus the use of bagasse for conversion energy are among the contributors to its low GHG profile[1].

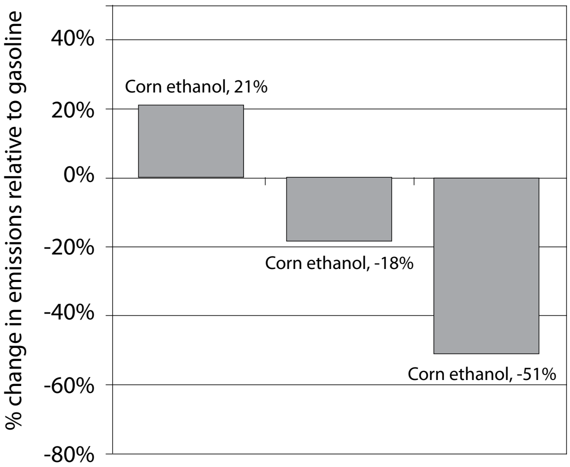


Figure 14. Corn ethanol greenhouse gas emissions compared to gasoline

Source: UCS (2007)

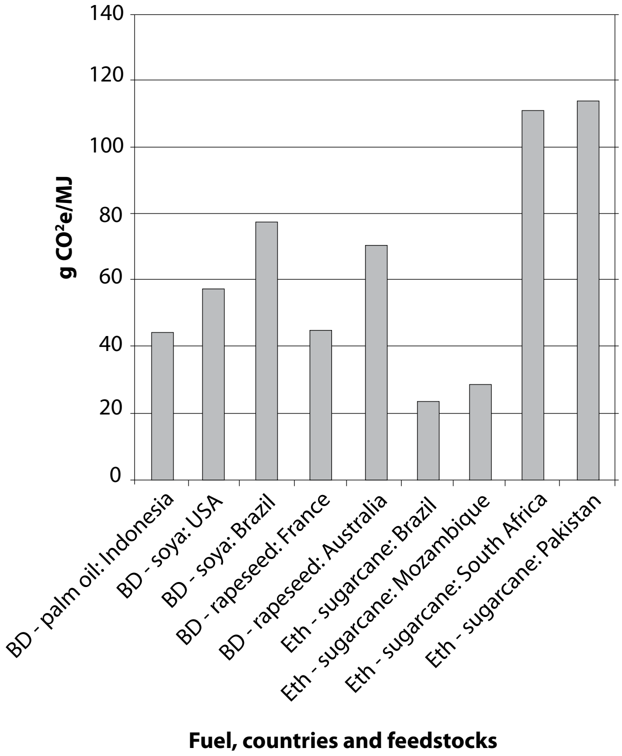


Figure 15. Fuel ethanol and biodiesel CO_2 emissions by feedstock and nation

Source: DFT (2008)

BD=biodiesel   Eth=ethanol

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[1] As an annually renewed source of biomass, bagasse has no net CO_2 emissions, at least if as much sugarcane is grown in subsequent years.

9. Conclusions

The production of liquid biofuels is seen as one option to mitigate global climate change by substituting a renewable resource for fossil fuel based transportation fuels and thereby reducing GHG emissions. Partly for this reason, and partly due to interests in energy security and support for rural areas, mandates and incentives to drive greater use of biofuels for transportation are being adopted in both developed and developing nations. For developing countries, increased income from trade and exports are also important goals. However, particularly due to carbon dioxide emissions caused by land use change driven by new biofuel production, the effectiveness of biofuels in reducing GHG emissions is open to question in many cases.

Current biofuel pathways in which both the feedstock and conversion technology qualify as first generation include bioethanol through fermentation of sugar crops and sugars derived from starches, and biodiesel through transesterification of oils from seeds. Second generation conversion technologies (i.e. technologies not yet deployed commercially) will be needed to produce biofuels from non-food-based materials such as lignocellulosic feedstocks (e.g. woodchips, straw, algae). Such technologies include thermochemical as well as enzymatic processes.

Currently ethanol represents 90% of all biofuels produced, primarily from corn (US) and sugarcane (Brazil). Biodiesel production (mainly from soya and rapeseed in the EU) accounts for 10%. In many developing countries, production of palm oil as a biodiesel feedstock is becoming increasingly important. Feedstock yields vary by species, soil, climate conditions and farming practices. Yields are an important issue due to competition for land with food production.

Oil seed crops like oil palm (Indonesia, Malaysia), soya (US, Brazil), rapeseed (EU) and jatropha (Asia and Africa) as well as waste oil (China) are mainly converted chemically to biodiesel (FAME) via transesterification. Sugar- and starch-based crops like sugarcane (Brazil, Australia, Mexico etc.), sugar beet (Chile, EU, Mexico), corn (US, Canada, China), rye (Russia) and wheat (China, Russia) mainly undergo fermentation to ethanol and a co-product animal feed.

In general, the simpler and easier the production chain, the cheaper the fuel production costs. The most common and least expensive form of production is still to generate bioethanol out of sugarcane. Land use options, competition between food and non-food production, efforts to avoid deforestation and climate change, and the level of oil and fuel prices influence worldwide biofuel production significantly. In terms of production costs, bioethanol from sugarcane is the only biofuel competitive with fossil based transportation fuels. High volatility in commodity prices affects first generation fuel production pathways significantly and can result in both booms and busts, including plant closures. For the foreseeable future, most ethanols, all biodiesels and all second generation pathways need additional support (e.g. subsidies or mandates) or rising fossil fuel prices to be a realistic opportunity to supply transportation fuels. For developing countries interested in producing feedstocks or biofuels for export, the magnitude of fuels imported by developed countries, particularly by their prime trading partners will be important.

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This report provides an overview of the state of the art of first and second generation biofuel production pathways. Information is provided on primary feedstocks, typical feedstock yields, available conversion technologies, biofuel production costs and market opportunities. In this report, a pathway element is considered first generation if it is deployed at commercial scale. Thus corn, sugarcane, oil palm, and soya are first generation feedstocks, whereas jatropha is a second generation feedstock. Conversion technologies are similarly divided into first and second generation according to their level of deployment. Preferred feedstock production systems depend on country or regional circumstances. Factors such as climate and soils, marketing opportunities, traditional crop and land uses, and local production costs determine preferred biofuel production pathways.

Currently the primary feedstocks for ethanol are corn and sugarcane, whereas soya, rapeseed and oil palm are the primary feedstocks used for biodiesel production. The easiest and lowest greenhouse gas (GHG) production path to ethanol is fermentation of sugarcane. Converting corn or similar starches into ethanol is more complex, because the raw material has to be converted to sugar prior fermentation. These pathways also tend to result in higher GHG emissions. Conversion of plant oils to biodiesel is primarily done via transesterification. Conversion of lignocellulosic materials (woodchips, straw, algae etc.) to ethanol or biodiesel requires second generation conversion technologies. Thermochemical processes can be used to convert these feedstocks into biodiesel (e.g., via Fischer-Tropsch processes), or enzymatic hydrolysis can be used to produce bioethanol.

Currently ethanol from sugarcane is the only biofuel that is cost-competitive with fossil-based transportation fuels. Both biodiesel via transesterification and biofuels produced via second generation conversion processes have high production costs and need subsidies or higher fossil fuel prices to be competitive. Although export of biofuels could be a source of income for developing countries, trade in biofuels is expected to remain a small fraction of total biofuel production.

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