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Recent advances on the production and utilization trends of bio-fuels: A global perspective

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Abstract

Bio-fuels are important because they replace petroleum fuels. There are many benefits for the environment, economy and consumers in using bio-fuels. Bio-oil can be used as a substitute for fossil fuels to generate heat, power and/or chemicals. Upgrading of bio-oil to a transportation fuel is technically feasible, but needs further development. Bio-fuels are made from biomass through thermochemical processes such as pyrolysis, gasification, liquefaction and supercritical fluid extraction or biochemical. Biochemical conversion of biomass is completed through alcoholic fermentation to produce liquid fuels and anaerobic digestion or fermentation, resulting in biogas. In wood derived pyrolysis oil, specific oxygenated compounds are present in relatively large amounts. Basically, the recovery of pure compounds from the complex bio-oil is technically feasible but probably economically unattractive because of the high costs for recovery of the chemical and its low concentration in the oil.

Keywords: Biomass; Bio-conversion; Bio-fuel; Bio-oil; Biogas; Chemicals; Ethanol; Bio-diesel

1. Introduction

Bio-fuel has been a source of energy that human beings have used since ancient times [1]. Increasing the use of bio-fuels for energy generation purposes is of particular interest nowadays because they allow mitigation of greenhouse gases, provide means of energy independence and may even offer new employment possibilities [2]. Bio-fuels are being investigated as potential substitutes for current high pollutant fuels obtained from conventional sources [3].

Energy problems are increasing in the world, and many countries are making use of their bio-fuel products resulting from very efficient agriculture and forestry industries. Products such as straw, grasses, wood shavings, sawdust, roots, branches, leaves and bark are used in some form for energy production. The way to use these products is by direct burning or by the production of gaseous or liquid derivatives, e.g. methane

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or ethanol. Sometimes these bio-fuel products are mixed with semi-fossil peat and fossil coal for obtaining better control of the burning process. Another growing market for bio-fuels is the production of briquettes and pellets for the consumer market.

Bio-fuels are important because they replace petroleum fuels. Bio-oil can be used as a substitute for fossil fuels to generate heat, power and/or chemicals. Upgrading of bio-oil to a transportation fuel is technically feasible but needs further development. There are many benefits for the environment, economy and consumers in using bio-fuels. Beyond the energy benefits, development of bio-fuels promotes rural economies that produce crops used for bio-fuels. Transportation fuels, such as methanol and Fischer–Tropsch fuels, can be derived from bio-oil through synthesis gas processes. Furthermore, there is a wide range of chemicals that can be extracted or derived from bio-oil.

Some advantages of bio-fuels are the following [4]:

- Bio-fuels represent a carbon dioxide (CO_2) cycle. In combustion, most of them have better emissions, are biodegradable and contribute to sustainability.
- Bio-fuels have considerable environmentally friendly potential.

The increase in bio-fuels utilization has also been accompanied over the past 3–4 years by policy decisions that encourage future growth of these fuels. In North America, policies that help grain based ethanol compete in the market were extended, and additional policies to increase bio-diesel utilization are being discussed. In Europe, guidelines to ensure motor fuels contain certain levels of alternate fuels have been established, and bio-fuels are expected to be the primary way these goals are met. In South America, Brazil also continued policies that mandate at least 22% ethanol in engine fuels and encourage the use of vehicles that use hydrous ethanol to replace gasoline. In the past decade, the use of bio-fuels has increased dramatically to a total volume of approximately 30 billion (30×10^9) l in 2003. The increase in the use of bio-diesel has been particularly rapid, growing from essentially zero in 1995 to more than 1.5 billion liters in 2003. The use of ethanol and ethanol derived ethyl-tertiary-butyl-ether (ETBE) has also grown steadily, experiencing a nearly threefold increase in a decade [5].

The international bio-fuel market is still at an early and very dynamic stage. Future conditions for an international bio-fuel market in Europe will largely be decided by the European Union (EU) policies on renewable energy and their interplay with national energy policies. So far, the Commission has indicated that biomass will play an important role in the future. In that context, bio-fuel trade seems to be a plausible scenario for Europe. It is likely that seemingly strange trade flows will appear and disappear as this new fuel market evolves [6].

The aim of the present paper is to investigate bio-fuels produced from biomass materials by thermochemical and biochemical methods and the utilization trends of the products in the world.

2. Biomass conversion processes to bio-fuels

Bio-fuels are liquid or gaseous fuels made from plant matter and residues, such as agricultural crops, municipal wastes and agricultural and forestry by products. They can substitute for conventional fuels in vehicle engines—either totally or partially in a blend [7]. Bio-fuels are made from biomass through biochemical or thermochemical processes. Biochemical conversion of biomass is completed through alcoholic fermentation to produce liquid fuels and anaerobic digestion or fermentation, resulting in bio-gas. Anaerobic digestion of biomass has been practiced for almost a century and is very popular in many developing countries such as China and India. The organic fraction of almost any form of biomass, including sewage sludge, animal wastes and industrial effluents, can be broken down through anaerobic digestion into methane and carbon dioxide. This "bio-gas" is a reasonably clean burning fuel that can be captured and put to many different end uses such as cooking, heating or electrical generation [8]. Bio-gas is an environmentally friendly, clean, cheap and versatile fuel [9]. Fig. 1 shows the deployment of anaerobic digestion in the EU and the world.

The chief commercial product, sugar, is extracted from sugar cane by removing the juice. The remainder of the plant, called "bagasse", still contains the chemical energy of the sun. As with any biomass, bagasse produces heat when burned. Ethanol, another biomass fuel, is an alcohol distilled mostly from corn. The potential

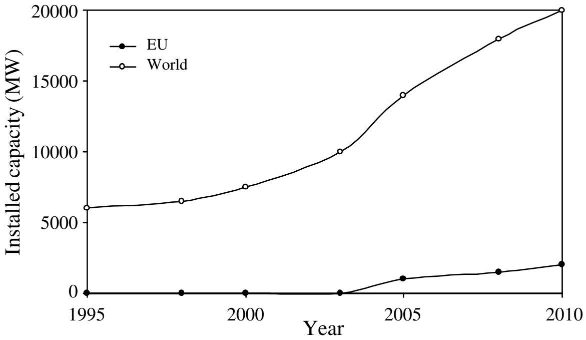

Fig. 1. Deployment of anaerobic digestion in the EU and the world.

for ethanol production from wood and other lignocellulosics is much greater than that from corn. Sugar cane, sugar beet, corn and sweet sorghum are agricultural crops presently grown commercially for both carbohydrate production and animal feeds [8]. Ethanol is also produced from a wet milling process. Many larger ethanol producers use this process, which also yields products such as high fructose corn sweetener. Ethanol is most commonly used to increase octane rating and improve the emissions quality of gasoline. Ethanol is blended with gasoline to form an E10 blend (10% ethanol and 90% gasoline), but it can be used in higher concentrations such as E85 or E95. Original equipment manufacturers produce flexible fuel vehicles that can run on E85 or any other combination of ethanol and gasoline [10,11].

Among the liquid bio-fuels, bio-diesel, derived from vegetable oils, is gaining acceptance and market share as Diesel fuel in Europe and the United States. The technical aspects of bio-diesel are approached, such as the physical and chemical characteristics of methyl esters, relative to its performance in compression ignition engines. Bio-diesel has become more attractive recently because of its environmental benefits and the fact that it is made from renewable resources [12]. Bio-diesel fuel can be made from new or used vegetable oils and animal fats, which are non-toxic, biodegradable, renewable resources. The fats and oils are chemically reacted with methanol or ethanol (methanol is the usual choice) to produce chemical compounds known as fatty acid methyl esters. Bio-diesel can be produced by a variety of esterification technologies [10]. Direct use or blending, microemulsions, thermal cracking and transesterification of vegetable oils have been explored as potential alternatives to Diesel. Direct use of vegetable oils and the use of blends of oils have several problems. Microemulsions with alcohols have been prepared to overcome the problem of the high viscosity of vegetable oils. Microemulsions of sunflower oil in Diesel have also been synthesized. Pyrolysis/cracking, defined as the cleavage to smaller molecules by thermal energy, of vegetable oils over petroleum catalysts has been investigated [13]. Since the prices of edible vegetable oils are higher than that of Diesel fuel No. 2, waste vegetable oils and non-edible crude vegetable oils take priority over the edible vegetable oils in bio-diesel production [14]. A comparison of the fuel properties of bio-diesel and No. 2 Diesel fuels are tabulated in Table 1.

Benefits include reduced unburned hydrocarbons, carbon monoxide and particulate matter. Bio-diesel offers safety benefits over petroleum Diesel because it is much less combustible, with a flash point greater than 423 K compared to 350 K for petroleum Diesel. It is safe to handle, store and transport. Bio-diesel is safe, biodegradable and reduces serious air pollutants such as particulates, carbon monoxide, hydrocarbons and air toxics. Blends of 20% bio-diesel with 80% petroleum Diesel (B20) can be used in unmodified Diesel engines, or bio-diesel can be used in its pure form (B100) but may require certain engine modifications to avoid maintenance and performance problems. Using bio-diesel in a conventional Diesel engine substantially reduces emissions of unburned hydrocarbons, carbon monoxide, sulfates, polycyclic aromatic hydrocarbons, nitrated polycyclic aromatic hydrocarbons and particulate matter. These reductions increase as the amount of bio-diesel blended into the Diesel fuel increases. The best emissions reductions are seen with B100. Scientists believe carbon dioxide is one of the main greenhouse gases contributing to global warming. Neat bio-diesel (100% bio-diesel) reduces carbon dioxide emissions by more than 75% relative to petroleum Diesel. Using a blend of 20% bio-diesel reduces carbon dioxide emissions by 15% [11].

Table 1
Comparing of fuel properties of biodisel and No. 2 Diesel fuels

Property	Biodiesel	No. 2 Diesel
Specific gravity, kg/L	0.87–0.89	0.84–0.86
Cetane number	46–70	47–55
Cloud point, K	262–289	256–265
Pour point, K	258–286	237–243
Flasf point, K	408–423	325–350
Sulfur, wt.%	0.0000–0.0024	0.04–0.01
Ash, wt.%	0.002–0.01	0.06–0.01
Iodine number	60–135	–
Kinematic viscosity, 313 K	3.7–5.8	1.9–3.8
Higher heating value, MJ/kg	39.3–39.8	45.3–46.7

Source: Refs. [10,11].

Table 2
Merits and demerits of different processes of biomass conversion to hydrogen

Conversion process	Merits	Demerits
Steam gasification	Maximum product can be obtained	Significant gas conditioning is required
Fast pyrolysis	Bio-oil and chemicals are produced	Changes of catalyst deactivation
Solar gasification	High hydrogen yield can be obtained	Requires effective collectors
Supercritical fluid extraction	Products can be obtained without gasification	Selection of supercritical medium
Microbialfermentation	Wastewater can also be treated simultaneously	Selection of suitable microorganisms

Source: Ref. [19].

Hydrogen can be produced economically from woody biomass [15]. Biomass can be thermally processed through gasification or pyrolysis to produce hydrogen. The main gaseous products from biomass are the following [16]:

$$\text{Pyrolysis of biomass} \rightarrow H_2 + CO_2 + CO + \text{Hydrocarbon gases}$$

$$\text{Catalytic steam reforming of biomass} \rightarrow H_2 + CO_2 + CO$$

$$\text{Gasification of biomass} \rightarrow H_2 + CO_2 + CO + N_2$$

Hydrogen from organic wastes has generally been based on the following reactions:

$$\text{Solid waste} \rightarrow CO + H_2$$

$$\text{Biomass} + H_2O + \text{Air} \rightarrow H_2 + CO_2$$

$$\text{Cellulose} + H_2O + \text{Air} \rightarrow H_2 + CO + CH_4$$

Hydrogen is produced from pyroligneous oils produced from the pyrolysis of lignocellulosic biomass [17]. Conventional pyrolysis of biomass is associated with the product of interest that is high charcoal content, but fast pyrolysis is associated with the products of interest that are tar, at low temperature (675–775 K) [18], and/or gas, at high temperature [15]. Table 2 shows a comparison of the different conversion processes for hydrogen production on the basis of the relative merits and demerits of the treatments [19].

3. Bio-fuels in the world

Brazil and the United States have the largest programs promoting bio-fuels in the world. The EU is in the third rank of bio-fuel production world wide, behind Brazil and the United States. In Europe, Germany is the largest and France the second largest producer of bio-fuels [20]. In 2002, the German Parliament decided to exempt all bio-fuels from the gasoline tax. The exemption is in force only until the end of 2009, and a report by the government on progress in market introduction of bio-fuels and on the price development of biomass, crude oil and fuels is required every other year to allow for adaptations if necessary [21].

According to the International Energy Agency (IEA), scenarios developed for the USA and the EU indicate that near term targets of up to 6% displacement of petroleum fuels with bio-fuels appear feasible using conventional bio-fuels, given available crop land. A 5% displacement of gasoline in the EU requires about 5% of available crop land to produce ethanol, while in the USA, 8% is required. A 5% displacement of diesel requires 13% of USA crop land and 15% in the EU. Land requirements for bio-diesel are greater, primarily because average yields (liters of final fuel per hectare of crop land) are considerably lower than for ethanol. Land requirements to achieve 5% displacement of both gasoline and Diesel would require the combined land total of 21% in the USA and 20% in the EU [22].

The dwindling fossil fuel sources and the increasing dependence of the USA on imported crude oil have led to a major interest in expanding the use of bio-energy. The recent commitment by the USA government to increase bio-energy threefold in 10 years has added impetus to the search for viable bio-fuels. The EU has also adopted a proposal for a directive on the promotion of the use of bio-fuels with measures ensuring that bio-fuels account for at least 2% of the market for gasoline and Diesel sold as transport fuel by the end of 2005, increasing in stages to a minimum of 5.75% by the end of 2010 [23].

The large scale use of biomass energy in the EU would be facilitated by a European market for bio-fuels. Regions rich in biomass resources could become net exporters of bio-fuels to regions with fewer opportunities for bio-fuel production, which would increase the Union's total use of biomass energy. Inter-regional and international bio-fuel trade is also a likely consequence of the growing use of biomass energy. At the moment, there is a mounting interest in bio-fuel trade in Europe [6]. Sweden has good access to biomass, and the total use of bio-fuel in 2001 was 98 TW h, or about 16% of the country's total energy supply. The Swedish National Energy Administration estimated that up to 160 TW h of bio-fuel could be used in Sweden by the year 2010 [24].

The total bio-fuel consumption of China in the rural area in 2000 was 219 Mtce, among which straw and stalk accounted for 124 Mtce and firewood accounted for 95 Mtce. Only 15 Mtce was used by rural enterprises, the rest being mainly used in livelihood [1].

3.1. Ethanol in the world

In 2004, 3.4 billion gallons of fuel ethanol were produced from over 10% of the corn crop. Ethanol demand is expected to more than double in the next ten years. For the supply to be available to meet this demand, new technologies must be moved from the laboratories to commercial reality [25]. The world ethanol production is about 60% from feedstock from sugar crops. The Americas (North and South), including Brazil, produce 65%. Ethanol is a well-established bio-fuel for transport and industry sectors in several countries, notably in Brazil [25]. Fig. 2 shows the world ethanol production in 1990–2003.

Brazil's ethanol production in 2003 was 9.9 million tons over 20 times the European production. All petrol sold in Brazil contains around 25% ethanol [7]. The United States has used ethanol produced from maize in

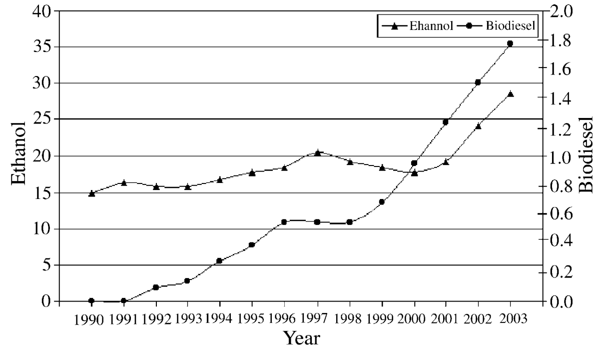

Fig. 2. Fuel ethanol and bio-diesel production, world total, 1990–2003 (billion liters) *Source:* Ref. [28].

fuel blends since the 1980s. The United States ethanol production, with corn as the primary feedstock, totaled 2821 million gallons in 2003 and is projected to increase to 4544 million gallons in 2025 [22].

India is the largest producer of sugar in the world. Presently, in India, ethanol is being marketed as a 5% blend with gasoline in nine states and about 500 mL would be needed for full implementation. A road map to increase it to 10% is envisaged. The total demand of ethanol is about 4.64 GL against the present/planned availability of about 744 mL, resulting in a scarcity of 3.89 GL ethanol in the year 2005–2006 [26].

Ethanol production for 2003 was 446,140 tons in the EU-25 (Table 3). Only five countries produced ethanol. Spain is the largest producer with 180,000 tons in 2003. Spain is the leading ethanol producer, followed by Poland, France, Sweden and the Czech Republic. The use of ethanol as a direct blend in petrol is increasing. At present, France, Spain and Poland convert most or all their ethanol production into ETBE; Sweden and the Czech Republic use their ethanol production directly [7]. Via a chemical process, ethanol can be transformed to ETBE, which can be added to petrol up to 15%. ETBE consists of 47% ethanol and 53% fossil fuel [20]. ETBE production for 2002 in the EU was 568,000 tons from two countries [27].

In France, ethanol transformation into ETBE started in 1993. Today, the three existing facilities have a capacity of 219,000 tons/year. Around 800,000 tons of ethanol is currently produced in France, 75% of which are made from sugar beet and 25% from cereals. The high share of sugar beet is also due to the fact that 1 hectare (ha) of sugar beet can produce 5.5 tons of ethanol, whereas one hectare of wheat only brings 2.5 tons of ethanol. 85,000–100,000 tons of ethanol are used for ETBE production. Only 14,000 ha of the 440,000 ha of sugar beet produced in France every year are used for ethanol production [20].

3.2. Bio-diesel in the world

The world total bio-diesel production was around 1.8 billion liters in 2003 (Fig. 2) [28]. Fig. 3 shows the world bio-diesel capacity between 1991 and 2003. In the EU, bio-diesel is by far the biggest bio-fuel and represents 82% of the bio-fuel production [29]. Bio-diesel production for 2003 in the EU-25 was 1,504,000 tons from nine countries (Table 4). Germany led production, followed by France and Italy. All these countries increased production during 2003, in particular Germany and Italy where the impact of legislation favorable to bio-diesel is helping to encourage the increase. According to the European Commission's 2004 figures, Germany produced an estimated 715,000 tons in 2003, France produced 357,000 tons and Italy produced 273,000 tons [7].

Pure bio-diesel use is predominant in Germany. It was only in 2004 that also the sale of a mix of bio-diesel and fossil Diesel started there. The production capacity per year rose from 90,000 tons to 1,060,000 tons in 2004, and the sale reached 1,000,000 tons, which makes Germany the largest bio-diesel producer in Europe. In 2005, the capacity is supposed to increase to 1,600,000 tons. In January 2004, there were 1800 filling stations for bio-diesel existing. The production capacity varies greatly—between 2000 and 150,000 tons/year. In France, bio-diesel production started in 1992. In 2004, the production capacity was 520,000 tons, which makes

Table 3
EU-25 ethanol production in 2003

Country	Ethanol (tons)
Germany	–
France	77,200
Italy	–
Czech Republic	5000
Denmark	–
Austria	–
United Kingdom	–
Spain	180,000
Sweden	52,300
Poland	131,640
Total (EU-25)	446,140

Source: Ref. [7].

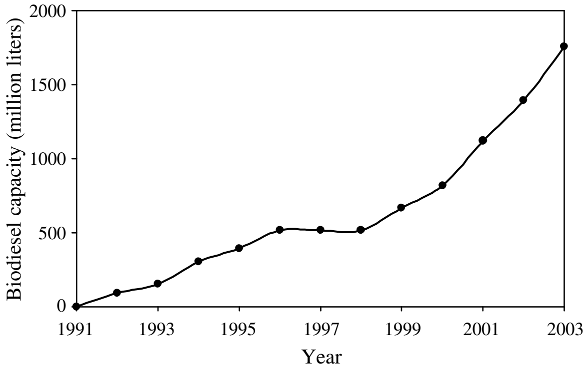

Fig. 3. World bio-diesel capacity, 1991–2003 (*Source*: Ref. [22]).

Table 4
EU-25 biodiesel production (tons)

Country	2002	2003	2004[a]
Germany	450,000	715,000	1,088,000
France	366,000	357,000	502,000
Italy	210,000	273,000	419,000
Czech Republic	68,800	70,000	47,000
Denmark	10,000	41,000	44,000
Austria	25,000	32,000	100,000
United Kingdom	3000	9000	15,000
Spain	–	6000	70,000
Sweden	1000	1000	8000
Poland	–	–	1200
Hungary	–	–	2000
Total (EU-25)	1,133,800	1,504,000	2,296,200

[a] Estimates (*Source:* Refs. [7,29]).

Table 5
Crude biogas production in 2002 in EU (thousands of tons oil equivalent)

Country	2001	2002	Growth (%)
United Kingdom	904	952	5.3
Germany	600	659	9.8
France	276	310	12.3
Spain	134	168	25.4
Italy	153	155	1.3
The Netherlands	161	134	−16.8
Sweden	112	115	2.7
Denmark	73	62	−15.1
Austria	56	59	5.4
Belgium	45	56	24.4
Greece	33	42	27.3
Ireland	28	28	0.0
Finland	18	18	0.0
Luxemburg	2	2	0.0
Portugal	1	2	100.0
Total	2596	2762	6.4

Source: Ref. [27].

France the second largest bio-diesel producer in Europe. In contrast to Germany, French bio-diesel is exclusively sold as a mix with either 5% or up to 30% bio-diesel added to fossil diesel [20].

3.3. Situation of bio-gas in the world

During the year 2002, the total production of crude bio-gas of the countries of the EU amounted to 2762 ktoe (thousands of tons of oil equivalent). European production took a 6.4% leap forward compared with the figures for 2001 (Table 5). The United Kingdom is the number one country in Europe with 952 ktoe produced in 2002. Biogas is one sector that has really been able to take advantage of the liberal framework established in Britain. Germany is found in second place with 659 ktoe, recording a 9.8% advance with respect to 2001 [27].

A total of about 3.4 million family size biogas plants had been installed all over India by December 2002. This is only 28.3% of the total potential (12 million) of the family size biogas plants that can be put in India [9].

The existence of 15 million tons of municipal solid waste and the production of 4.6×10^9 m^3 of urban and industrial sewage (with a collection and burial cost of US$ 225 million) in Iran points to the value of developing biogas technology [30].

4. Properties of bio-fuels from woody biomass

The properties of pyrolysis oil from wood are listed in Tables 6–8. It is typically a liquid, almost black through dark red brown. The density of the liquid is about 1200 kg/m^3, which is higher than that of fuel oil and significantly higher than that of the original biomass. The viscosity of the oil varies from as low as 25 cp up to 900 cp depending on the water content, the amount of light ends and the extent to which the oil has aged. The bio-oils have water contents of typically 14–33 wt.%, which can not be removed by conventional methods like distillation. Phase separation may occur above certain water contents. The higher heating value (HHV) is below 27 MJ/kg (compared to 43–46 MJ/kg for conventional fuel oils).

In wood derived pyrolysis oil, specific oxygenated compounds are present in relatively large amounts. Basically, the recovery of pure compounds from the complex bio-oil is technically feasible but probably economically unattractive because of the high costs for recovery of the chemical and its low concentration in the oil. A large fraction of the oil is the phenolic fraction, consisting of relatively small amounts of phenol, eugenol, cresols and xylenols and much larger quantities of alkylated (poly-) phenols (the so-called water insoluble pyrolytic lignin). It has showed good performance as an adhesive for water proof plywood. Components that can

Table 6
Elemental analysis for the wood derived bio-oil (wt.% moisture free)

C	H	O	N	S	Ash	HHV (MJ/kg)
56.8–65.9	5.8–7.9	28.7–38.3	0.07–0.41	0.00–0.03	0.02–0.24	19.8–26.7

Pyrolysis conditions: temperature: 775–925 K; particle size: 025–0.65 mm.

Table 7
The properties for the wood derived bio-oil

Water content (wt.%)	Density (kg/m^3)	Viscosity cP, at 315 K	Pour point (K)	Yield of distillate (wt.%)			
				430 K	466 K	492 K	516 K
14–33	1120–1260	30–960	245–270	10	20	40	50

Pyrolysis conditions: temperature: 775–925 K; particle size: 025–0.65 mm.

Table 8
The yield of products from the wood derived bio-oil

Organic liquid	Gaseous materials	Char	Water
61–68	8–12	6–9	10–14

Pyrolysis conditions: temperature: 775–925 K; particle size: 025–0.65 mm.

also be derived from bio-oil are carboxylic acids. In the aqueous fraction of the bio-oil, these acids are present in small amounts.

Gasification of bio-oil with pure oxygen and further processing of the crude synthesis gas in Fischer–Tropsch processes may become technically and economically feasible. Experimental tests are conducted in gasifying bio-oil, gasification with air and pure oxygen.

5. Bio-fuel economy

Before tax, bio-fuels are currently appreciably more expensive than conventional fuels. The explanatory memorandum to the originally proposed bio-fuels directive states that bio-diesel costs approximately €0.50/l to manufacture, while replacing 1 l of conventional Diesel requires 1.1 l of bio-diesel. Mineral Diesel costs (net of tax) some €0.20–0.25/l. These figures suggest that pure bio-diesel is on the order of 120–175% more expensive [5].

Most of the bio-diesel that is currently made uses soybean oil, methanol and an alkaline catalyst. The high value of soybean oil as a food product makes production of a cost effective fuel very challenging. However, there are large amounts of low cost oils and fats, such as restaurant waste and animal fats, that could be converted to bio-diesel. The problem with processing these low cost oils and fats is that they often contain large amounts of free fatty acids (FFA) that cannot be converted to bio-diesel using an alkaline catalyst [31].

The cost of bio-diesel is higher than that of Diesel fuel. Currently, there are seven producers of bio-diesel in the United States. Pure bio-diesel (100%) sells for about $1.50 to $2.00 per gallon before taxes. Fuel taxes will add approximately $0.50 per gallon. A mix of 20% bio-diesel and 80% Diesel will cost about 15¢ to 20¢ more per gallon over the cost of 100% Diesel [32]. The cost of bio-diesel production results in a generally accepted view of the industry in Europe that biodiesel production is not profitable without fiscal support. Table 9 shows the cost and return scenario for a 60,000 ton bio-diesel plant [33].

A review of 12 economic feasibility studies shows that the projected costs for bio-diesel from oil seed or animal fats have a range US$0.30–0.69/l, including meal and glycerin credits and the assumption of reduced capital investment costs by having the crushing and/or esterification facility added onto an existing grain or tallow facility. Rough projections of the cost of bio-diesel from vegetable oil and waste grease are, respectively, US$0.54–0.62/l and US$0.34–0.42/l. With pre-tax Diesel priced at US$0.18/l in the US and US$0.20–0.24/l in some European countries, bio-diesel is thus currently not economically feasible, and more research and technological development will be needed [34].

The most important reason for the failure of bio-gas technology is that the initial cost is often prohibitive for most rural households. The typical cost of a simple, unheated biogas plant, excluding the cost of land, is between $50 and $75 per cubic meter capacity [35].

Table 9
Cost and return scenario for a 60,000 tons biodiesel plant

	Million Euros
Income	
60,000 tons biodiesel at €617/ton	37.03
7500 tons 80% glycerine at €500/ton	3.75
Undetermined amount of free fatty acids sold as livestock feed	
Total income	40.78
Expenses	
60,900 tons vegetable oil at €520/ton	31.67
6000 tons methanol at €265/ton	1.59
Undetermined amount of NaOH included in variable costs	
Undetermined amount of HCl included in variable costs	
€30 million investment amortized over 10 years at 10% interest	4.70
Variable costs equal to fixed costs	4.70
Total cost	42.66

Source: Ref. [33].

6. Conclusion

There are many benefits for the environment, economy and consumers in using bio-fuels. Bio-oil can be used as a substitute for fossil fuels to generate heat, power and/or chemicals. Bio-fuels are made from biomass through thermochemical processes such as pyrolysis, gasification, liquefaction and supercritical fluid extraction or biochemical processes. Biochemical conversion of biomass is completed through alcoholic fermentation to produce liquid fuels and anaerobic digestion or fermentation to produce biogas. In wood derived pyrolysis oil, specific oxygenated compounds are present in relatively large amounts.

Basically, the recovery of pure compounds from the complex bio-oil is technically feasible but probably economically unattractive because of the high costs for recovery of the chemical and its low concentration in the oil.

Ethanol, bio-diesel and bio-gas are the most useful fuels from agricultural sources. Ethanol demand is expected to more than double in the next ten years. For the supply to be available to meet this demand, new technologies must be moved from the laboratories to commercial reality. The world ethanol production is about 60% by feedstock from sugar crops. Most of the bio-diesel that is currently made uses soybean oil, methanol and an alkaline catalyst. The high value of soybean oil as a food product makes production of a cost effective fuel very challenging. However, there are large amounts of low cost oils and fats such as restaurant waste and animal fats that could be converted to bio-diesel.

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