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Research and Development Trends in Energy Crops and Biofuel Conversion Technologies

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1 Introduction

To solve global warming problems and ensure sustainable development of the economy, it is necessary to increase the use of renewable biomass resources. The magazine "Science & Technology Trends", published articles on the possibilities of bio-energy and the trends in the technological developments, spread and introduction of policies adopted in many countries[1,2]. In recent years, there have been active movements to accelerate the spread of liquid biofuels as alternative to gasoline and diesel fuel in a large number of countries, for enhancing their energy security, managing high crude oil prices and overcoming gloval warming problems.

Recently, international crude oil prices have risen rapidly and temporarily exceeded US$80/barrel. The increases in prices were due to various factors such as the risk of political instability, the rapid development of BRICs' economy, and the disruption of oil supply infrastructures by natural disasters. Considering that the world production of oil will inevitably reach its peak in the medium or long term, it is most likely that the trend for oil prices to increase will continue. In such a tough situation, most of the transportations such as automobiles, aircrafts and ships continue to depend on crude oil by the reason of no alternatives for economically providing energy.

In many countries, it is generally recognized that it is urgently necessary to reduce dependence on oil for transport energy. Thus, much attention is concentrated on research on energy crops to provide biomass as an energy resource and on low-cost biofuel conversion technologies indispensable for the widespread adoption of bio-energy.

In Japan, where self-sufficiency in food is 40% at most, discussions on biomass use have been limited to the utilization of domestically unused wastes as energy resources, given that any increase in producing biomass as an energy resource would be in competition with food production. Therefore, sufficient study has not been made of the requirements, such as the availability of biomass resources, costs and quality stability, for the large-scale introduction of biofuels as alternatives to crude oil. Japan has started somewhat late in its movement toward the commercialization of biofuels, compared with other countries where such movements are increasingly active.

This article reviews the potential of biofuels as alternatives to crude oil in the world and in Japan, and summarizes the research and development trends for energy crops and biofuel conversion technologies essential to the development of biofuels. In addition, it describes problems encountered in the efforts made in Japan to develop biofuel technologies, and discusses the issues on which future research should focus.

2 Present situation and potential of biofuels as transport energy resources

2-1 Social background to biofuel production

Carbon contained in biomass is derived from CO_2 fixed from the atmosphere while plants are growing. Biomass could be considered to be a carbon-neutral energy resource if the release of CO_2 into the atmosphere as a result of the combustion of biomass is counterbalanced by the fixing of CO_2 as part of the solar energy driven carbon cycle (Figure 1). Then, if the biomass is used as a fuel alternative to fossil resources-based fuels such as crude oil, it is possible to reduce the emissions of greenhouse gases during the life cycle of the biomass, and provide a very effective means to take measures against global warming[4].

Biomass-based liquid fuels, what are called biofuels, are the most likely of the potential renewable energy resources for transport energy to succeed, because it is relatively easy to introduce biofuels, independently or as a mixture with a fossil-based liquid fuel, into existing internal combustion engine and distribution infrastructures. In Japan, annual CO_2 emissions are now 1.36 billion tons-CO_2, of which the emissions from motor vehicles accounts for about 20%, or 2.3 million tons-CO_2[5]. If total CO_2 emissions in Japan were reduced by 20% by replacing all fuels for motor vehicles with carbon-neutral biofuels, emissions would decrease to 1.13 billion tons-CO_2, which is lower than the reduction target of 1.23 billion tons-CO_2 (6% lower than the level in 1990).

Amongst biomass-related technologies, there are various combinations of raw materials, conversion technologies and use patterns (Figure 2). Liquid biofuels are suitable for use as transport energy because of high energy density. At present, the use of biofuels is mostly confined to agricultural countries which have abundance of low cost energy crops (Figure 3). However, in Japan, which has scanty energy crop resources,

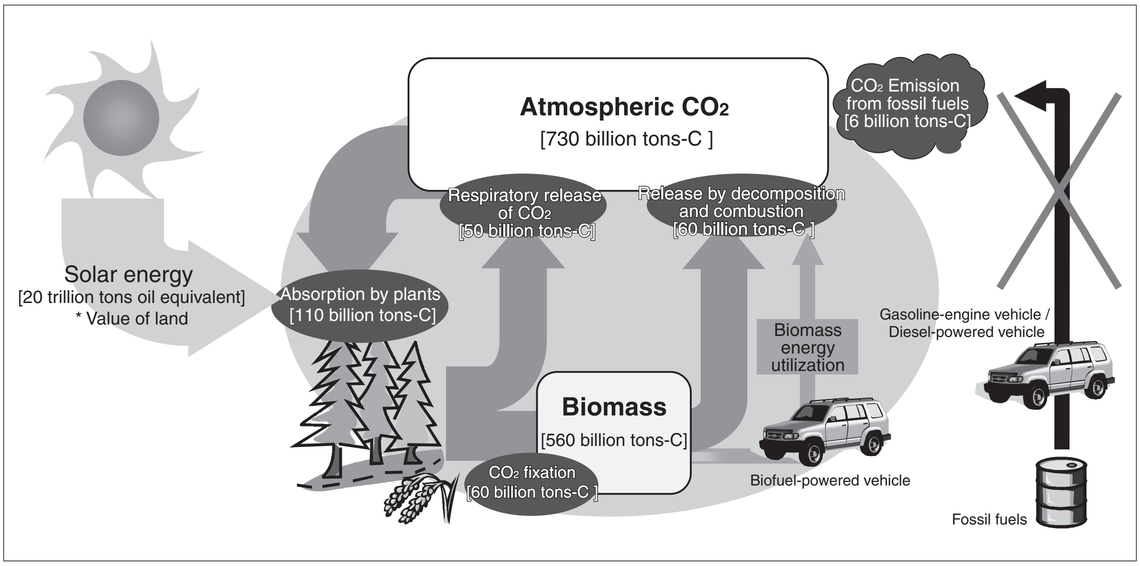

Figure 1 : Atmospheric carbon cycle and carbon-neutral biomass energy

Prepared by the STFC based on Reference[3]

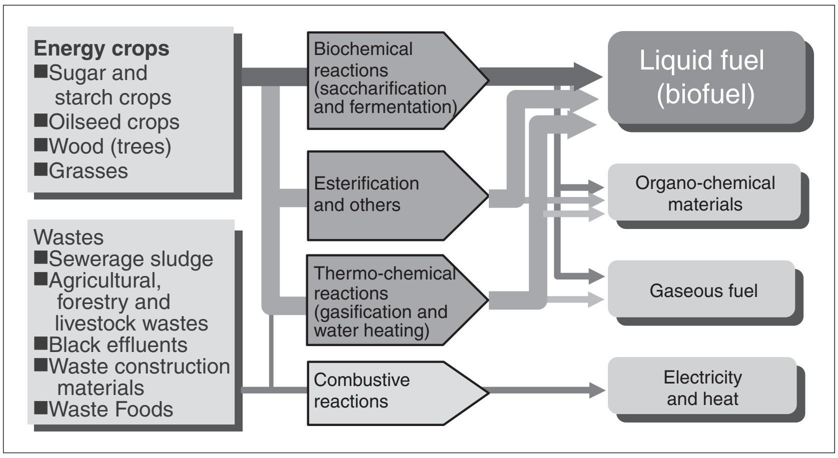

Figure 2 : Raw materials and use for biomass-related technologies

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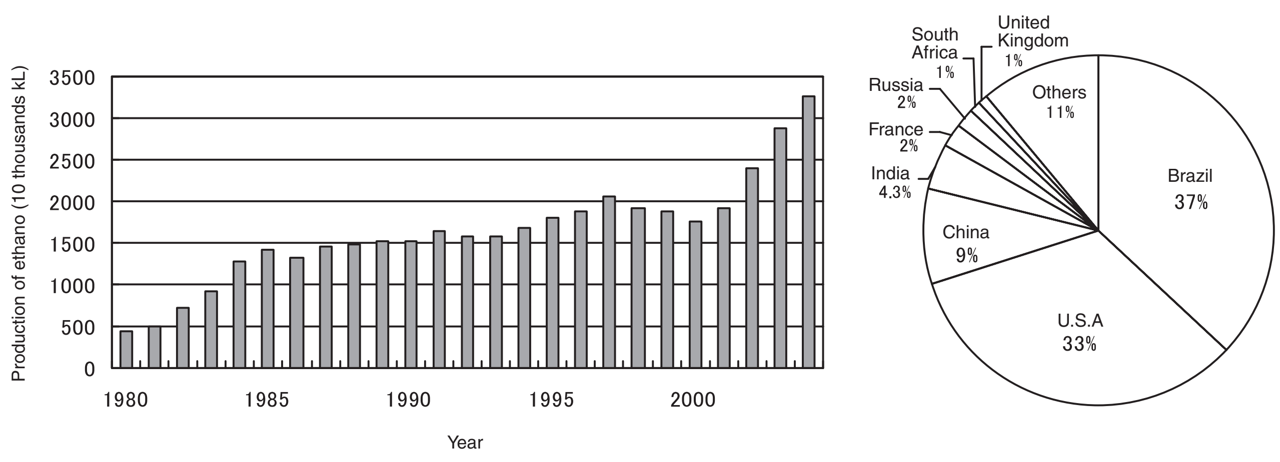

Figure 3 : World trend of bio-ehtanol production and each country's share in 2004

Prepared by the STFC based on Reference[6]

biofuels are produced mainly from waste-based resources such as waste construction materials and food oil, and the production of biofuels is extremely limited in regional and quantitative terms.

2-2 Global trends of biofuel promotion policy

There are many overseas countries where the spread and introduction of biofuels is actively promoted. In these countries, not only compulsory quantitative targets for the introduction of biofuels in the medium- and long-term established, but other measures for accelerating the spread of biofuels, including changes in the taxation system, are being established (Table 1). In the U.S.A. and the EU, importance is attached to promoting agriculture and forestry, both to ensure energy security and to take measures against global warming. In China, in addition to these challenges, greater importance is attached to coping with the increasing energy consumption by the growing economy. In Brazil and ASEAN countries, priority has primarily been given to industrial development and the eradication of poverty mainly by increasing exports to foreign countries. As a consequence, these countries are inevitably required to reduce the resultant adverse influences on the environment such as excessive deforestation of tropical rain forests.

Thus, the policies leading to the spread of biofuels had different origins in different countries. However, the policy in each country clearly considers biofuels to be alternatives to transport energy in the medium- and long-term. It is common to all countries that they have produced crops for energy (energy crops) with economical feasibility, have set quantitative targets for the introduction of biofuels, including compulsory targets, and established a variety of systems supporting the production and spread of biofuels.

In Japan as well, the "Kyoto Protocol Target Achievement Plan"[7], adopted by the Cabinet Council in April 2005, set a quantitative target of 500 thousand kl-crude oil equivalent for biofuels used in the transport sector. The "Biomass Nippon Strategy"[8], decided by Cabinet Council in March 2006, established the significance and objectives for the introduction biofuels, and has accelerated the implementation of the measures taken to promote the utilization of biofuels. In November 2006, Mr. Abe, Former Prime Minister, ordered an increase in the domestic production of biofuels, from the viewpoints of protecting the global environment and supporting regional development and agriculture. To comply with the Prime Minister's order, an implementation plan was developed by the "Biomass Japan Comprehensive Strategy Promotion Council" in which the Ministries and Agencies concerned, including the Ministry of Agriculture, Forestry and Fisheries, participated[9]. The industries concerned in Japan also provided a model for the large-scale production of low cost biofuels as well as their proposals on the roadmap for

Table 1 : Biofuels introduction policies by country

Region	Country	Mixing ratio	Materials	Vehicle provisions	Target / obligation to introduce biofuels	Actions to support the spread of biofuels
North America	U.S.A	E10/E85	Corn	E10 suitable vehicles marketed FFVs marketed	Obligatory quantitative targets for renewable fuels introduced were set under the Energy Policy Act in 2005 2006: 4.0 billion gallons (about 15 million kl, equivalent to 2.8% of the total gasoline distribution) 2012: 7.5 billion gallons (about 2.8 millions kl) Quantitative targets for the introduction of renewable and alternative fuels were set in the US president's State of the Union address in 2007 2017: 35 billion gallons (about 1.3 billion kl)	Fuel tax credit action Support and loan project for fuel manufacturers
		B2~5/B20/B100	Soybean and waste food oil	B10 and B100 suitable vehicles marketed		
	Canada	E5~10/E85	Corn, wheat and barley	E10 suitable vehicles marketed FFVs marketed	A quantitative target for the introduction of ethanol was set in the Ethanol Utilization Increase Program in 2003. 2010: 35% of the gasoline consumption will be replaced with E10.	Fuel tax reduction Financial support for the construction of fuel manufacturing facilities
Middle & South Americas	Brazil	E20/E25/E100	Sugar cane	E25 suitable vehicles marketed FFVs marketed	A compulsory mixing ratio of 20 to 25% ethanol to gasoline was imposed.	Actions for reducing the federal industrial tax and local tax on ethanol available vehicles
		B2	Soybean	B25 and B100 suitable vehicles marketed	A compulsory mixing ratio of bio-diesel to light oil was imposed (2% by 2008 and 5% by 2013).	Fuel tax reduction
Europe	EU	—	—	—	Quantitative targets for Biofuels introduction were set under the EU Biofuel Directive in 2003 and the EU Renewable Energy Road Map in 2007. 2005: A ratio of 2% of biofuel to transport fuel 2010: 5.75% biofuel to transport fuel (equivalent to 21 million kl) 2020: At least 10% biofuel to transport fuel The obligatory introduction of biofuel is under consideration under the Biomass Action Plan of 2005 and the Biofuel Strategy of 2006	Support for the cultivation of energy crops
	Germany	ETBE	Rye and wheat		A quantitative target for biofuel introduction was set under the EU Biofuel Directive in 2003 2005: A ratio of 2% of biofuel to transport fuel	Fuel tax reduction Support for the cultivation of energy crops
		B5/B100	Rapeseed	B100 suitable vehicles marketed		
	France	ETBE6~7	Sugar beat and wheat		A quantitative target for biofuel introduction was set under the EU Biofuel Directive in 2003 2005: A ratio of 3% biofuel to transport fuel	Fuel tax reduction Support for the cultivation of energy crops
		B5/B30	Rapeseed	B30 suitable vehicles marketed		
	United Kingdom	E5	Corn		Quantitative targets for biofuel introduction were set under the EU Biofuel Directive in 2003 2005: A ratio of 0.3% of biofuel to transport fuel 2010: A ratio of 5% of biofuel to transport fuel (*The compulsory introduction system will start to be implemented in 2008)	Fuel tax reduction Support for the cultivation of energy crops
	Sweden	E5/E85	Wheat	FFVs marketed	A quantitative targets for biofuel introduction were set under the EU Biofuel Directive in 2003 2005: A ratio of 3% of biofuel to transport fuel	Fuel tax reduction Support for the cultivation of energy crops
	Spain	ETBE3~4 ETBE6~7	Wheat and barley		A quantitative target for biofuel introduction was set under the EU Biofuel Directive in 2003 2005: A ratio of 2% of biofuel to transport fuel	Fuel tax reduction Tax exemptions for fuel manufacturers Support for the cultivation of energy crops
	Italy	B5/B30	Rapeseed and sunflower	B30 suitable vehicles marketed	A quantitative target for biofuel introduction was set under the EU Biofuel Directive in 2003 2005: A ratio of 2% of biofuel to transport fuel	Fuel tax reduction Support for the cultivation of energy crops
Asia	India	E5	Sugar cane		The introduction of E5 over the entire country began in 2003. The final goal is to spread E10 all over the country.	Fuel tax reduction
		B5	Jatropha		2005 to 2007: Demonstration testing 2007 to 2010: The supply area will be expanded, and B5 production and distribution facilities will be established. 2011 to2012: The introduction of B5 over the entire country will begin.	
	China	E10	Corn and wheat		A quantitative target for biofuel introduction was set under the Ethanol-Gasoline Introduction Plan in 2004. 2005: E10 was adopted in 4 provinces.	Consumption tax exemption for ethanol producers Support for the cultivation of energy crops Ethanol indirect tax refund action
	Thailand	E10	Cassava		A quantitative target for biofuel introduction has been set 2011: The introduction of E10 will be completed. .	Excise tax exemption for ethanol Support for E10 producers
		B2	Palm		Quantitative targets for biofuel introduction have been set. 2006: B2 introduction was completed. 2011: B3 introduction will be completed.	
	Philippines	E5	Sugar cane	E10 suitable vehicles marketed since 1995	A quantitative target for biofuel introduction was set under the National Ethanol Fuel Program in 2005. 2010: The introduction of E10 will be completed.	
		B1	Coconut		The compulsory use of B1 will be imposed on Government vehicles	
	Malaysia	B2~5	Palm		A quantitative target for biofuel introduction was set under the National Biofuel Policy in 2005.	
	Indonesia	B5	Palm		A quantitative target for biofuel introduction was set under the National Energy Management Law. 2025: The use of BDF will be 4.7 millions kl.	
Oceania	Australia	E10	Sugar cane	E10 suitable vehicles marketed	A quantitative target for biofuel introduction will be set under the Federal Government's Targets. 2010: 350 thousands kl	Support for ethanol producers

Abbreviations: E is ethanol, B is bio-diesel, and ETBE is ethyl tertiary-butyl ether. The figures are mixing ratios by volume.

Prepared by the STFC based on Reference[6] technological development, on research and development organization, and on cooperation with the other Asian countries[10].

However, Japan, unlike some overseas countries, has not yet introduced any biofuel that could compete in terms of cost with conventional fossil fuels. Therefore, obligatory medium- and long-term targets for the introduction of biofuels and incentives for the widespread distribution and adoption of biofuels, including changes to the tax system, have not been established in Japan.

2-3 Potential for supplying biofuels in view of land use availability

In contemplating introduction of biofuels as a full-scale alternative to conventional fossil fuels, it is necessary to take the potential competition over land between biofuels and food crops into consideration. It is predicted that the world population will reach a peak of about 9.2 billion around 2050[11]. The question is whether the world's agricultural lands will be able to supply the demands for both biofuel and food production at that time.

Table 2 : Estimations of biofuel supply potential in 2050

(a) Case based on predictions by the United Nations

Year	1970	2000	2015	2030	2050
World Population	3.7 billion	6.1 billion	7.1 billion	8.1 billion	9.1 billion
Annual demand for cereals per capita	0.33 t/capita	0.34 t/capita	0.33 t/capita	0.33 t/capita	0.33 t/capita
Warld's total annual demand for cereals	850 million t	2,040 million t	2,320 million t	2,680 million t	3,010 million t
Annual yield per area	1.3 t/ha	2.9 t/ha	3.3 t/ha	3.3 t/ha	3.3 t/ha
Necessary area for food producing	650 million ha	670 million ha	700 million ha	810 million ha	910 million ha
Required increase in food producing area (over the area in 2000)					240 million ha
Area available for energy production					260 million ha
Annual production of ethanol (estimated)					1,030 million kl

(b) Case assuming increased demand for foods

Year	1970	2000	2015	2030	2050
World Population	3.7 billion	6.1 billion	7.1 billion	8.1 billion	9.1 billion
Demand for cereals per capita	0.33 t/capita	0.34 t/capita	0.35 t/capita	0.37 t/capita	0.41 t/capita
World's total annuals demand for cereals	850 million t	2,040 million t	2,500 million t	3,010 million t	3,760 million t
Yield per area	1.3 t/ha	2.9 t/ha	3.3 t/ha	3.3 t/ha	3.3 t/ha
Necessary area for food producing	650 million ha	670 million ha	760 million ha	910 million ha	1,140 million ha
Required increase in food producing area (over the area in 2000)					470 million ha
Area available for energy production					30 million ha
Annual production of ethanol (estimated)					130 million kl

(c) Case assuming increased yield/ha

Year	1970	2000	2015	2030	2050
World Population	3.7 billion	6.1 billion	7.1 billion	8.1 billion	9.1 billion
Demand for cereals per capita	0.33 t/capita	0.34 t/capita	0.35 t/capita	0.37 t/capita	0.41 t/capita
World's total annuals demand for cereals	850 million t	2,040 million t	2,500 million t	3,010 million t	3,760 million t
Yield per area	1.3 t/ha	2.9 t/ha	3.3 t/ha	3.6 t/ha	3.9 t/ha
Necessary area for food producing	650 million ha	670 million ha	760 million ha	850 million ha	960 million ha
Required increase in food producing area (over the area in 2000)					290 million ha
Area available for energy production					210 million ha
Annual production of ethanol (estimated)					860 million kl

Prepared by the STFC based on References[11-14]

The total area of land in the world is 145 billion ha, of which present agricultural land accounts for about 10 % of the total area[12]. A United Nations' FAO study reports that the total area of agricultural lands may be increased by about 1.8 billion ha[13]. However, 60% of the increase in agricultural land area will be forests and reserves, and 2/3 of them will be defective in terms of soil quality and topography. Therefore, if these areas are subtracted, it is estimated that the real increase in agricultural land area may be about 500 million ha.

Based on the United Nations' projections for the demand for cereals, it will be necessary to increase the food producing area by 240 million ha by 2050 when the world population is expected to reach its peak. Therefore, if the increase of 240 million ha in food producing area is subtracted from the total increase in agricultural land, the biofuels producing area is estimated at 260 million ha in 2050. The potential annual production of ethanol is estimated to be about 1.0 billion kl from this biofuels-producing area, assuming that the biomass productivity is 10dry-t/ha and the ethanol conversion efficiency is 0.4kl/dry-t (Table 2 (a)). The United Nations' projection assumes that future demands for cereals per capita will be almost the same as at present. However, the figure for future consumption seems to be rather low, considering the high economic growth in developing countries. The demand for cereals per capita has increased by 10% for the past 30 years. Supposing that this rate of increase will continue in the future, it is estimated that the potential annual production of ethanol would be decreased to 130 million kl (Table 2 (b)).

There are two possible approaches to ensuring the compatibility of the supply of foods with that of biofuels as described hereinafter. The first approach is to increase the yield of crops per hectare. The estimation above was based on the assumption that increases in the yield per hectare will level off after 2015. The yield of cereals per hectare increased at an annual rate of 3% in the 1960s, and it has increased at an annual rate of 1.5% since 1980s. It is predicted that the annual rate of increase will decrease to 1.1% by 2015[14]. Assuming that the yield per hectare increases at an annual rate of 1% after 2015, the potential annual production of ethanol in 2050 will be about 860 million kl (Table 2 (c)). It can be expected that this value will be readily attained if the productivity of crops is effectively improved by applying gene modification technologies to crops.

The second approach is by establishing innovative biofuel production technologies. In the U.S.A. and the EU, these technologies are generically known as the "second-generation" biofuel technologies, and research in this field has become increasingly active in recent years (Table 3). This is especially true of research in technologies for converting lignocellulose into ethanol at a low cost. Lignocellulose has not previously been widely used in biofuel production.

Lignocellulose is the main component of the plants cells in woods and caules (woody stems), and has the highest quantitative potential from the viewpoint of energy resources. It is composed mainly of cellulose, hemicellulose and lignin

Table 3 : Second-generation biofuels

	Type	Designation	Raw materials	Production technologies
Bio-ethanol	1st generation	Conventional bio-ethanol	Sugar beet (sugar) Cereals (starch)	Hydrolysis (saccharification) + fermentation
	2nd generation	Cellulose-based bio-ethanol	Woods and herbage (Lignocellulose)	Pretreatment Hydrolysis (saccharification) + fermentation
Bio-diesel	1st generation	Fatty acid methyl ester (FAME)	Vegetable oil crops (e.g. rapeseed) Waste food oil	Pressure extraction + ester exchange
	2nd generation	BTL (Biomass to Liquid)	Woods and herbage (Lignocellulose)	Gasification + FT synthesis
		BHD (Bio-Hydrofined Diesel)	Vegetable oil crops & animal fats	Hydrogenolysis

Prepared by the STFC based on References[15-16]

(Figure 4).

However, while there are simple technologies for converting saccharides and starches in relatively wide use, there are no practical technologies for converting lignocellulose into ethanol[4]. If a suitable technology for converting lignocellulose into ethanol is developed, not only the starches and saccharides produced by cereals, but all parts of the plant including their stems and leaves, and also grasses and trees, will be effectively used as raw materials for producing ethanol. Thus, the amount of natural resources available for producing biofuels will be significantly increased. In the U.S.A. and Europe, therefore, much attention is concentrated on research on technologies for converting lignocellulose into ethanol.

2-4 Potential of biofuels in Japan

Here, the potential of biofuels in Japan is considered in terms of quantity and cost. The Biomass Japan Comprehensive Strategy Promotion Council estimates that it will be possible to produce 6 million kl/year of ethanol using domestic biomass resources in Japan (Table 4). To avoid competition with food production, it is supposed that non-food herbage-based biomass such as straw, and wood-based biomass such as the residual woods in forest lands will be used as raw materials for producing ethanol and that energy crops, such as rice and sorghum, will be grown on currently unused land.

In addition, the case for importing ethanol produced overseas as well as producing ethanol domestically using biomass resources

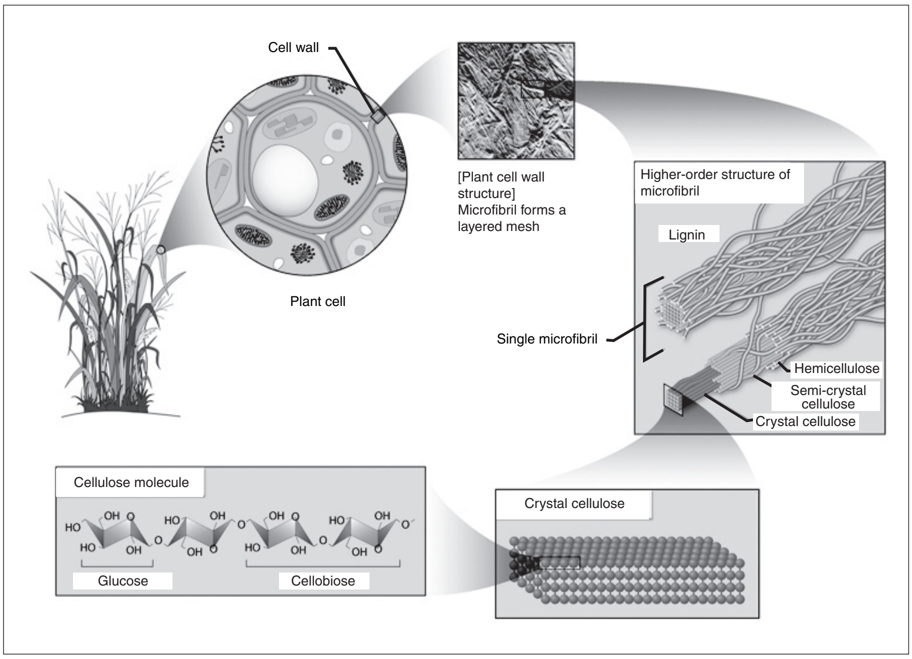

Figure 4 : Plant fiber structure and lignocellulose

From Reference[16]

Table 4 : Presumption of Japan's domestic biofuel supply under the Biomass Japan Comprehensive Strategy Promotion Council

Raw materials	Predicted Production (FY2030)	
	Ethanol equivalent kl	Crude oil equivalent kl
1. Sugar and starch (by-products in food production processes and sub-standard agricultural products)	50 thousand kl	30 thousand kl
2. Herbage (such as rice straw and wheat straw)	1,800 to 2,000 thousand kl	1,100 to 1,200 thousand kl
3. Energy crops (such as rice and sugar beet)	2,000 to 2,200 thousand kl	1,200 to 1,300 thousand kl
4. Woods (such as waste construction materials and residual timber from forest lands)	2,000 to 2,200 thousand kl	1,200 to 1,300 thousand kl
5. Bio-diesel fuels	100 to 200 thousand kl	60 to 120 thousand kl
Total	Approx. 6,000 thousand kl	Approx. 3,600 thousand kl

From Reference[9]

is considered. A comparison of the two cases is shown in Figure 5. Bio-ethanol fuels which can compete with gasoline in price have already been distributed in the U.S.A. and Brazil, countries which are more advanced in terms of biofuels. In assessing the economics of importing bio-ethanol fuels from these countries, it is of course necessary to add to their prices the overhead costs of importing and distributing the fuel, customs charges on the imported fuels, and the investment costs for an ethanol distribution infrastructure. However, even when these costs are added to the prices for bio-ethanol fuels produced either in the U.S.A from corn or from sugar cane in Brazil, the lower limit of the estimated price range for ethanol fuels is lower than the gasoline prices in Japan, and prices are sufficiently competitive with the latter. In contrast, if ethanol is produced in Japan on the same scale as in the U.S.A. and Brazil using wheat as the cheapest edible cereal produced in Japan (at the price of 164 yen/kg), its price is estimated to equal or exceed 450 yen/l excluding gasoline tax. At these prices Japanese produced bio-ethanol would not be cost competitive with gasoline and the ethanol fuels produced overseas.

If ethanol is produced domestically in Japan, using domestic irregular rice not suitable for human consumption as a raw material (at the price of 20 yen/kg), its price without gasoline tax may be almost competitive with the prices for overseas produced ethanol and gasoline. The amount of irregular rice would have been limited in Japan and would not fill up the demand of bio-ethanol fuel. However, if non-edible rice, whose taste and appearance are not taken into account,

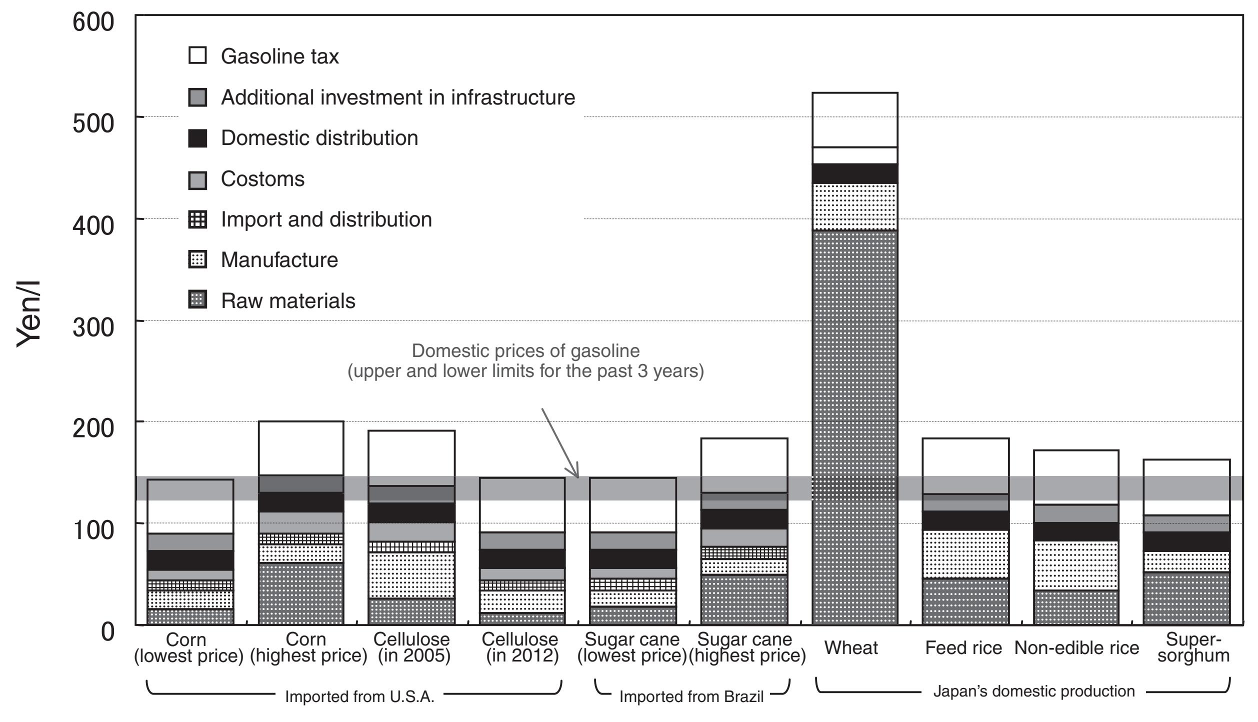

Figure 5 : Breakdown price comparison between import and domestic production of bio-ethanol in Japan

[Assumptions used in the calculations]

i) Corn produced in the U.S.A.: The upper and lower limits of the prices for ethanol produced in the U.S.A. (free on oil tank yard) for the past 3 years. Plant capacity: 263 thousand kl/year. Ethanol made in U.S.A was transported by 1.9 DT chemical tankers. $1 = ¥120. Alcohol customs tariff: 23.8%.

ii) Cellulose produced in the U.S.A.: The costs for raw materials and manufacture are based on the real prices in 2005 and the US Dept. of Energy target values for 2012. The other values are as in Item i) above.

iii) Sugar cane produced in Brazil: The upper and lower limits of the prices for ethanol imported from Brazil (free on oil tank yard) for the past 3 years. The other values are as in Item i) above.

iv) Domestic wheat and feed rice: The costs for raw materials are based on the statistics provided by the Ministry of Agriculture, Forestry and Fisheries. Plant capacity: 36 thousand kl/year.

v) Non-edible rice: Based on a large-scale production model on a reclaimed land located in the Prefecture of Mie. The unpolished-rice harvest process was used. Rice hulls and straw were effectively used. The manufacturing costs are based on the US Dept. of Energy target values for 2012 as in Item ii) above.

vi) Super-sorghum: High-yield "ultra-sorgo" based on Reference[20]. The manufacturing costs are based on the US Dept. of Energy target values for 2012 as mentioned in Item ii) above.

Prepared by the STFC based on References[17-20]

is mass-produced domestically (at a price of 15 yen/kg) and if effective technologies for using the lignocellulose in the whole rice plant are developed, it is estimated that the price (without gasoline tax) for ethanol produced domestically from non-edible rice may be sufficiently competitive with the price of gasoline. Thus, the supply of domestic ethanol will be achievable on an economic and profitable basis, if Japan can satisfy the requirements for ethanol production already prevailing in the U.S.A. and Europe; these include "innovative technologies for conversion of biomass into ethanol", "the large-scale production of raw materials" and "fuel tax incentive system".

However, realistically, the ability of Japan to satisfy the requirements for the agricultural lands required for the large-scale production of raw materials, is limited[10]. The total area of unused agricultural lands which could be available to cultivate energy crops is 390 thousand ha (Table 5), of which about 80% is in small scattered lots not greater than 5 ha in size[21].

To achieve large-scale introduction of biofuels into Japan, the importation of overseas-produced ethanol must also be considered. However, it should be noted that the ethanol price volatilities in the U.S.A and Brazil have been extremely large, compared with the gasoline prices, for the past three years. The reasons must be that raw materials for ethanol production are limited to corn in the U.S.A and to sugar cane in Brazil, that the production of these materials depends on regional weather conditions and natural disasters, and the prices of these materials are liable to be volatile as speculation-driven futures markets. In the U.S.A., R&D efforts have been actively made to develop second-generation biofuel technologies in order to diversify the range of raw materials, including lignocellulose, for ethanol production and consequently to ensure a stable supply of biofuels at a cost comparable to that for corn-based ethanol.

From the short-term viewpoint of energy security, it is important for Japan to make efforts to develop and diversify domestic energy resources, such as improving the use of conventional fossil fuels, and increasing Japanese interests for developping overseas agricultural land for energy crops. To secure the projects in overseas, there is a long-term need for Japan to increase R&D efforts in developing its own second-generation biofuel technologies that cannot be provided by other countries, especially those rich in biomass resources.

3 Trends and problems in the development of second-generation biofuel technologies

This chapter describes trends in the R&D efforts aimed at overcoming the major barriers to the development of second-generation biofuel technologies. The R&D areas can be roughly classified into following 3 types.

Table 5 : Land use in Japan

Mountainous lands	25 million ha	Natural forests	15 million ha		
		Artificial forests	10 million ha	Forests in service	3.3 million ha
				Unused forests	6.7 million ha
Flat lands	13 million ha	Agricultural lands	4.7 million ha	Paddy fields	1.6 million ha
				Production-adjusted land	1.0 million ha
				Non-paddy fields and pastures	2.1 million ha
		Lakes, ponds, rivers and channels	1.3 million ha		
		Roads	1.3 million ha		
		Housing lands	1.8 million ha		
		Others (including 0.39 million ha of unused agricultural lands)	3.9 million ha		

Prepared by the STFC based on References[22-23]

3-1 Energy crop production technology

Energy crops can be roughly classified into cereals, herbage (soft biomass), woods (hard biomass) and oil plants and can be compared in terms of dry matter yield per unit area of land. Within each of these classifications there are several candidates for use as energy crops (Table 6). Unlike edible crops, energy crops are primarily required to maximize dry matter yields per unit input of energy used to grow the crop with the lowest possible production costs; they do not need to satisfy any requirement for taste, color or shape quality. To minimize the competition for land between energy crop and edible crop production, it is assumed that energy crops can be produced on less fertile lands than edible crops. There is a large accumulation of research on increasing the production of edible crops and improving their resistance to adverse environmental influences. However, whether or not this accumulated knowledge can be effectively used for the production of energy crops is likely to depend on the weather and soil conditions of agricultural lands supposed to use for energy crops. It is unlikely that energy crops can be produced on the lands that suffer

Table 6 : Representative energy crops and research and development trends

Classi-fication	Variety	Dry yield [t / (ha • year)]	Research trend
Sugar and starch crops	Sugar cane (Sorghum)	64.1 (Tropical, Hawaii) 49.5 (Subtropical, Okinawa) 28.8 (Temperate, Nagano)	Increasing the production of sugar by gene modification (Asahi Breweries, ltd., and National Agricultural Research Center) Improving resistance to environmental stresses (SCIVAX Co., ltd.)
	Corn	34.0 (Temperate, Italy)	Deciphering the genome (US DOE/DOA) Developing hybrid varieties containing easily decomposable cellulose (Edenspace System Corp., US)
	Rice	19.2 (Temperate, Iwate)	Deciphering the genome (Japan and China) High-yield rice cultivars (Japan)
	Potato	9.0 (Temperate)	Improving resistance to environmental stresses by gene transfer (Toyobo Co. , ltd.); conferring resistance to blight (Toyota Central R&D Labs., Inc.); and deciphering the genome (US DOE/DOA)
Vege-table oil crops	Palm (oil palm)	20.0 (Tropical)	
	Rape	1.4-2.5 (Temperate)	Increasing the production of unsaturated fatty acid by gene modification (The Dow Chemical Company /U.S. NRC)
	Soybean	1.8-2.3 (Temperate)	Increasing the production of unsaturated fatty acid by gene modification (Suntory , ltd.) Deciphering the genome (US DOE Joint Genome Institute) Analyses of the proteome and metabolome (Australia)
Herbage	Napier grass	84.7 (Tropical, Puerto Rico)	
	Guinea grass	48.8 (Tropical, Puerto Rico) 51.1 (Subtropical, Okinawa) 24.3 (Temperate, Kumamoto)	
	Switchgrass	16.0 (Temperate, U.S.A.)	Deciphering the genome (US DOE)
	Giant Miscanthus	60.0 (Temperate)	Development of a hybrid varieties, euralia genus, rice family (Illinois University, US)
	Others		Methods for growing a variety of perennial herbs in devastated agricultural lands (Minnesota University, US)
Trees	Poplar	15-22 (Temperate, U.S.A and Ireland)	Deciphering the genome (US DOE Joint Genome Institute / Oak Ridge National Laboratory)
	Eucalyptus	10-30 (Tropical and subtropical)	Cultivation in acidic soils (Oji Paper Co., ltd.)
	Japanese white birch	7.4-10.8 (Subarctic, Hokkaido)	
	Willow	19.0-20.5 (Hokkaido)	
	Japanese cedar	4-7 (Hokkaido)	

Prepared by the STFC based on References[4,24-29] from extremely dry weather and those that are deteriorated by salt contamination. On the contrary, lands selected as candidates for energy crop production require soils which are not too acidic or alkaline soils and which have a reliable precipitation level. It is expected that unused agricultural lands which can meet these requirements exist around the world. In the future, it is urgently necessary for Japan to establish the requirements (in terms of weather and soil) that domestic and international lands must be suitable for production of energy crops, and to identify the targeted lands that meet these requirements for efficient research activity.

There are two main research areas of improving energy crop dry matter production.

One is the molecular biological approach to understanding the nutritive mechanisms of crops in research conducted to improve plant varieties so as to be adaptable to deteriorated lands. Recently, a research team in the University of Tokyo investigated the nutritive mechanism of iron in deteriorated soil, and published a report on the development of a high-productivity crop by gene modification. The report attracted widespread attention[23].

The second approach is to improve the suitability of varieties of crops for use in commercializing the technology used to convert lignocellulose into ethanol. Specifically, research in the U.S.A. has actively focused on increasing the dry matter yields of cereal plants other than their edible parts and on modifying the structures of plants to make them more easily converted to ethanol.

3-2 Lignocellulose-to-ethanol conversion technologies[3,4]

To manufacture bio-ethanol fuels from lignocellulose, it is necessary to add several processes to treat the plant material before the fermentation step used to produce ethanol (Figure 6). These processes are required to produce the starches and saccharides that are fermented into ethanol and include pre-treatment to unravel plant fibers, a process to convert cellulose and hemicellulose to saccharides (saccharification), and a process to remove lignin unnecessary for the fermentation to ethanol.

Sugar provided by conventional sugar and starch crops consists mainly of C6 saccharides such as glucose. If lignocellulose is saccharified, however, the product contains C6 saccharides and C5 saccharides such as xylose in the ratios of 2:1-3:1. Some of the conventional ferments have the disadvantage of not being able to ferment C5 saccharides, while others may restrict the fermentability of C5 saccharides in the presence of C6 saccharides. Thus, the conventional technologies cannot effectively use the saccharic

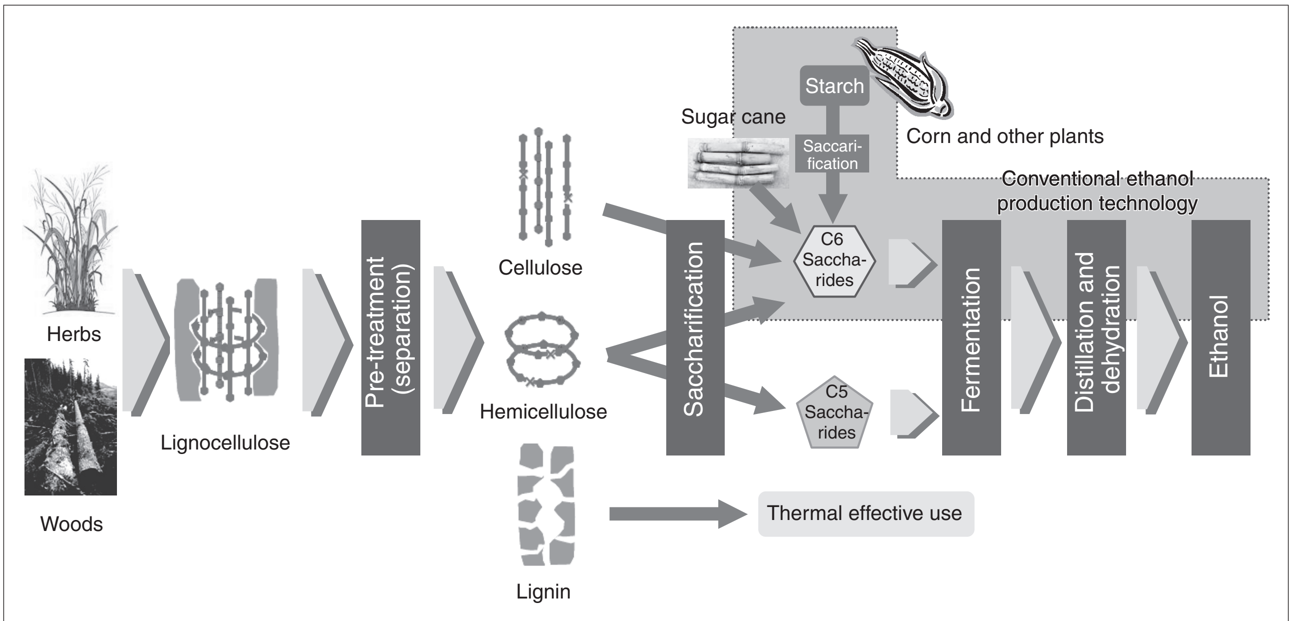

Figure 6 : Lignocellulose-to-ethanol conversion processes

Prepared by the STFC based on References[4,10] components of lignocellulose.

As a result, present commercialized technologies cannot produce lignocellulose based bio-ethanol fuels in a manner competitive with fossil fuels in terms of energy efficiency, production costs and environmental load.

In reviewing various technologies for converting lignocellulose into ethanol, the key factors in identifying and optimizing the best technology are (1) higher efficiency and lower cost of the pre-treatment and saccharification processes and (2) higher efficiency in the fermentation process. Therefore, these factors have been reviewed (Table 7).

To achieve the twin goals of higher efficiency and lower cost of the pre-treatment for the saccharification processes, the conventional acid hydrolysis process is being replaced with a promising new technique, "enzymatic saccharification" (Figure 7). The new technique can decompose cellulose by using specific enzymes, cellulases, under moderate conditions

Table 7 : Research on second-generation conversion technologies for lignocellulose-based ethanol fuels

Item	Research subject	Research institution	Research stage
Pre-treatment	Alkali treatment/lignin solubilization and removal	Forestry and Forest Products Research Institute (Japan)	Basic research
	Acidic treatment and non-crystallization of cellulose / separation of saccharides from hemicellulose / lignin removal by organosolation	Virginia Polytechnic Institute and State University (USA)	Basic research
	Lignin decomposition with white rot bacteria	Joint Genome Institute (USA) and Kyoto University (Japan)	Basic research
Saccharification	Saccharification and double-fermentation in parallel with on-site production of enzyme	University of Tokyo (Japan) and Lunds University (Sweden)	Basic research
	Production of enzyme by solid fermentation	University of Tokyo / Riken (Japan)	Basic research
	Production of different kind of enzyme with different species of bacteria	Kobe University / Gekkeikan Sake Co., ltd. (Japan)	Basic research
	Production of enzyme with gene-modified microbes (Trichoderma reesei)	Iogen Corporation (Canada)	Trial production
	Integration of pre-treatment and saccharification by steam/subcritical/critical water processing	Kyoto University (Japan) and British Columbia University (Canada)	Basic research
Fermentation	CO2 removal & on-line product separation	Kyowa Hakko Kogyo Co., ltd. (Japan)	Demonstration
	Simultaneous fermentation of C5/C6 saccharides by a gene-modified ferment	Pardue University (USA) / Iogen Corporation (Canada)	Trial production
	Fermentation of C5 saccharides with Pichia ferment and Zymomonas bacteria	Akita Research Institute for Food and Brewing (Japan), Tottori University (Japan) and NREL (USA)	Basic research
	Simultaneous saccharification and fermentation with cellulase, glucosidase gene-linked ferment on cell wall surface, and cellulase gene-transferred bacteria	Kyoto University / Kobe University (Japan) Dartmouth College / Mascoma Corporation (USA)	Basic research Demonstration
	Fast fermentation with yeasts resistant to heat and ethanol produced by gene modification	Massachusetts Institute of Technology (USA)	Basic research
Separation & concentration	Reduction of energy consumption by zeolite separation membranes	Kyowa Hakko Kogyo Co., ltd. (Japan)	Demonstration
	Continuous production with concentration switching membranes	National Agriculture and Food Research Organization / University of Tokyo (Japan)	Basic research
Production of by-products	Liquidation and conversion of cellulose and lignin	Department of Agriculture in University of Tokyo, Forestry and Forest Products Research Institute, and Kyoto University (Japan)	Basic research
	Production of valuable by-products from lignin	STFI-packforsk AB / Chalmers tekniska högskola / LignoBoost AB (Sweden)	Trial production
	Production of organic acid & polyhydric alcohol with separated bio-reactor	Argonne National Laboratory / Archer Daniels Midland Company (USA)	Basic research

Prepared by the STFC based on references[28-29,31-33] to produce saccharides, and are more energy efficient than acid hydrolysis. Strains of bacteria which could produce useful cellulases have been detected among the bacteria present in the internal organs of plant-eating animals and the bodies of white ants. Fungi producing cellulases are common in leaf mold. Gene modification technologies have been used in attempts to improve the efficiency of enzyme production[3].

The discovery of the cellulosome, an exocellular multiprotein complex specialized in cellulose degradation, lead to research becoming increasingly focused on the use of gene modification technology in the creation of complex plural enzyme function modules required in the cell wall decomposition process[37].

To achieve a higher efficiency in the fermentation process, ferments which can simultaneously ferment C5 and C6 saccharides have been subjected to gene modification technology linking a sacharifying enzyme with the surface layer of a second enzyme, with the aim of developing ferments which have a high resistance to ethanol and heat, and which can simultaneously undertake both saccharification and fermentation.

In the U.S.A. greater importance has been attached to the use of molecular genetics (Figure 8) to rapidly improve the productivity and reduce the cost of using enzyme technologies (Figure 9). To obtain new useful microbes, enzymes and metabolic routes, and to establish the enzymatic hydrolysis method, R&D efforts have been actively made to understand the genome/protein/metabolic mechanism linkages and to create a database of these mechanisms by using rapid analyzers and simulation techniques.

For example, a large enzyme manufacturer and the National Renewable Energy Laboratory (NREL) in the U.S.A published a report on the results of research aimed at understanding the interaction of cellulose and the enzyme (cellulase), particularly the active point of decomposition in the high-order structure of cellulose, with the intention of producing more active cellulases at a lower cost[16]. Today, a venture business supported by the US Department of Energy (DOE) is conducting preliminary testing prior to launching into the

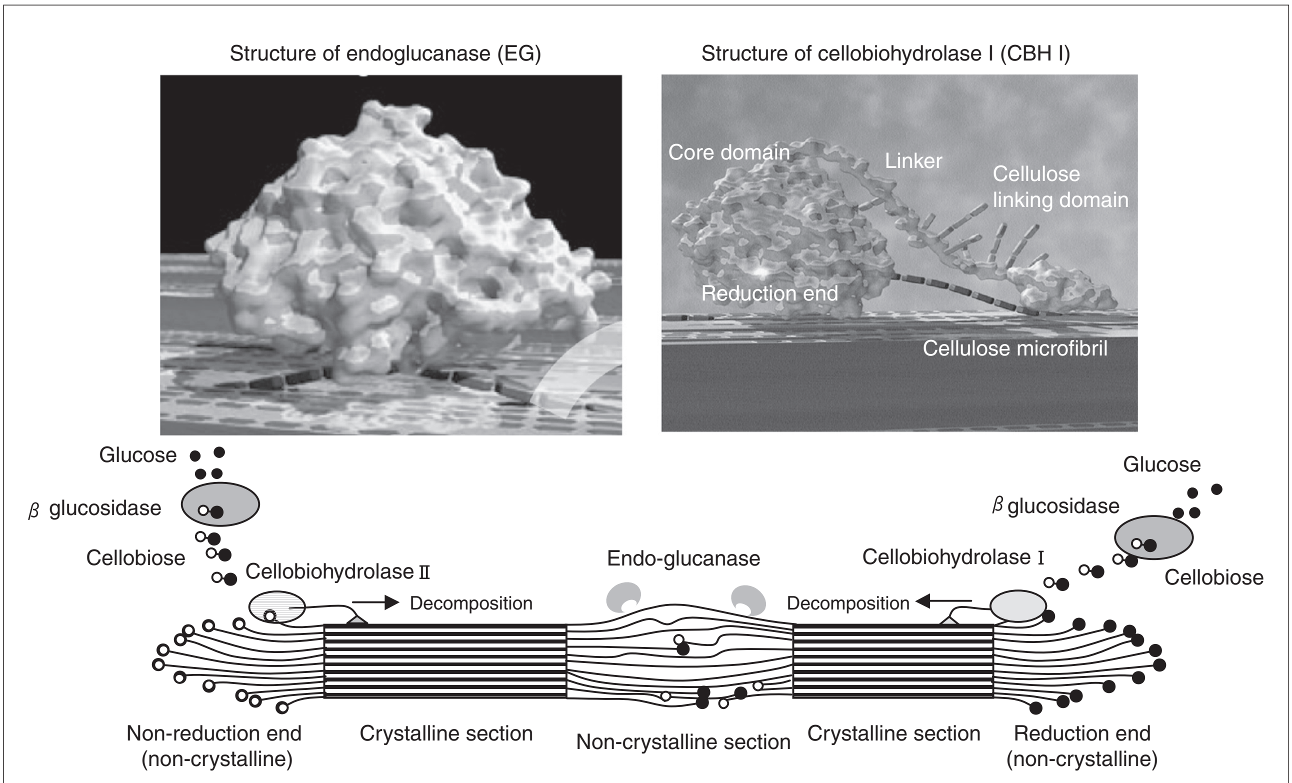

Figure 7 : Cellulase enzymes and the bio-chemical cellulose decomposing mechanism

Prepared by the STFC based on References[3,34-35]

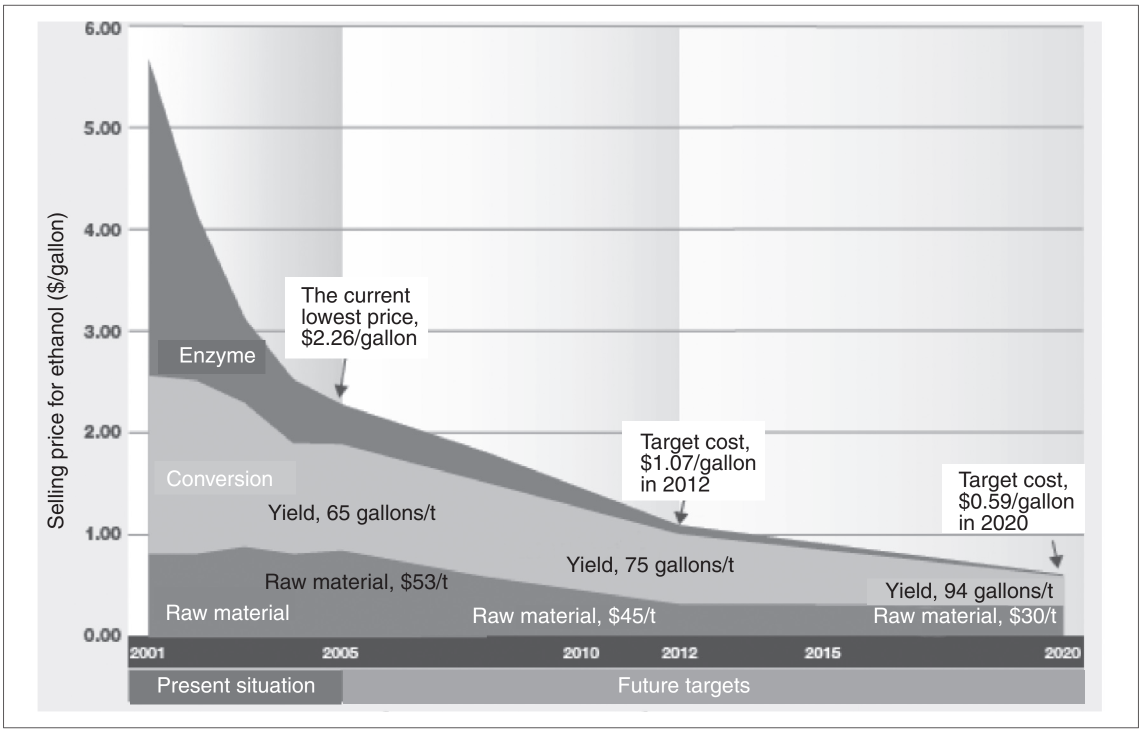

Figure 8 : US Dept. of Energy target costs for cellulosic ethanol

From Reference[36]

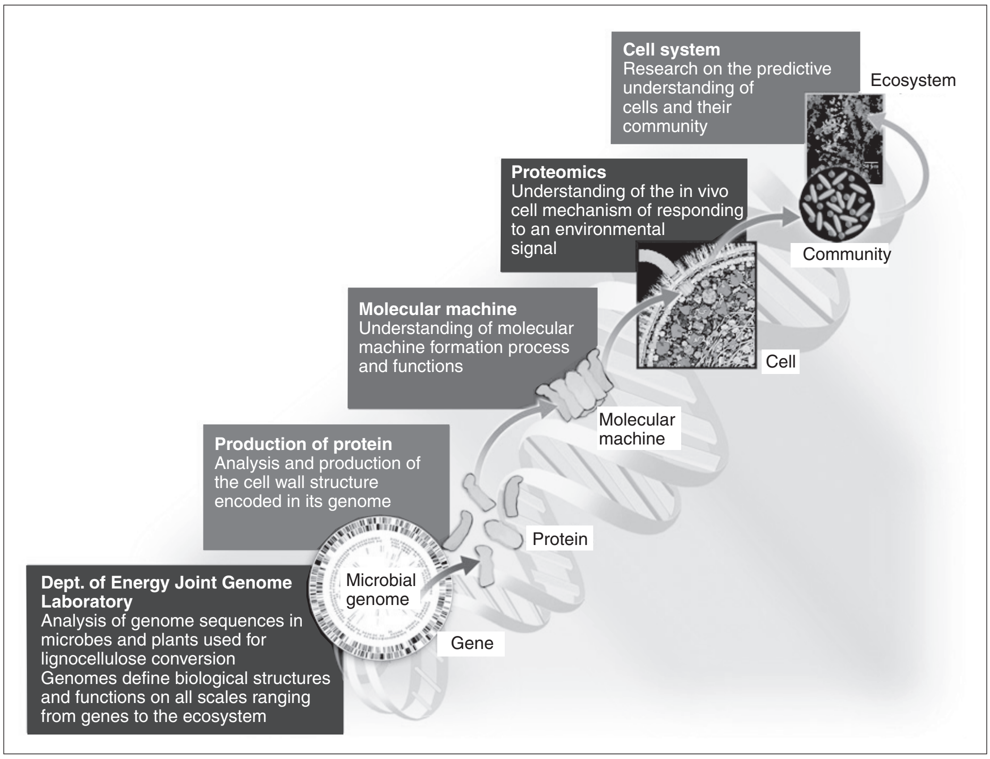

Figure 9 : Molecular biology research on bio-ethanol production in the U.S.A (DOE)

From Reference[36]

industrial production of cellulase and cellulosic ethanol. The knowledge obtained from these R&D efforts is now being fed back into the research aimed at improving plant varieties so that they are more easily decomposed.

3-3 Bio-diesel fuel-related technologies

Fatty acid methyl ester (FAME) produced from plant oils is now used as a bio-diesel fuel (BDF) and is actively commercialized, mainly in Europe and East South Asia. However, FAME has disadvantages in that it is prone to oxidization

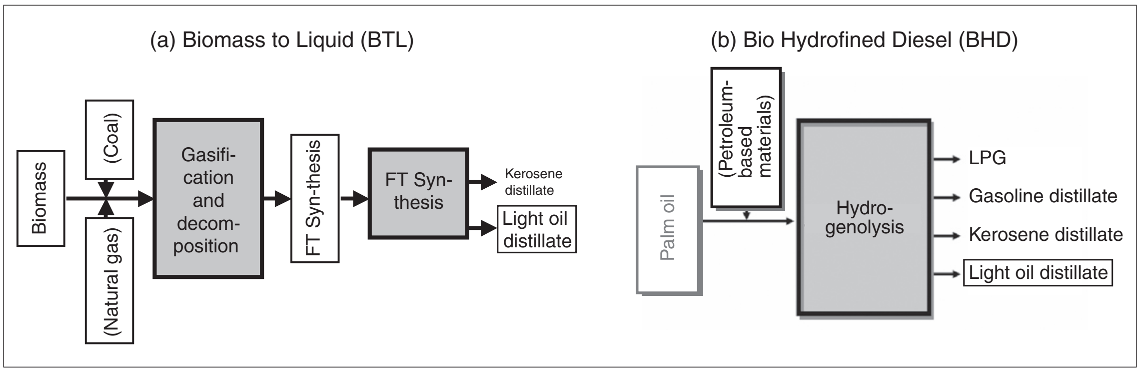

Figure 10 : Comparison of the two second-generation bio-diesel fuel technologies

Prepared by the STFC based on Reference[38]

and it has a low stability during storage. In addition, the properties of this fuel depend on the source plant oils and fat materials used in its manufacture. Some materials are so easily solidified that they cannot be used during winter in regions at medium and high latitudes. Thus, FAME presents many disadvantages in terms of distribution, which prevents the widespread use of this fuel.

In developing second-generation biofuel technologies, the main challenge is to convert a variety of plant oils and fat materials into BDF that has stable properties. The second-generation BDF technologies which are now proposed are roughly divided into 2 types, Biomass to Liquid (BTL) and Bio-Hydrofined Diesel (BHD) (Figure 10). In recent years, the industrial practicality of BHD technology has been demonstrated and the technology is approaching the commercialization stage earlier than the lignocellulose-to-ethanol conversion technology.

3-4 Comparison of research trends in countries by analysis of published research papers

The number of scientific and technological papers published on biofuel-related technologies has rapidly increased in all countries since 1990. The number of papers published on research on ethanol, BDF and energy crops has been highest in the EU-15 countries and the U.S.A. (Figure 11). The difference between the number of publications of the EU-15 countries and the U.S.A. and that of all other countries has rapidly increased, especially since the 1990s. In the U.S.A., the amended Clean Air Act, which stipulates the obligation of adding oxygen-containing compounds to vehicle fuels to reduce carbon monoxide emissions, was enforced in 1990 and since then the demand for ethanol has rapidly increased[39]. It is apparent that this act was a major factor influencing the increase in research activity into biofuels since the 1990s.

In China, the number of papers published has increased rapidly since 2000. As a result, the number of papers published on research on bio-ethanol, BDF and energy crops was higher in 2006 in China than in Japan. In China, priority has been given to research and development of biofuels under the “National Project for High-Technology Research and Development Program of China (863 Program)”, implementation of which started in January 1986[40]. Under the “Ethanol-Mixed Gasoline Development Project” introduced in the “10th 5-Year Plan” in 2001, a model project for introducing ethanol-blended gasoline was implemented and the law supporting the project was established. Under the “11th 5-Year Plan” in 2006, renewable energy development was introduced as the priority area in the National Energy Strategy. The Chinese Government also enforced the “Renewable Energy Law of the People’s Republic of China” in 2006, ahead of the other Asian countries, and the policy of raising the share of renewable energy, especially biomass, up to 16% of the total supply of primary energy by 2020 was established under the “Middle and Long-Term Development Plan of Renewable Energies”[41]. In this context, it is probable that research on biofuels will become increasingly active in China.

In Brazil and Canada, research is focused on mainly bio-ethanol production. In recent years, however, research on BDF has also been more

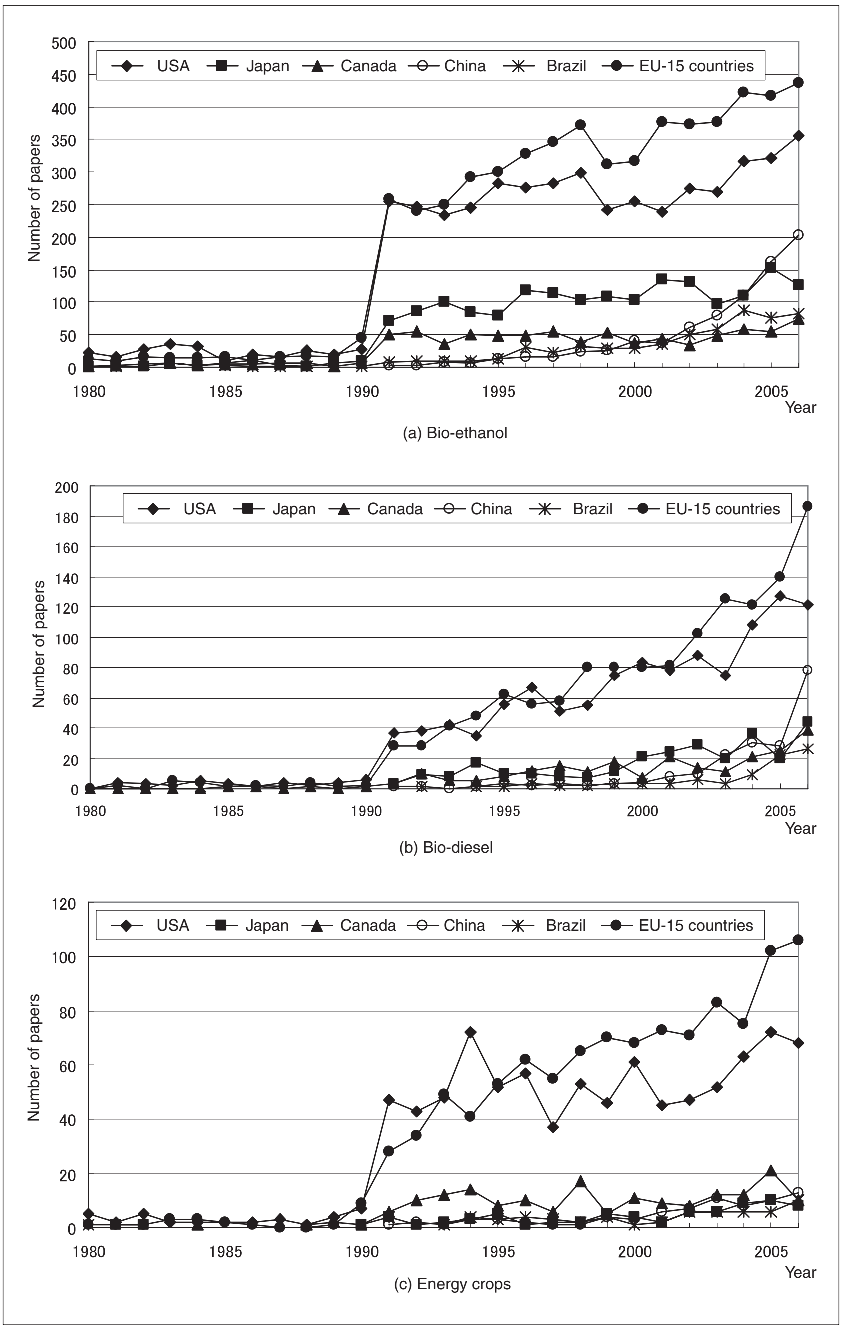

Figure 11 : Number of scientific and technological papers published on biofuel-related technologies by country

The data shown in the charts were calculated by the National Institute of Science and Technology Policy using Thomson Scientific's database "Web of Science".

actively pursued.

A comparison by region has been made in the number of papers published on the various disciplines in lignocellulose-to-ethanol conversion technologies. This shows that, while Japan, the U.S.A. and the EU are almost level pegging in the fields of chemical engineering and applied chemistry, the U.S.A. and the EU are outstripping Japan in the fields of biotechnology, molecular biology and microbiology (Figure 12). Although Japan was considered to be strong in the field of microbiology, especially fermentation[42,43], it has not applied this strength sufficiently to research on lignocellulose-to-ethanol conversion technologies.

The U.S.A. accounted for the majority of the research institutions that published the greatest numbers of papers in each field. However, it should be noted that Lunds University in Sweden and the University of British Columbia in Canada ranked above US research institutions in the field of lignocellulose-to-ethanol conversion technologies (Table 8). It is notable that the two universities have not only conducted advanced

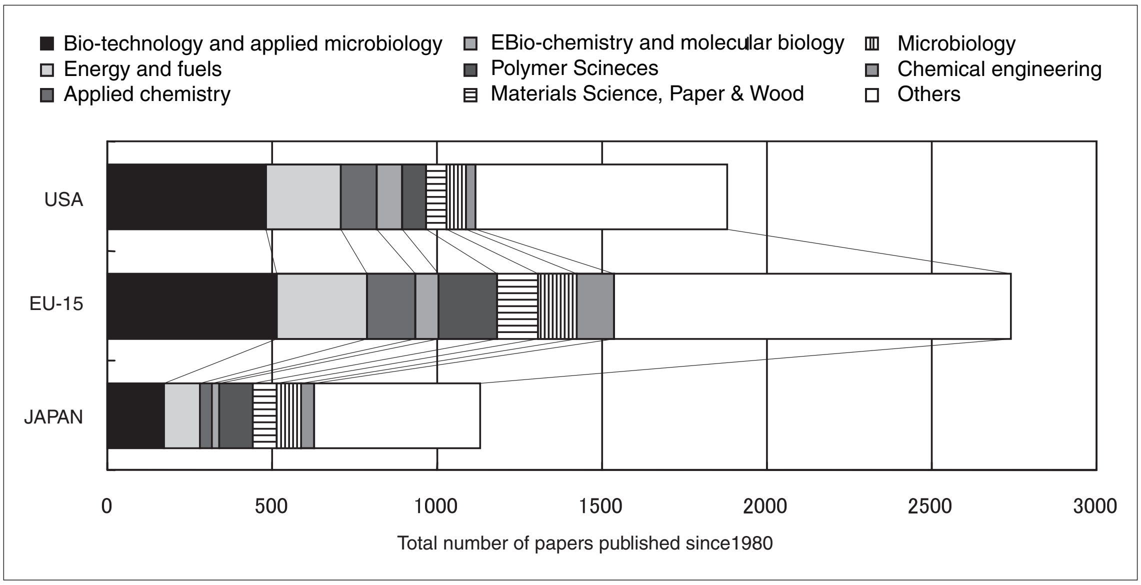

Figure 12 : Comparisons of the number and fields of papers published in each country on lignocellulose-to-ethanol conversion technologies

Table 8 : Ranking of biofuel-related research institutions in the total number of papers published since 1980

Ethanol (lignocellulose)				Bio-diesel				Energy crops			
Rank	Research institution	Country	Number of papers	Rank	Research institution	Country	Number of papers	Rank	Research institution	Country	Number of papers
1	Lunds University	Sweden	132	1	Indian Institute of Technology	India	55	1	DOA, Agriculture, Science and Education Administration	USA	153
2	British Columbia University	Canada	101	2	Chinese Academy of Science	China	46	2	National Institute for Agricultural Research (INRA)	France	83
3	DOA, Agriculture, Science and Education Administration	USA	97	3	DOA, Agriculture, Science and Education Administration	USA	45	3	Swedish University	Sweden	52
4	Russian Academy of Science	Russia	69	4	US Department of the Environment	USA	40	4	California University, Davis School	USA	45
5	National Renewable Energy Laboratory (NREL)	USA	64	5	Nebraska University	USA	35	5	Oak Ridge National Laboratory	USA	42
6	Kyoto University	Japan	63	6	Texas University	USA	34	6	Texas A&M University	USA	37
7	National Institute for Agricultural Research (INRA)	France	61	7	California University, Barkley School	USA	29	7	DOA, Agricultural Research Service	USA	36
8	University of Tokyo	Japan	57	8	Kyoto University	Japan	26	7	Chinese Academy of Science	China	36
9	Chinese Academy of Science	China	51	8	Athens Institute of Technology	Greece	26	7	Florida University	USA	36
10	Cornell University	USA	50	8	Idaho University	USA	26	7	University of Reading	UK	36

Calculated by the National Institute of Science and Technology Policy using Thomas Scientific's database "Web of Science".

research, mainly on woody lignocellulose-based energy crops, but also have become key centers for cooperation in the fields of energy and life sciences by establishing partnerships with industry and other research institutions interested in biomass utilization systems. It is also notable that the Indian Institutes of Technology and the Chinese Academy of Sciences have ranked above most other research institutions in the field of BDF related technologies.

4 Challenges facing Japan's R&D initiatives

It is essential that worldwide research on innovative second-generation biofuel technologies is based on knowledge in the life sciences field, especially molecular biology and crop nutrition (Table 9). It must be noted that Japanese research in the energy field has not been based on active

Table 9 : Research on biofuels requiring a knowledge of life sciences

Field of research		Goal	Research subject	Theme of research	Required resources and bases
Production of microbes	Fermentation	Rapidly improved fermentation productivity	Primary and secondary metabolic products Synthetic intermediates and other in vivo components	Identifying new useful microbes Identifying new useful enzymes/group of enzymes/metabolic routes Establishment of high-level manifestation control methods Establishing high-level metabolism control methods Establishing methods for control of cell/organism interactions Establishing feed-back control methods Accelerating cell proliferation and metabolic rates Establishing a rapid no-/low-oxygen fermentation	Rapid analysis of trace compounds in complex systems Analyses of chronic and continuous transcription and metabolism Analysis of phenomena in single cells Understanding of all protein synthesis and control mechanisms in specific strains of bacteria Understanding of cell/organism interactions Understanding of feedback response mechanism High-efficiency gene manipulation technologies, database for microbial genome/protein/metabolic interactions, metabolism/fermentation simulation technologies, instrumentation and control technologies, and separation and refining technologies
	Production system	Increased use of bio-energy at low cost	Crop ecosystem environment	Community genomics Understanding of microbe interactions in non-sterile systems Eco-system control	Meta-genome, meta-transcriptome Super-trace substance identification equipment Ecosystem structure analysis and simulation technology
Productivity of plant	Agricultural products	Increased yield	Energy crops (cereals, beans, potatoes, oil and fat plants)	Understanding of crop properties on genome basis Heterosis, reproductive isolation, and sink -source transition functions Resistance to stresses and adaptability to the environment Organism interactions (parasitism, symbiosis, mycorrhiza ,bacteria and soil microbes) Genome level analysis of the growth process Transfer of useful genes into crops	Genome data Wild resources High throughput screening methods Metabolome and proteome Mating groups for QTL analysis Open systems for the evaluation of gene-modified crops Genetic control manifestation control for plants Plant factories
	Production by trees and herbage	Increased yield of plants	Lignocellulose	Efficient sequential process for the conversion of lignin Conversion and separation of wood components Deciphering of cycle design for plant material Understanding of biosynthetic systems and biosynthetic control systems Development of bio-component conversion methods (in cooperation with the field of microbiology) Production of cellulose decomposing systems (hydrolysis to saccharides) using fermentation	

Prepared by the STFC

exchange and cooperation with researchers in the life sciences field.

Under the 3rd Science and Technology Basic Plan, biomass related technologies have been selected as the priority subject in the science and technology strategy for the environmental field. The Council for Science and Technology Policy has prepared a series of partnership measures for biomass, and is committed to promoting partnerships and the exchange of information between biomass-related Ministries and Agencies. With respect to individual themes in biofuels R&D, cooperation and partnerships between research areas has not been sufficiently ongoing. The main public research institutions working on biofuels participate in the "Council for Promotion of Biofuels Research" established in April 2007[44], and it is expected that these participants will have an important role in promoting communication and cooperation for enhancing their multidisciplinary research areas.

5 Conclusions and Recommendations

In recent years, R&D efforts, mainly in the U.S.A. and Europe, have focused on (1) the development of "energy crops" as the basis for alternative transport fuel resources and (2) the "energy crop-to-biofuel conversion technologies", in order to reduce the medium- and long-term dependence on fossil fuels. This paper has described the potential biofuel alternatives to conventional petroleum in Japan in terms of quantity and cost. The important points are summarized as follows:

- It is expected that competition between energy crops and edible crops will be most intense in 2050 when the world population is expected to reach its peak. The possible supply of ethanol was estimated on the basis of realistic predictions on the increase in the total area of agricultural lands and on the demand for cereals. The results indicate that the potentially useable land available worldwide will be enough to satisfy both the demand for foods from the world population and the demand for biofuels.
- If the requirements for "innovative technologies for conversion of biomass into ethanol", "the large-scale production of raw materials" and "fuel tax incentive system" can be satisfied, it will be possible for Japan to supply domestic biofuels that are cost competitive with gasoline at the current price and with biofuels produced overseas. However, based on a realistic view of land use in Japan, it should be foreseen that the supply of domestic biofuels will be quantitatively limited.
- If Japan imports overseas-produced biofuels, the prices for the imported biofuels may be competitive with the current price of gasoline on the condition that fuel tax incentives are implemented. However, because of the large price volatilities of overseas produced ethanol, imported biofuel prices may not always be competitive.To diversify the raw materials supply, R&D efforts are being made throughout the world to develop second-generation biofuel technologies. Paying attention to these moves, Japan should also make efforts to develop its own second-generation biofuel technologies.

Based on these points, we make the following recommendations on the Japanese challenges in the research and development of second-generation biofuel technologies:

i) Preparation of a national biofuels introduction strategy and a roadmap for research and development of second-generation biofuel technologies and facilitation of the linkage between them

To introduce biofuels into the Japanese transport sector, it is essential to use domestic biomass resources most effectively. However, realistically, it is expected that the supply of biofuels domestically produced at costs comparable to those for fossil fuels will be quantitatively limited. Therefore, it will be necessary to make efforts to acquire Japanese interests in the exploitation of the increasing areas of overseas lands cultivated for energy resources. To secure the projects in overseas, it is necessary for Japan to develop its own second-generation biofuel technologies that will be regarded as valuable by overseas countries rich in biomass resources. The Japanese Government also is required to set both national quantitative targets and the time frame for the introduction biofuels. It should also prepare a resources strategy based on the balance between overseas and domestic biomass resources, review related policies and systems (such as the land use and agricultural policies, taxation incentives, and regulations); and prepare a roadmap for research and development of second-generation biofuel technologies, meeting the requirements mentioned above.

ii) Clarification of the requirements for lands to produce energy crops and the selection of research subjects

Energy crops require a greater emphasis on increasing productivity per unit input of energy and reducing production costs than edible crops. Therefore, research approaches will depend significantly on the conditions, such as weather and soil, pertaining in lands selected for producing energy crops. To avoid competition between the production of energy crops and the production of foods while at the same time achieving acceptable energy crop productivity, it is likely that the lands used for energy crops will be currently uncultivated and have acidic or alkaline soils and a reasonable precipitation level, but not be extremely dry or deteriorated by salinization. From the medium- and long-term perspectives, it is important to select as research targets technologies for producing energy crops that can be grown in the lands available for Japanese biofuel consumption.

iii) Cooperative multidisciplinary research in the fields of energy and life sciences required to develop second-generation biofuel technologies

Much of the worldwide research conducted on second-generation biofuel technologies is based on knowledge in the life sciences field, especially molecular biology and crop nutrition. Japanese research in the energy field has not been conducted in cooperation with researchers in life sciences, nor effectively used the accumulated knowledge in the field of microbiology, especially fermentation, where Japan is considered to be strong. In the future, therefore, it is important to more actively encourage exchanges of information and researchers in these fields. In addition, it is necessary to thoroughly investigate the factors responsible for successful industry-university partnerships in research centers in the U.S.A. and Europe, and to establish such partnership research centers in Japan and concentrate research resources on them. It is also necessary to actively invite researchers from other countries rich in energy resources to Japanese centers to conduct R&D into second-generation biofuel technologies, and to strengthen relationships between Japan and the other countries rich in biomass resources through the development of human resources and technological cooperation.

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