Chapter 3

Next-Generation Biofuels: Technology and Economy

1 Introduction

First-generation biofuels such as ethanol made from sugarcane and cassava, as well as biodiesel made from palm oil and coconut oil are widely used in East Asia Summit countries. To promote the introduction of biofuels, high-concentration use of biofuels is planned in the transportation sector in each country (Chapter 2). With an increase in biofuel consumption, oil crop plantations will expand in a disorderly manner and the expansion will cause serious environmental destruction such as disorderly felling in wildwoods and problems of haze. Utilisation of nonconventional biomass such as non-edible crops and farm wastes should be considered for the sustainable introduction of biofuels.

On the other hand, automobile manufacturers have requested the introduction of next-generation biofuels such as synthetic hydrocarbons made from biomass (Koyama et al., 2007). Synthetic hydrocarbons are more compatible as transportation fuels because they are similar to conventional petroleum fuels. Another merit of next-generation biofuels is that they can be produced from any kind of biomass.

Biofuels are gradually being introduced as alternative aviation fuels. The International Air Transport Association (IATA) has decided its Sustainable Alternative Aviation Fuels Strategy. According to the simulation of greenhouse gas (GHG) reduction in the aviation sector, the introduction of biofuel is effective for reducing GHGs. Alternative aviation fuel made from biomass is limited to synthetic paraffinic kerosene because aviation fuel is used in low temperature. The process for producing alternative aviation fuel is similar to that of synthetic hydrocarbons for automobiles.

To solve these problems using nonconventional resources, development of economic production of next-generation biofuels made from nonconventional resources will be needed. However, information on non-edible feedstocks such as availability is limited and the technical problems concerning production of biofuels are not clear. Therefore, economic production technology of the next-generation biofuel has not been established.

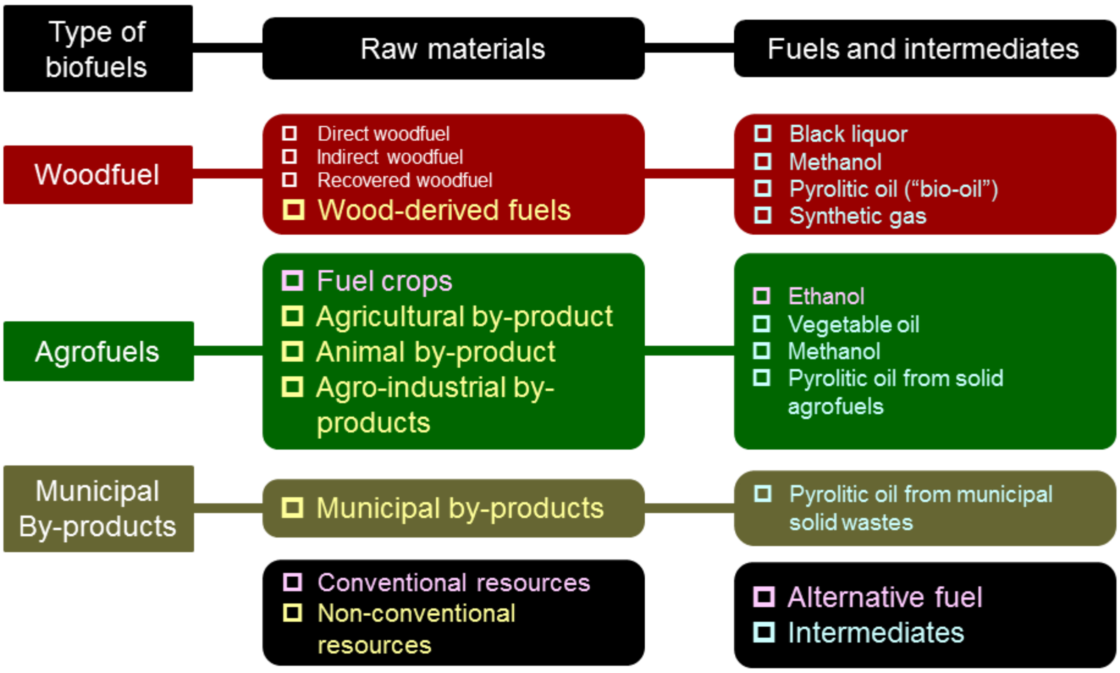
In this study, we consider three subjects: utilisation of nonconventional resources, production technology of next-generation biofuels and their quality, and cost performance improvement of next-generation biofuel production.

2 Utilisation of nonconventional resources

First-generation biofuels have been made from fuel crops. The production of fuel crops is limited and their utilisation as a biofuel resource also influences the food supply. To minimise the influence on the food supply and GHG emissions, the utilisation of waste biomass and agricultural by-products is desirable. Various processes give us intermediates from wood and farm waste (Figure 3.2-1). They can be converted into transportation fuels by catalyst technologies such as hydrotreating, transesterification, and Fischer-Trøpsch (FT) synthesis.

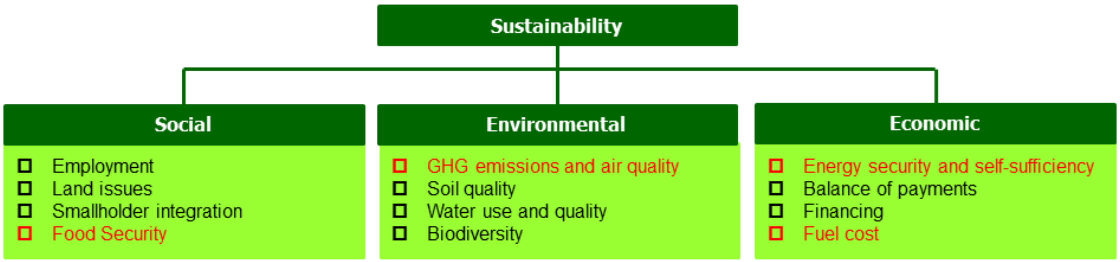
Of recent, the sustainability of biofuels is being considered when making policy to introduce biofuels. Sustainable production of next-generation biofuels includes three pillars of impacts: social, environmental, and economic (Figure 3.2-2). Social impacts include employment (job and income), land issues, food security, smallholder integration, and health problems. Environmental impacts include GHG balances, impact on soil, water and biodiversity, and direct and indirect land use changes. Apart from GHG balance, these factors mainly influence biomass production. Economic impacts include various factors in the security of biomass supply, the cost of fuel production, transportation cost, benefit of fuel supply, and the subsidy for the biofuel production.

Figure 3.2-1. Biofuel Classification



Source: FAO (2009).

Figure 3.2-2. Environmental, Social, and Economic Aspects of Biofuel and Bioenergy Production

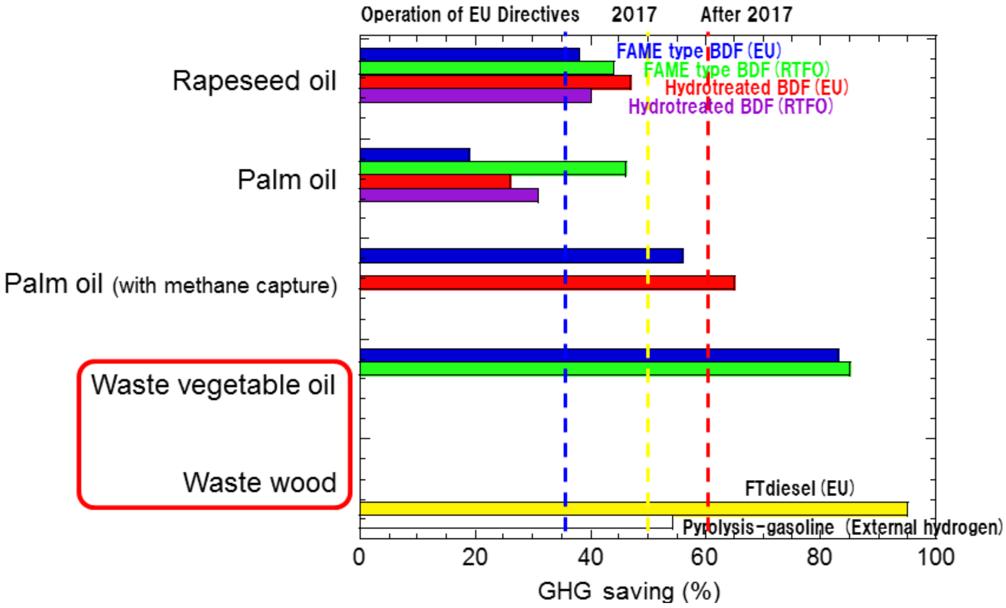


Note: Items in red font are considered in this chapter.
Sources: IEA (2010; 2011).

From the viewpoint of diversification of resources, the utilisation of nonconventional resources can satisfy food security (social problem) and energy security (economy).

Figure 3.2-3 shows GHG savings of diesel-substituted biofuel production. First- and next-generation biodiesel fuels made from farm products such as palm oil and rapeseed oil showed low GHG savings and are unable to meet EU directives. In case of facilities equipped with GHG traps (e.g. for methane capture), the rate of GHG savings in the reduction rate increases. The utilisation of waste materials is very effective for GHG reduction and increases sustainability in biofuel production.

Figure 3.2-3. Greenhouse Gas Savings of Diesel-Substituted Biofuel Production

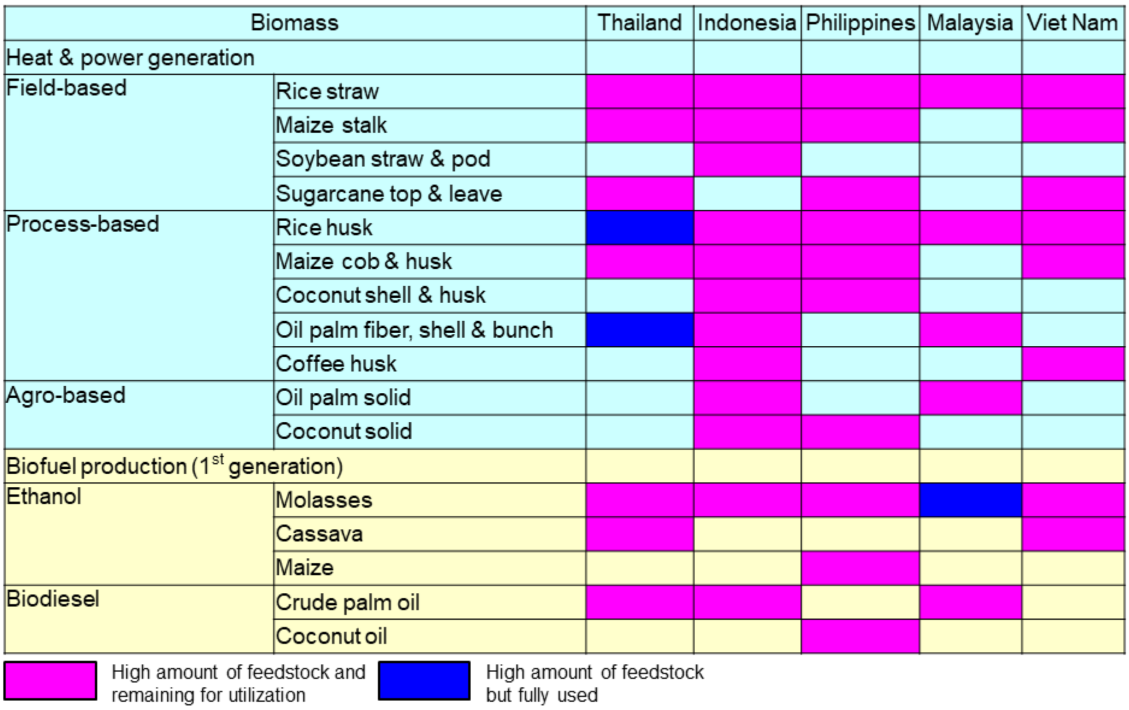


BDF = biodiesel fuel, EU = European Union, RTFO = Renewable Transport Fuel Obligation.
Sources: Argonne National Laboratory (2011); EU (2009); Renewable Fuels Agency (UK) (2012).

These results suggest that it is important to consider the selection of raw material and fuel production technology for sustainable introduction of biofuels.

ASEAN Member States produce various types of biomass. The availability of farm waste in the five ASEAN Member States is shown in Figure 3.2-4. Liquid biomass is mainly used as feedstocks of first-generation biofuels and solid biomass is mainly used for heat power and generation.

Figure 3.2-4. Biomass Potential Status in Major ASEAN Member States



Biomass		Thailand	Indonesia	Philippines	Malaysia	Viet Nam
Heat & power generation						
Field-based	Rice straw	🟪	🟪	🟪	🟪	🟪
	Maize stalk	🟪	🟪	🟪		🟪
	Soybean straw & pod		🟪			
	Sugarcane top & leave	🟪		🟪		🟪
Process-based	Rice husk	🟦	🟪	🟪	🟪	🟪
	Maize cob & husk	🟪	🟪	🟪		🟪
	Coconut shell & husk		🟪	🟪		
	Oil palm fiber, shell & bunch	🟦	🟪		🟪	
	Coffee husk		🟪			🟪
Agro-based	Oil palm solid		🟪		🟪	
	Coconut solid		🟪	🟪		
Biofuel production (1st generation)						
Ethanol	Molasses	🟪	🟪	🟪	🟦	🟪
	Cassava	🟪				🟪
	Maize			🟪		
Biodiesel	Crude palm oil	🟪	🟪		🟪	
	Coconut oil			🟪		

🟪 High amount of feedstock and remaining for utilization

🟦 High amount of feedstock but fully used

Sources: National Science Technology and Innovation Policy Office (Thailand); Joint Graduate School of Energy and Environment (2014).

The species and amounts of agricultural by-products depend on the farm products. For example, rice is grown in most ASEAN Member States. By-products of rice production such as rice straw and rice husk are available as energy resources in these countries. On the other hand, by-products from the palm industry are only available in Indonesia, Malaysia, and Thailand. Some agricultural wastes are fully used in conventional industry. When we use the biomass as a resource of fuel production, we must consider the amount of resources, availability considering conventional use, and locality.

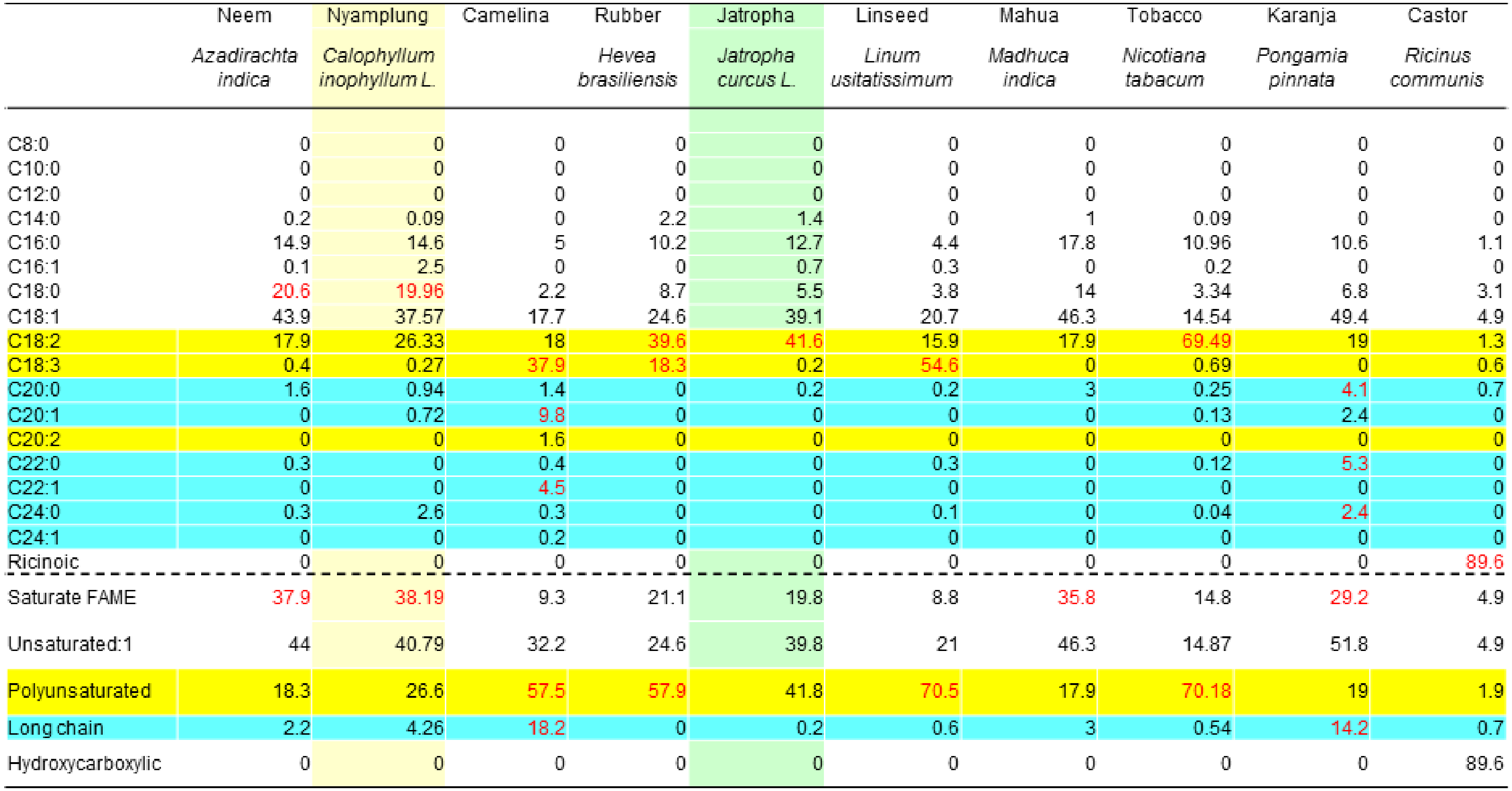
3. Production Technology of Next-Generation Biofuels and Their Quality

There are two ways of biofuel production from nonconventional resources. One is a method to produce biofuels using a conventional procedure. Sometimes, fuels obtained by this method are also called next-generation biofuels. Strictly, these fuels should be classified as first-generation biofuels. Typical fuels in this category are biodiesel fuels produced from non-edible biomass. The other method is a process using petroleum refinery facilities to produce hydrocarbon-type biofuels, which is described later.

When nonconventional resources are used for biofuel production, their properties influence the fuel quality and the difficulty of fuel production. Table 3.3-1 shows oil productivity and acid value of non-edible feedstocks. Some oils show high acid value derived from free fatty acids. Free fatty acids and homogeneous alkaline catalyst (KOH, NaOH) used in the conventional process form soap. To prevent soap formation, pretreatment (esterification, etc.) of free fatty acids is needed. The low-grade resources are inexpensive, but we should consider that they may cause a rise in the production cost.

The quality of ethanol made from biomass is almost constant because it is a pure chemical.

Table 3.3.-1 Yield, Oil Content, and Acid Value of Various Non-edible Oils



	Neem	Nyamplung	Camelina	Rubber	Jatropha	Linseed	Mahua	Tobacco	Karanja	Castor
	Azadirachta indica	*Calophyllum inophyllum L.*		*Hevea brasiliensis*	*Jatropha curcus L.*	*Linum usitatissimum*	*Madhuca indica*	*Nicotiana tabacum*	*Pongamia pinnata*	*Ricinus communis*
C8:0	0	0	0	0	0	0	0	0	0	0
C10:0	0	0	0	0	0	0	0	0	0	0
C12:0	0	0	0	0	0	0	0	0	0	0
C14:0	0.2	0.09	0	2.2	1.4	0	1	0.09	0	0
C16:0	14.9	14.6	5	10.2	12.7	4.4	17.8	10.96	10.6	1.1
C16:1	0.1	2.5	0	0	0.7	0.3	0	0.2	0	0
C18:0	20.6	19.96	2.2	8.7	5.5	3.8	14	3.34	6.8	3.1
C18:1	43.9	37.57	17.7	24.6	39.1	20.7	46.3	14.54	49.4	4.9
C18:2	17.9	26.33	18	39.6	41.6	15.9	17.9	69.49	19	1.3
C18:3	0.4	0.27	37.9	18.3	0.2	54.6	0	0.69	0	0.6
C20:0	1.6	0.94	1.4	0	0.2	0.2	3	0.25	4.1	0.7
C20:1	0	0.72	9.8	0	0	0	0	0.13	2.4	0
C20:2	0	0	1.6	0	0	0	0	0	0	0
C22:0	0.3	0	0.4	0	0	0.3	0	0.12	5.3	0
C22:1	0	0	4.5	0	0	0	0	0	0	0
C24:0	0.3	2.6	0.3	0	0	0.1	0	0.04	2.4	0
C24:1	0	0	0.2	0	0	0	0	0	0	0
Ricinoic	0	0	0	0	0	0	0	0	0	89.6
Saturate FAME	37.9	38.19	9.3	21.1	19.8	8.8	35.8	14.8	29.2	4.9
Unsaturated:1	44	40.79	32.2	24.6	39.8	21	46.3	14.87	51.8	4.9
Polyunsaturated	18.3	26.6	57.5	57.9	41.8	70.5	17.9	70.18	19	1.9
Long chain	2.2	4.26	18.2	0	0.2	0.6	3	0.54	14.2	0.7
Hydroxycarboxylic	0	0	0	0	0	0	0	0	0	89.6

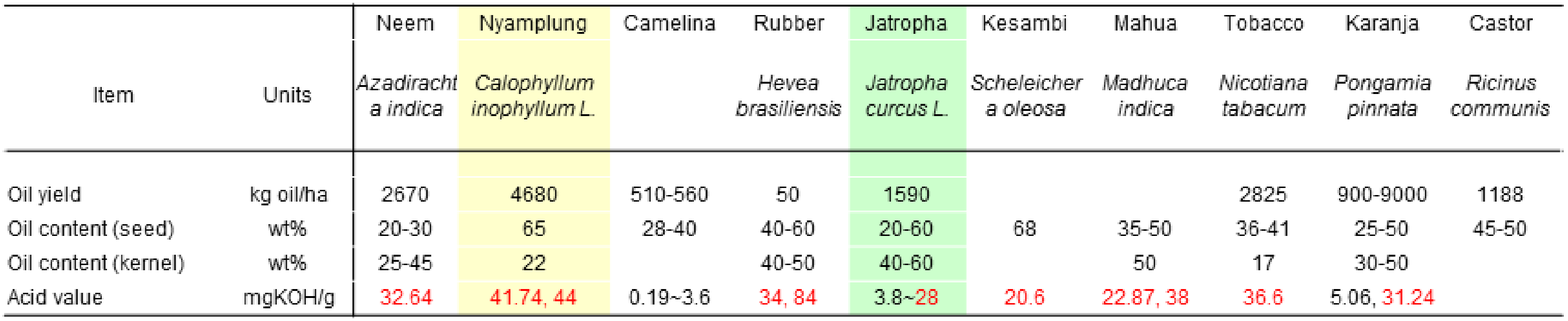
Sources: Bankovic-Ilic et al. (2012); Borugadda et al. (2012); Atabani et al. (2013); Silitonga et al. (2015); Wakil et al. (2015); Khayoon et al. (2012); Ahmad et al. (2014).

On the other hand, the quality of biodiesel fuel is not constant because it is a mixture of various fatty acid methyl esters (FAME). Therefore, the fatty acid composition of oil has a large influence on fuel property. Table 3.3-2 shows the fatty acid composition of biodiesel fuel produced from non-edible oil. Neem (scientific name: *Azadirachta indica*) and nyamplung (scientific name: *Calophyllum inophyllum L.*) biodiesel fuels contain high concentrations of saturated FAME such as methyl stearate, and their cloud points are relatively higher than other biodiesel fuels (see Table 3.3-3). Biodiesel fuels produced from rubber seed and tobacco oil contain 57.9% and 70.2% of polyunsaturated FAME, respectively (Table 3.3-2). Both fuels show low oxidation stability. If we use these feedstocks as biodiesel fuel production, improvement of quality is needed.

To use transportation fuels safely, the quality guarantee by the fuel standard is important. The fuel standard of first-generation fuels (ethanol and FAME-type biodiesel fuel) has already been introduced to control the quality of commercial biofuels. The proposed EAS–ERIA Biodiesel Fuel Standard (EEBS2013) is based on resources used in East Asia Summit countries and experimental data. The EEBS value has been adopted as the national standard of some countries (ERIA, 2015).

The limits of oxidation stability, monoglyceride content, and phosphorus content are getting strict in the recent revision of the biodiesel fuel quality standard. To meet the standard, biodiesel fuel must be upgraded through physical and chemical treatment (Table 3.3-4). For example, the oxidation stability of biodiesel can be improved by partial hydrogenation technology developed under the Science and Technology Research Partnership for Sustainable Development (SATREPS) project in collaboration with Japanese (National Institute of Advanced Industrial Science and Technology) and Thai (Thailand Institute of Scientific and Technological Research, National Science and Technology Development Agency/National Metal and Materials Technology Center) research institutes (Table 3.3-5). This technology enables the reduction of polyunsaturated FAME, which are easily oxidised by air. The upgraded biodiesel was named H-FAME. Development of H-FAME technology for commercialisation has already started under a new alternative energy development plan of the Thai government (Alternative Energy Development Plan 2015).

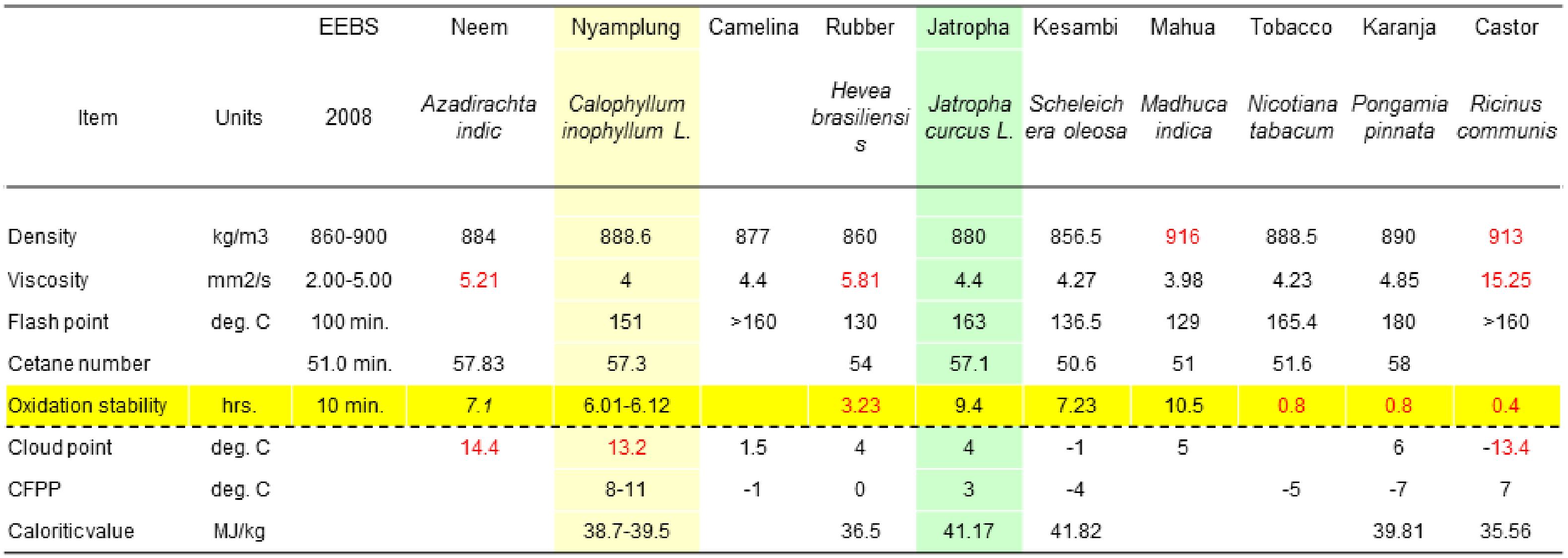
Table 3.3-2. Fatty Acid Composition of Various Non-edible Oils



Item	Units	Neem	Nyamplung	Camelina	Rubber	Jatropha	Kesambi	Mahua	Tobacco	Karanja	Castor
		Azadirachta indica	*Calophyllum inophyllum L.*		*Hevea brasiliensis*	*Jatropha curcus L.*	*Scheleichera oleosa*	*Madhuca indica*	*Nicotiana tabacum*	*Pongamia pinnata*	*Ricinus communis*
Oil yield	kg oil/ha	2670	4680	510-560	50	1590			2825	900-9000	1188
Oil content (seed)	wt%	20-30	65	28-40	40-60	20-60	68	35-50	36-41	25-50	45-50
Oil content (kernel)	wt%	25-45	22		40-50	40-60		50	17	30-50	
Acid value	mgKOH/g	32.64	41.74, 44	0.19~3.6	34, 84	3.8~28	20.6	22.87, 38	36.6	5.06, 31.24	

Source: Atabani et al. (2013).

Table 3.3-3. Properties of Fatty Acid Methyl Ester Produced from Various Non-edible Oils



		EEBS	Neem	Nyamplung	Camelina	Rubber	Jatropha	Kesambi	Mahua	Tobacco	Karanja	Castor
Item	Units	2008	*Azadirachta indic*	*Calophyllum inophyllum L.*		*Hevea brasiliensis*	*Jatropha curcus L.*	*Scheleichera oleosa*	*Madhuca indica*	*Nicotiana tabacum*	*Pongamia pinnata*	*Ricinus communis*
Density	kg/m3	860-900	884	888.6	877	860	880	856.5	916	888.5	890	913
Viscosity	mm2/s	2.00-5.00	5.21	4	4.4	5.81	4.4	4.27	3.98	4.23	4.85	15.25
Flash point	deg. C	100 min.		151	>160	130	163	136.5	129	165.4	180	>160
Cetane number		51.0 min.	57.83	57.3		54	57.1	50.6	51	51.6	58	
Oxidation stability	hrs.	10 min.	*7.1*	6.01-6.12		3.23	9.4	7.23	10.5	0.8	0.8	0.4
Cloud point	deg. C		14.4	13.2	1.5	4	4	-1	5		6	-13.4
CFPP	deg. C			8-11	-1	0	3	-4		-5	-7	7
Caloritic value	MJ/kg			38.7-39.5		36.5	41.17	41.82			39.81	35.56

Sources: Bankovic-Ilic et al. (2012); Atabani et al. (2013); Silitonga et al. (2015); Khayoon et al. (2012); Ahmad et al. (2014); Atabani et al. (2014); Ong et al. (2013).

The conclusions regarding the utilisation of nonconventional biomass as feedstocks of conventional biofuel are the following: (1) we should consider not only productivity of fruit/seed, but also composition and physical properties in case of raw material selection, (2) a pretreatment process is sometimes needed to improve fuel quality when low-grade non-edible oils are used as raw materials, and (3) fuel properties such as oxidation stability can be improved by reforming and refining technologies.

Table 3.3-4. EAS–ERIA Biodiesel Fuel standard and Improvement of Oxidation Stability, Monoglyceride Content, and Phosphorus Content

	EEBS2013	Upgrading method
Oxidation stability	10 h minimum	Antioxidant addition Partial hydrogenation
Monoglyceride	0.7 mass % maximum	Wintering + filtration Partial hydrogenation + filtration/adsorption
Phosphorus	4.0 mass % maximum	Water washing

ASEAN = Association of Southeast Asian Nations, EAS = East Asia Summit, ERIA = Economic Research Institute for ASEAN and East Asia, h = hour.
Source: ERIA (2015).

Table 3.3-5 Oxidation Stability of Various Biodiesels and Partial Hydrogenated Biodiesels Measured by Rancimat (EN14112)

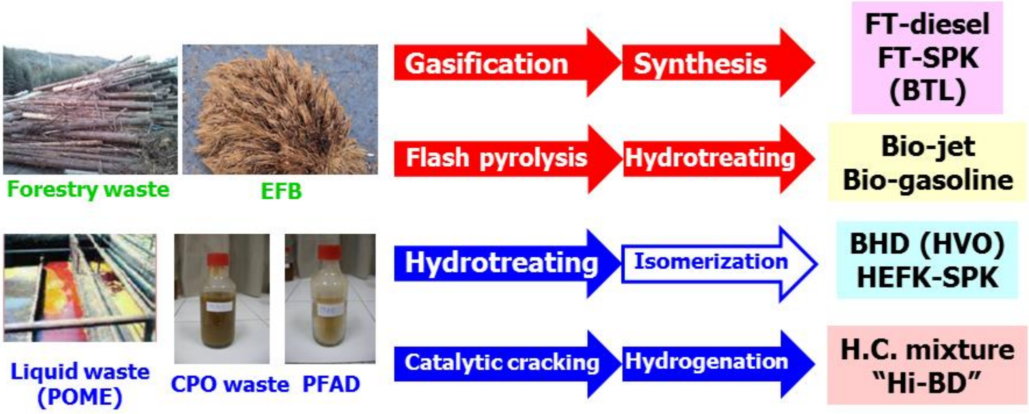
	Feed (h)	Hydrogenated (h)
Rapeseed ME	6.75	71.36
Soybean ME	1.54	87.19
Palm ME	5.72	100.21
Jatropha ME	0.58	11.91

ME = Methyl Ester.
Source: PCT/JP2011/053473, PCT/JP2014.077636, TH Pat. 54699.

Hydrocarbon-type next-generation biofuels produced by refinery systems are welcomed by automobile manufacturers because their qualities are similar to conventional petroleum transportation fuel. Another advantage of next-generation biofuels is the utilisation of solid resources and low-grade waste materials. Many processes to produce next-generation biofuels have been proposed (Figure 3.3-1). Those processes consist of various new technologies such as gasification, flash pyrolysis, hydrotreating, cracking, and FT synthesis. The property of the product and results of the cost calculation are reported in some articles. In the current state, it is not sufficient to accept these technologies as economic methods for biofuel production.

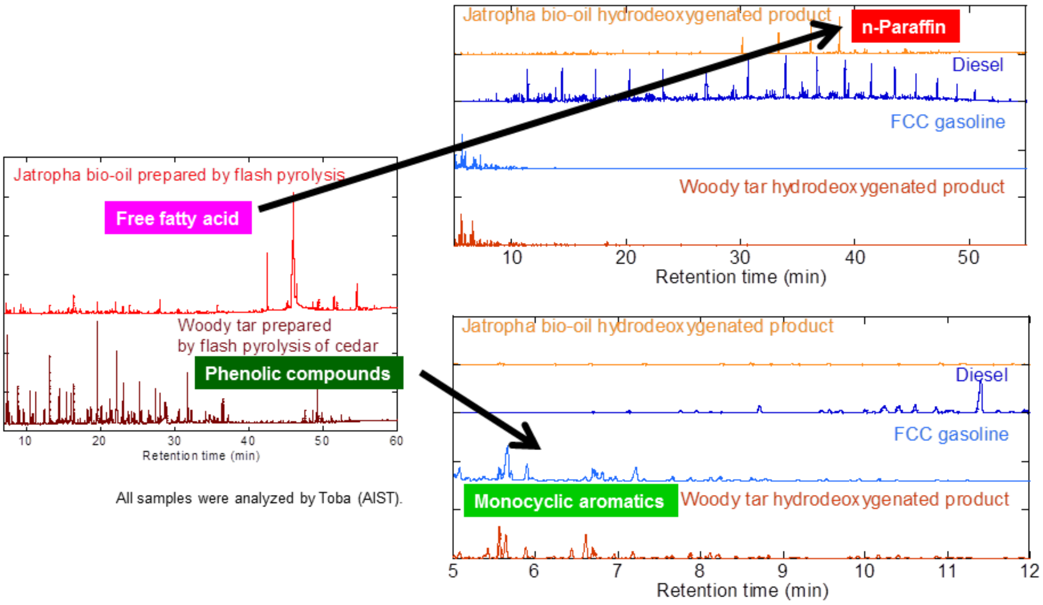
The end use of the product depends on the property of the raw material. Figure 3.3-2 shows gas chromatograms of bio-oils produced by flash pyrolysis of solid biomass and final products. Compared with conventional petroleum gasoline and diesel, a final product obtained from Jatropha bio-oil is similar to diesel. A final product obtained from woody tar is similar to fluid catalytic cracked (FCC) gasoline.

Figure 3.3-1. Production of Hydrocarbon-Type Next-Generation Biofuels



BHD = bio-hydrogenated diesel, BTL = biomass to liquid, CPO = crude palm oil, EFB = empty fruit bunch, FT = Fischer–Tropsch, H.C. = hydrocarbon, HEFA-SPK = hydroprocessed esters and fatty acids-synthetic paraffinic kerosene, HVO = hydrotreated vegetable oil, PFAD = palm fatty acid distillate, POME = palm oil mill effluent.
Source: Authors.

Figure 3.3-2. Gas Chromatograms of Bio-oils and Final Products Made by Flash Pyrolysis and Upgrading Reaction



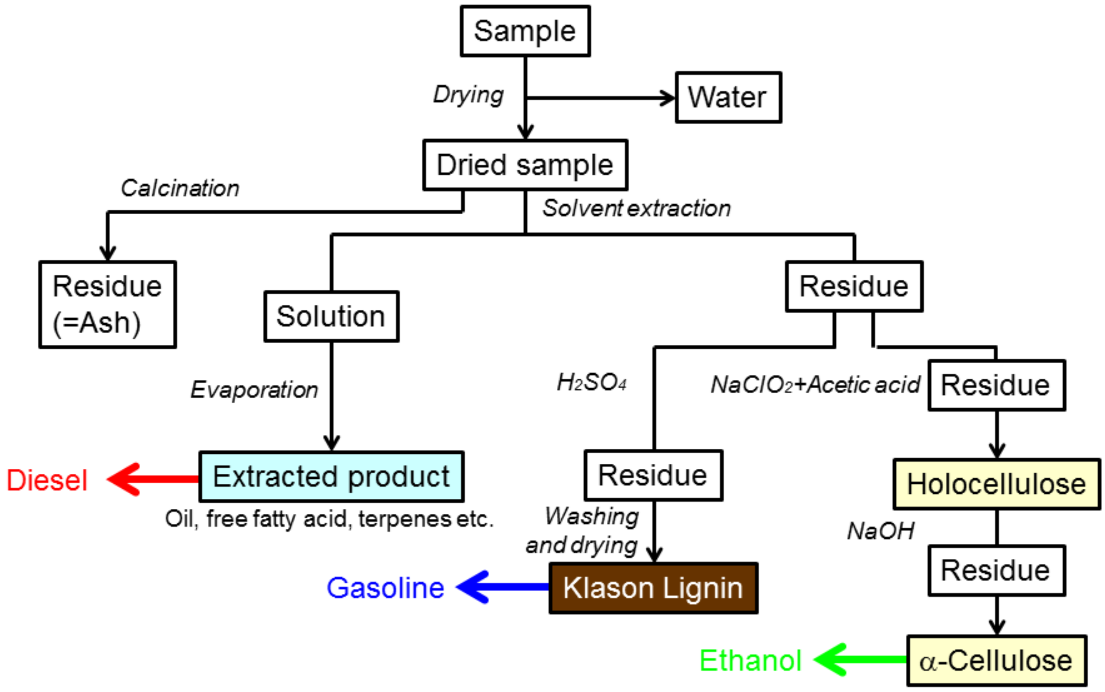
All samples were analyzed by Toba (AIST).

FCC = Fluid Catalytic Cracking.
Source: Authors.

These results show that we have to choose the raw material and a manufacturing process appropriately, according to the final product. Therefore, analysis of the biomass composition is very important before using it. In the case of biomass gasification, this factor is not important because the intermediate of gasification of any biomass is synthetic gas.

Except gasification, quantification of biomass components is very important to decide the final products. The main components of biomass are usually cellulose, hemicellulose, lignin, and triglycerides. Cellulose and hemicellulose are easily decomposed into small molecules such as furan compounds, cyclic ketones, and short chain carboxylic acids under high temperature treatment. These compounds are more suitable for intermediates of fine chemicals producing. For transportation fuel, cellulose and hemicellulose should be converted into ethanol. Basic structures of lignin and triglycerides are stable under thermochemical conversion. Useful intermediates for producing alternative fuels are obtained from lignin and triglycerides by thermal or catalytic conversion. The typical quantification method of biomass components is shown in Figure 3.3-3. We can estimate the fuel potential of each biomass using a simple analysis.

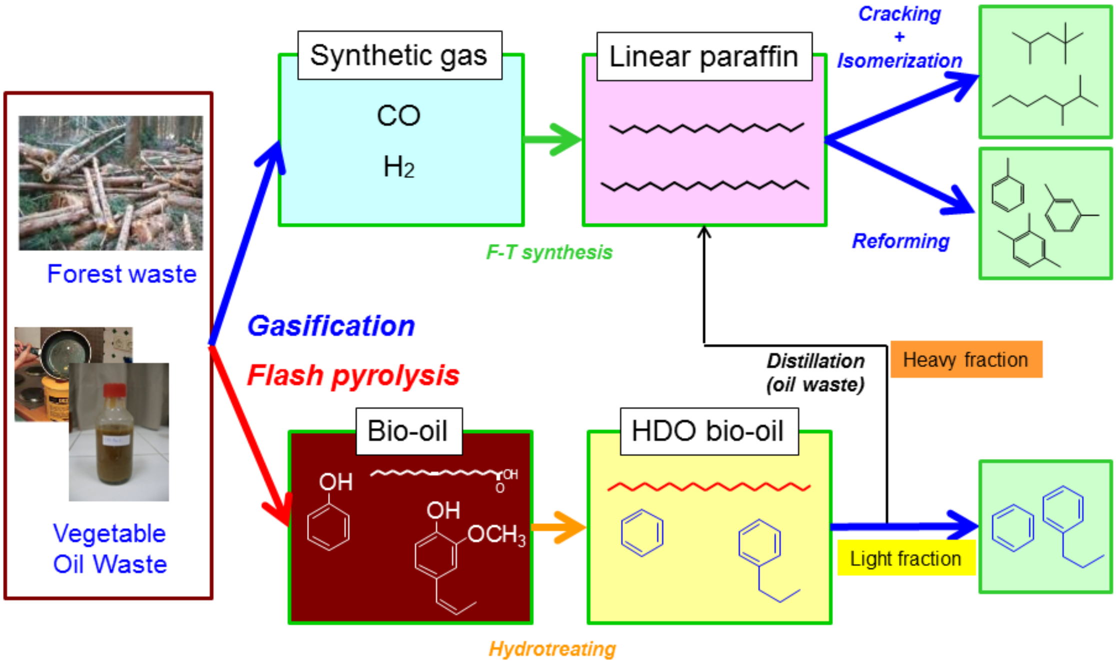
Figure 3.3-3. Systematic Quantitative Analysis of Biomass Components



Source: Authors.

Two ways of producing alternative hydrocarbon gasoline from biomass are considered (Figure 3.3-4). In the case of biomass gasification, synthetic gas is obtained as an intermediate. Synthetic gas is converted into linear paraffins by FT synthesis. Finally, iso-paraffinic hydrocarbons are obtained by catalytic cracking and isomerisation, and aromatic hydrocarbons are obtained by reforming. On the other hand, flash pyrolysis of the biomass gives us bio-oil containing oxygen compounds such as phenolic compounds, free fatty acids, and cyclic ketones. The components contained in bio-oil are converted into hydrocarbons by deoxygenation. Aromatic hydrocarbons (high-octane compounds) derived from phenolic compounds are contained in the fraction of low boiling point. Linear paraffins derived from fatty acids are contained in the heavy fraction. These components can be divided by distillation.

Figure 3.3-4. Alternative Gasoline Production from Waste Biomass

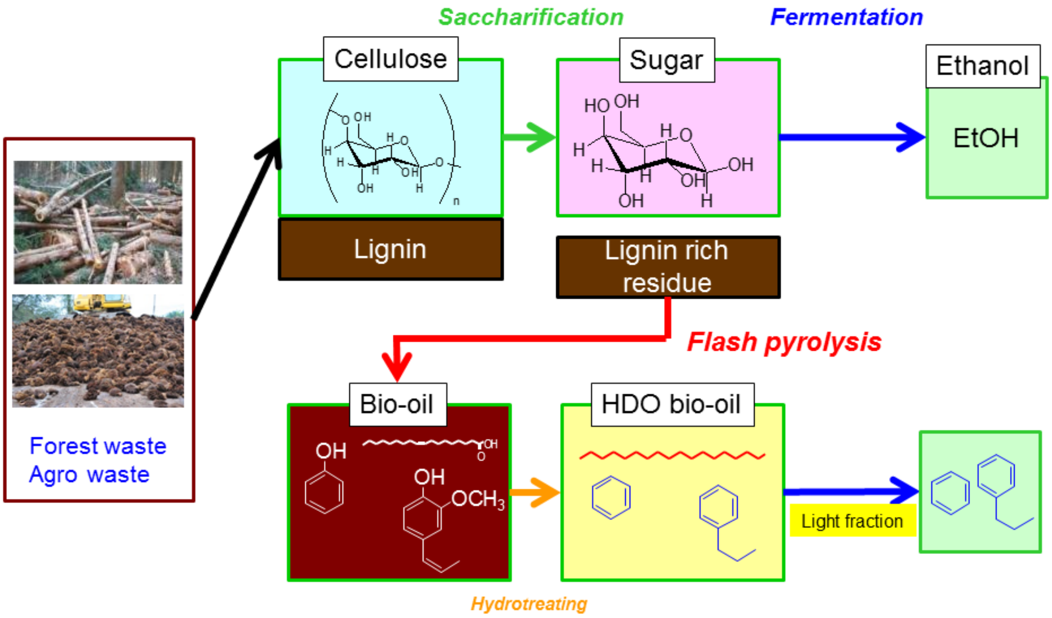


HDO = heavy duty oil.
Source: Authors.

It is difficult to produce transportation fuel properly with the components derived from cellulose and hemicellulose by usual flash pyrolysis. In this case, saccharification and fermentation for producing ethanol are carried out in the first step. Then, lignin-rich residue obtained from the saccharification process is converted into bio-oil by flash pyrolysis (Figure 3.3-5). Figure 3.3-6 shows gas chromatograph of bio-oils obtained from willow and saccharised residue of willow. Saccharised residue still contains lignin, and it can give phenolic compounds as intermediates of the production of aromatic gasoline.

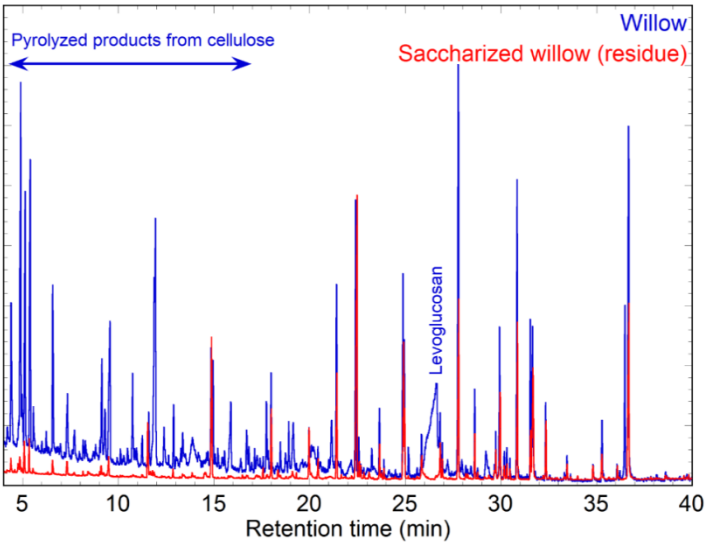
In the case of alternative diesel production by biomass gasification (Figure 3.3-7), linear paraffins are obtained by FT synthesis. The intermediates can easily be converted into products by isomerisation (and cracking). Synthetic gas is converted into linear paraffins by FT synthesis.

Figure 3.3-5. Combined Ethanol and Alternative Gasoline Production from Waste Biomass



Source: Authors.

Figure 3.3-6. Gas Chromatograms of Bio-oils Obtained from Willow and Its Saccharised Residue



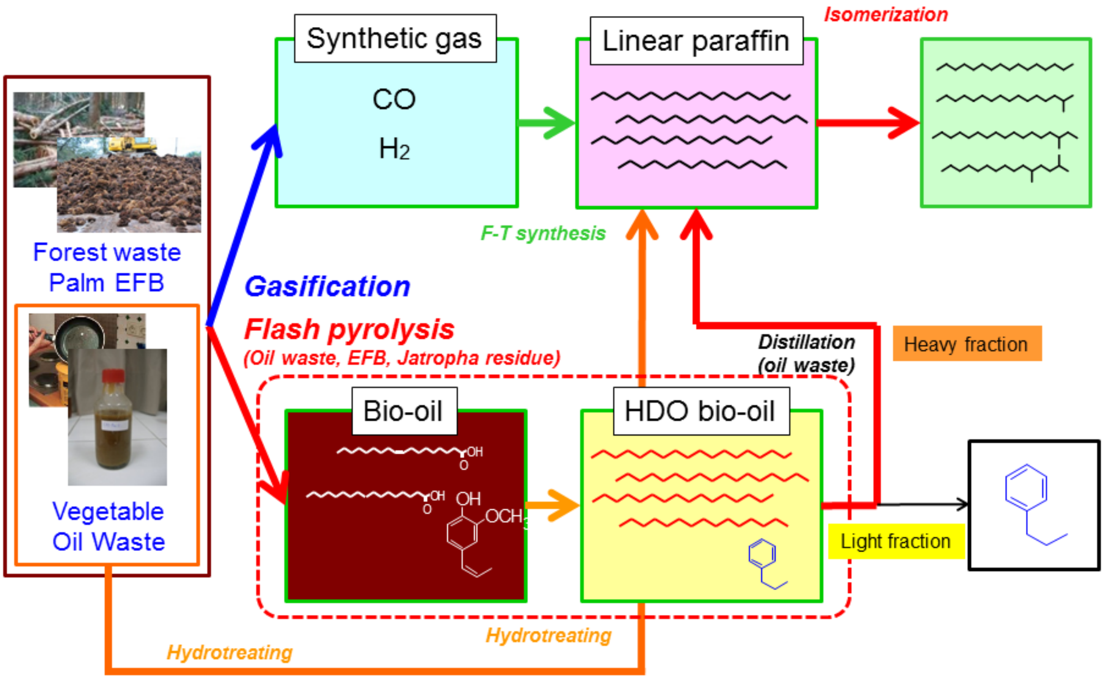
Source: Authors.

Glycerides and fatty acid contained in oil waste can be converted into linear paraffins by catalytic hydrodeoxygenation. These compounds form linear paraffins through flash pyrolysis. Alternative diesel can be obtained from usual woody biomass only through gasification.

The target fuel and production process depends on the composition of key compounds in the biomass resources. Analysis of raw materials is important for evaluating the potential of fuel productivity.

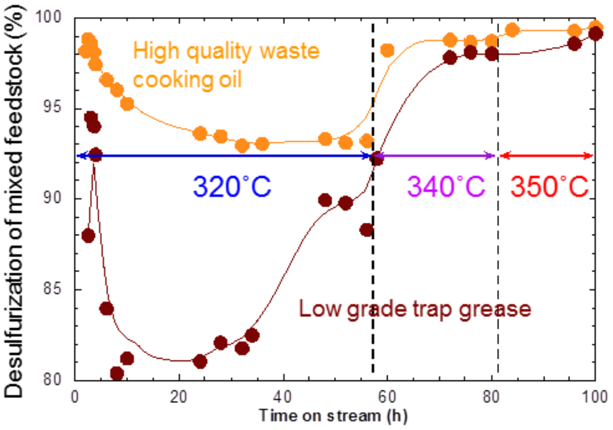
When low-grade materials or new resources are used as the feedstock of fuel production, their quality sometimes influences the activity and life of the catalyst. Such technical information is scarce, though these factors are important in the simulation of production cost (prediction of catalyst life). Figure 3.3-8 shows the effect of feedstock on hydrotreating of 10 weight% waste cooking oil or trap grease/straight-run diesel mixture based on our experimental data. Trap grease, a waste material from sewage, contains a high concentration of free fatty acids and its acid value is much higher than that of waste cooking oil. Catalytic activity was seriously damaged in the hydrodesulfurisation of trap grease/straight-run diesel mixture. To produce high-quality diesel like sulfur-free diesel, the reaction must be carried out under a more severe condition and the catalyst life may shorten.

Figure 3.3-7. Alternative Diesel Production from Waste Biomass



Source: Authors.

Figure 3.3-8. Hydrotreating of Waste Cooking Oil or Trap Grease/Straight-Run Diesel Mixture



Source: Ministry of the Environment, Japan (2012).

Recently, the standard of hydrocarbon biofuel as a blendstock of diesel fuel has been established (EN15940:2016). The quality of some alternative diesel fuels is shown in Table 3.3-6.

Some blendstocks do not meet with the conventional petroleum diesel fuel standard (EN590) and have a high cetane number and cloud point compared with petrodiesel. However, the properties of most these blendstocks meet with the new standard. In the future, it will be necessary to discuss the standard of the next-generation biofuel, which is produced from the biomass obtained in East Asia Summit countries.

The conclusions in this section are the following:

(1) The advantage of next-generation fuel is to be able to use inexpensive raw materials such as waste materials from the viewpoint of production. It also contributes to reduction of GHG emissions.

(2) There are various processes such as gasification, pyrolysis, and hydrotreating for producing next-generation biofuels. The final product and its productivity depend on the manufacturing process.

(3) The analysis of the biomass composition is indispensable to decide the use of the final product.

(4) When low-grade material is used as a feedstock, its quality influences catalytic activity. In this case, a durable catalyst must be developed. It is necessary to clarify technological problems through experimental works.

(5) Fuel blended with hydrocarbon biofuel not always meets the conventional fuel standard. The quality of blendstock should be defined by the standard specification.

3.4 Cost Performance Improvement of Next-Generation Biofuel Production

Generally, the prices of current biofuels are higher than those of conventional petroleum fuels. To promote biofuel, funding system has been introduced.

Table 3.3-6. Properties of Various Alternative Diesel Fuel (HVO, FT-Diesel)

			JIS No.2	AAF recommendation		HVO	GTL	Petro-diesel	HVO	Petro-diesel	HVO				Iso-HVO	
				Euro4	Euro5	NESTE	SASOL	B0	B30	B0	B10	B20	B30	B100	B10	B20
Density@15℃ (kg/m3)			0.86 max.	0.820-0.845	0.820-0.845	0.78	0.774	0.8375	0.8122	0.824	0.819	0.815	0.811	0.779	0.819	0.814
Cetane number		Min.		51	51	94.8	>73	51.2	60.7	51.7	56.7	61.7	66	95	56	59.1
Cetane index		Min.	45	51	51											
Viscosity @ 40℃ (mm2/S)		Max.	2.7 min. (30℃)	2.0-4.5	2.0-4.5	2.99	2.34	2.681	2.545	2.46	2.53	2.59	2.67	3.26	2.5	2.55
Sulfur (ppm)		Max.	10	50	10			<10	<10	4	4	4	4			
Flash point (℃)		Min.	50	55	55					52	54	54	56	132	54	56
Distillation	10% (℃)	Max.		Report	Report			202.4	204.3	176	180	181	187	277	178	186
	50% (℃)	Max.		Report	Report			265.6	273.2	261	270	275	278	287	270	271
	90% (℃)	Max.	350 (360)	Report	Report			335.8	317.2	343	336	330	326	298	342	334
	95% (℃)	Max.		360	360											
	FBP (℃)	Max.		Report	Report			364.6	349.2	382	380	380	379	328	383	381
PAH (mass%)		Max.		11	8			25.7(total)	16.1(total)							
Oxygenates	FAME (vol%)	Max.	(0.1/5)	5	5											
	Alcohols contents (vol%)	Max.		Not detected	Not detected											
Lubricity (HFRR, mm)		Max.		460	460	334	211									
Carbon residue, 10% (mass%)		Max.	0.1	0.3	0.3											
Water content (ppm)		Max.		200	200											
Oxidation stability	conventional	Max.		25	25											
	Modified Rancimat	Min.		35	35											
	D TAN	Max.		0.12	0.12											
	PetroOXY	Min.		65	65											
Copper corrosion		Max.		1	1											
Particles (mg/L)		Max.		10	10											
Ash content (mass%)		Max.		0.01	0.01											
Cloud point (℃)		Max.		Decided by out-side temp in winter	Decided by out-side temp in winter					-1	3	5	8	19	-2	-3
Pour point (℃)		Max.	-7.5													
CFPP (℃)		Max.	-5			-21	-7									
						Ref.1		Ref.2		Ref.3						

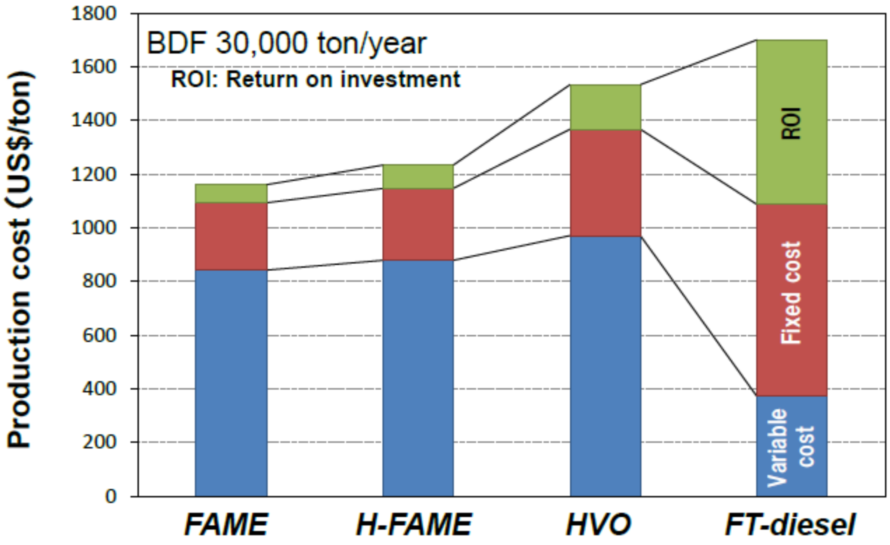
FT = Fischer-Trøpsch, HVO = hydrotreated vegetable oil.
Source: Authors.

However, it is predicted that the next-generation biofuels will be more expensive. In this section, the factors to reduce the price of next-generation biofuel are clarified.

Raw Material Cost

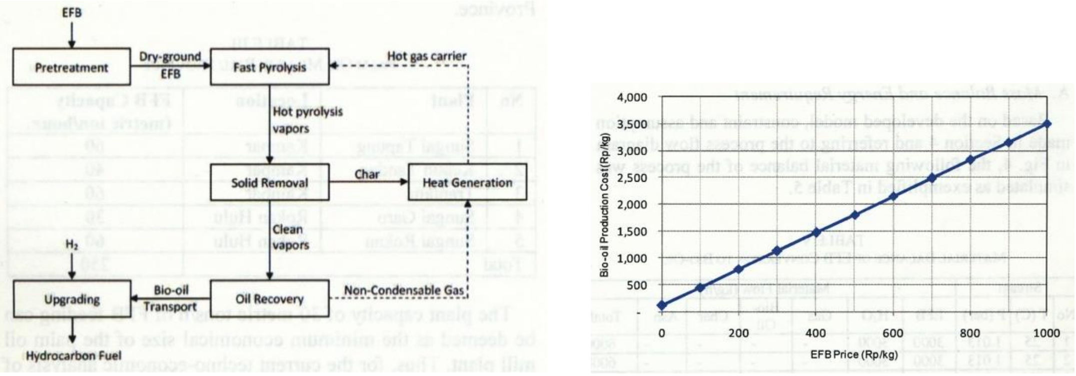
Currently, edible feedstocks are mainly used as biofuel resources. For biodiesel production, more than 95% of biodiesel is produced from edible oils. The use of edible feedstocks in biofuel production has a large influence on food demand and supply. In addition, the price of transportation biofuel is usually higher than that of corresponding fossil fuel. To accelerate biofuel introduction, the fuel price must be reduced. According to feasibility studies of biofuel production, the biofuel price depends mainly on the cost of feedstock. Figure 3.4-1 shows production costs of conventional and next-generation biodiesel (Waseda University, 2011). FAME, H-FAME, and hydrogenated vegetable oil (HVO) are produced from palm oil. Of the total biodiesel cost, 64%–73% is the cost of feedstock. Baroi et al. (2015) showed that the raw material cost in total biodiesel manufacturing costs is 66.6%. Poddar et al. (2015) showed that the raw material cost in total biodiesel manufacturing costs is 83.6%. These results suggest that the cost reduction of feedstock is effective for improvement of the economy of biodiesel production.

Figure 3.4-1. Feasibility Study of Biodiesel Production from Palm Oil (FAME, H-FAME, and HVO) and Woody Biomass (FT-Diesel)



BDF = biodiesel fuel, FAME = fatty acid methyl esters, FT = Fischer-Trøpsch, H-FAME = hydrogenated FAME, HVO = hydrotreated vegetable oil.
Source: Waseda University (2011).

Figure 3.4-2 Fuel Production Scheme from Empty Fruit Bunch and Bio-oil Production Cost



Source: Peryoga et al. (2014).

Figure 3.4-2 shows the scheme of transportation fuel production from empty fruit bunch (EFB) of palm by pyrolysis and upgrading, and the results of bio-oil production cost analysis (Peryoga et al., 2014). The bio-oil production cost is proportional to the EFB price.

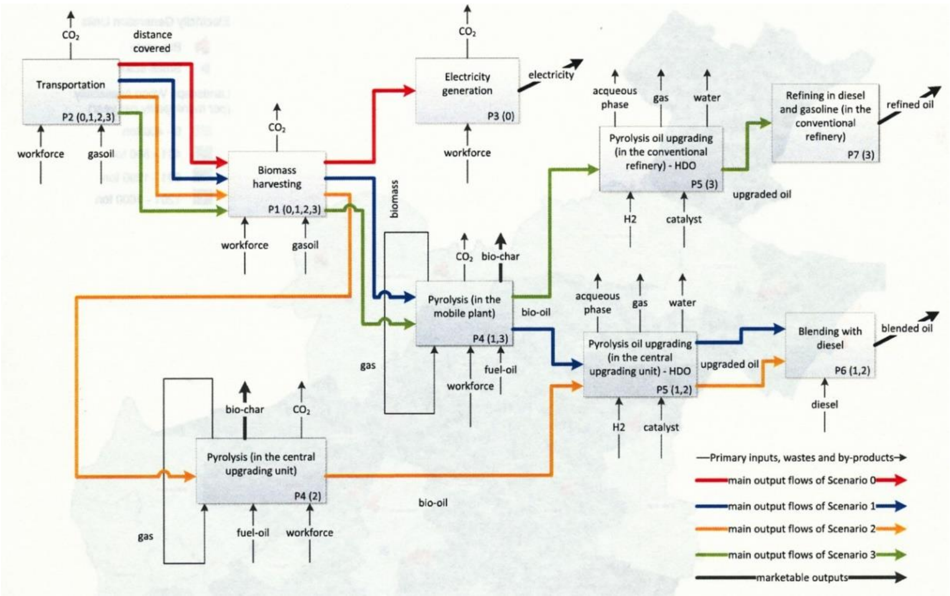
These results suggest that the cost reduction of feedstock is important for improvement of the economy of biodiesel production. The utilisation of cheap feedstocks such as non-edible feedstocks including waste materials contributes to the reduction of the biofuel price.

<u>Process Selection</u>

Utilisation of non-conventional resources contributes to reduction of feedstock cost. However, operation and management cost is usually more expensive than conventional biofuel production. In future, optimal process R&D is needed to reduce operation and management cost. In this section, we would like to show some examples of process selection to reduce cost of biofuel production.

Transportation fuel is usually produced via several steps. Each step has some possibilities to produce intermediates and products. Figure 3.4-3 shows a flow diagram of fuel production. Three scenarios were proposed for producing fuel (Scenarios 1–3). The diagram consists of three main steps: pyrolysis, upgrading (hydrodeoxygenation: HDO), and co-processing/blending. Pyrolysis is carried out using a mobile plant (S1, S3) or central unit (S2). Pyrolysis oil upgrading is carried out using a central unit (S1, S2) or conventional refinery (S3). Produced oil from the upgrading process is refined with crude petroleum fraction (co-processing: S3) or blended with refined petroleum fraction (S1, S2).

Figure 3.4-3. Supply Chain Flow Diagram of Fuel Production via Pyrolysis and Upgrading

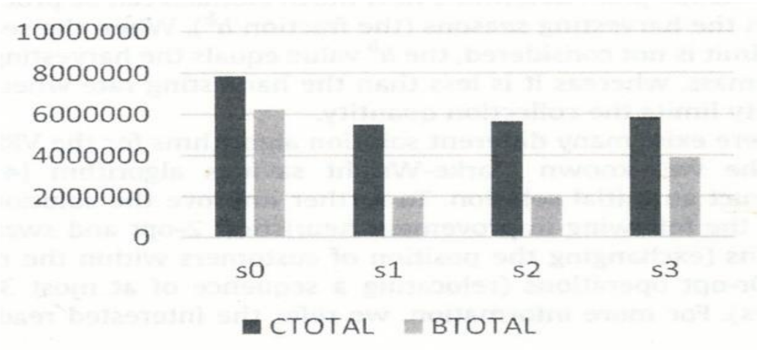


Source: Yazan et al. (2016).

The result of the cost calculation (in euro) of each scenario is shown in Figure 3.4-4. Compared with scenarios 1–3, the fuel production cost is almost equal. However, the benefit of scenario 3 is higher than that of scenarios 1 and 2. These results indicate that upgrading (HDO) and co-processing processes have more benefits than the pyrolysis process. In this case, we should choose scenario 3 to produce transportation fuel, economically.

Recently, various alternative jet fuels are proposed: GTJ – gas to jet, OTJ – oil to jet, ATJ – alcohol to jet, and STJ – sugar to jet. From solid waste, GTJ and OTJ processes are suitable for alternative jet fuel production. A comparison of intermediate production cost is shown in Table 3.4-1 (Wang et al., 2016). Pyrolysis can create an intermediate more cheaply more than FT synthesis. The final jet fuel cost depends on the cost of upgrading.

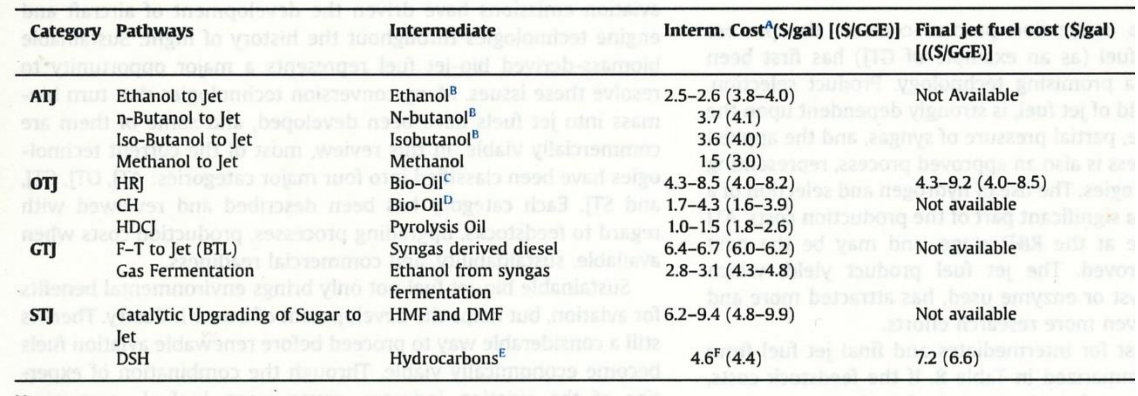
Figure 3.4-4. Total Production Cost and Benefit of Fuel Production



Source: Yazan et al. (2016).

Utilisation of by-products, or simultaneous production of valuable chemicals, contributes to cost reduction of fuel production. Table 3.4-2 shows the cost effect of fuel production using FT synthesis with/without the methanol to gas (MTG) process (Baliban et al., 2013). In the D-1 process, fuel is produced by FT synthesis using the Ir catalyst and methanol to gas process. On the other hand, fuel is produced by only FT synthesis using the Co catalyst in the K-1 process. While fuel can be produced for US$100.86 per barrel (bbl) in D-1, it costs US$110.96/bbl in K-1.

Table 3.4-1 Production Costs of Alternative Jet Fuel from Various Pathways

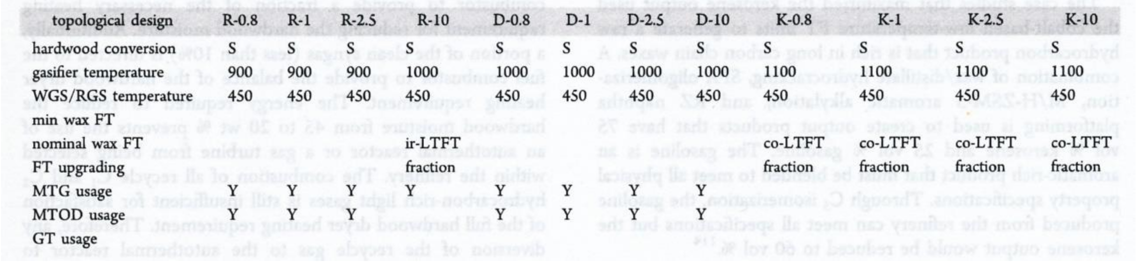


Category	Pathways	Intermediate	Interm. Cost[A]($/gal) [($/GGE)]	Final jet fuel cost ($/gal) [(($/GGE)]
ATJ	Ethanol to Jet	Ethanol[B]	2.5–2.6 (3.8–4.0)	Not Available
	n-Butanol to Jet	N-butanol[B]	3.7 (4.1)	
	Iso-Butanol to Jet	Isobutanol[B]	3.6 (4.0)	
	Methanol to Jet	Methanol	1.5 (3.0)	
OTJ	HRJ	Bio-Oil[C]	4.3–8.5 (4.0–8.2)	4.3–9.2 (4.0–8.5)
	CH	Bio-Oil[D]	1.7–4.3 (1.6–3.9)	Not available
	HDCJ	Pyrolysis Oil	1.0–1.5 (1.8–2.6)	
GTJ	F–T to Jet (BTL)	Syngas derived diesel	6.4–6.7 (6.0–6.2)	Not available
	Gas Fermentation	Ethanol from syngas fermentation	2.8–3.1 (4.3–4.8)	
STJ	Catalytic Upgrading of Sugar to Jet	HMF and DMF	6.2–9.4 (4.8–9.9)	Not available
	DSH	Hydrocarbons[E]	4.6[F] (4.4)	7.2 (6.6)

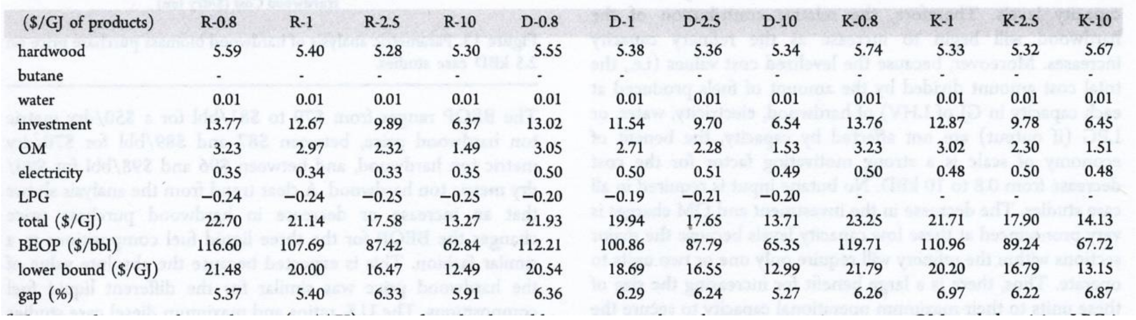
Source: Wang et al. (2016).

From the viewpoint of energy consumption, energy savings may contribute to cost reduction of fuel production. Figure 3.4-5 shows the simulation result of energy input for producing biofuel via a fast pyrolysis-upgrading process from solid biomass (Wong et al., 2016). Energy consumption of hydroprocessing (hydrotreating and hydrocracking) is much higher than other processes (harvesting, transportation, and pyrolysis). This result indicates that improvement of hydroprocessing may reduce energy consumption and contribute to cost cutting.

Table 3.4-2. Cost Effect of Fuel Production Using FT Synthesis with/without Methanol to Gas Process



topological design	R-0.8	R-1	R-2.5	R-10	D-0.8	D-1	D-2.5	D-10	K-0.8	K-1	K-2.5	K-10
hardwood conversion	S	S	S	S	S	S	S	S	S	S	S	S
gasifier temperature	900	900	900	1000	1000	1000	1000	1000	1100	1100	1100	1100
WGS/RGS temperature	450	450	450	450	450	450	450	450	450	450	450	450
min wax FT												
nominal wax FT				ir-LTFT fraction					co-LTFT fraction	co-LTFT fraction	co-LTFT fraction	co-LTFT fraction
FT upgrading												
MTG usage	Y	Y	Y	Y	Y	Y	Y	Y				
MTOD usage	Y	Y	Y		Y	Y	Y	Y				
GT usage												

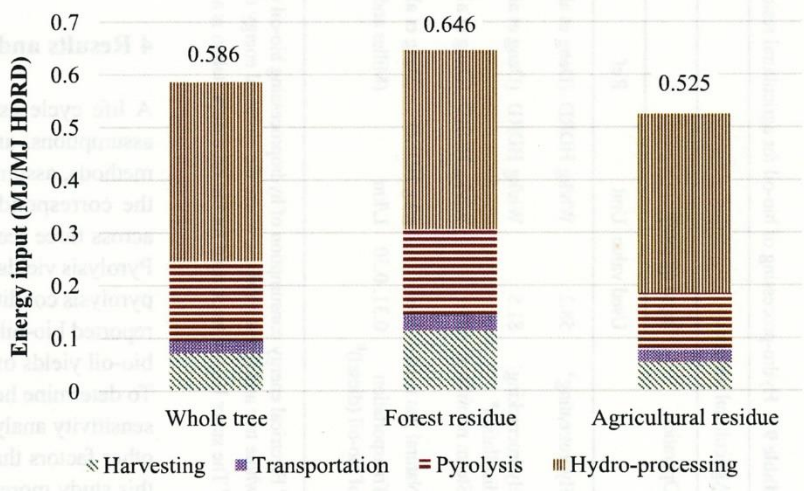


($/GJ of products)	R-0.8	R-1	R-2.5	R-10	D-0.8	D-1	D-2.5	D-10	K-0.8	K-1	K-2.5	K-10
hardwood	5.59	5.40	5.28	5.30	5.55	5.38	5.36	5.34	5.74	5.33	5.32	5.67
butane	-	-	-	-	-	-	-	-	-	-	-	-
water	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
investment	13.77	12.67	9.89	6.37	13.02	11.54	9.70	6.54	13.76	12.87	9.78	6.45
OM	3.23	2.97	2.32	1.49	3.05	2.71	2.28	1.53	3.23	3.02	2.30	1.51
electricity	0.35	0.34	0.33	0.35	0.50	0.50	0.51	0.49	0.50	0.48	0.50	0.48
LPG	−0.24	−0.24	−0.25	−0.25	−0.20	−0.19	−0.21	−0.20	-	-	-	-
total ($/GJ)	22.70	21.14	17.58	13.27	21.93	19.94	17.65	13.71	23.25	21.71	17.90	14.13
BEOP ($/bbl)	116.60	107.69	87.42	62.84	112.21	100.86	87.79	65.35	119.71	110.96	89.24	67.72
lower bound ($/GJ)	21.48	20.00	16.47	12.49	20.54	18.69	16.55	12.99	21.79	20.20	16.79	13.15
gap (%)	5.37	5.40	6.33	5.91	6.36	6.29	6.24	5.27	6.26	6.97	6.22	6.87

Source: Baliban et al. (2013).

To reduce hydroprocessing costs, upgrading of pyrolysis vapour using a supported metal catalyst with fixed bed flow rector is proposed (Area200 in Figure 3.4-6) (Dutta et al., 2016). In this process, partially upgraded (deoxygenated) products are obtained. In the hydrodeoxygenation of partially upgraded products, hydrogen consumption and catalyst life seem to be improved compared with those of hydroprocessing of usual bio-oil. Therefore, the cost of hydroprocessing and separation is very low (Area400) compared with the result of Figure 3.4-5.

Figure 3.4-5. Simulation Result of Energy Input for Producing Biofuel

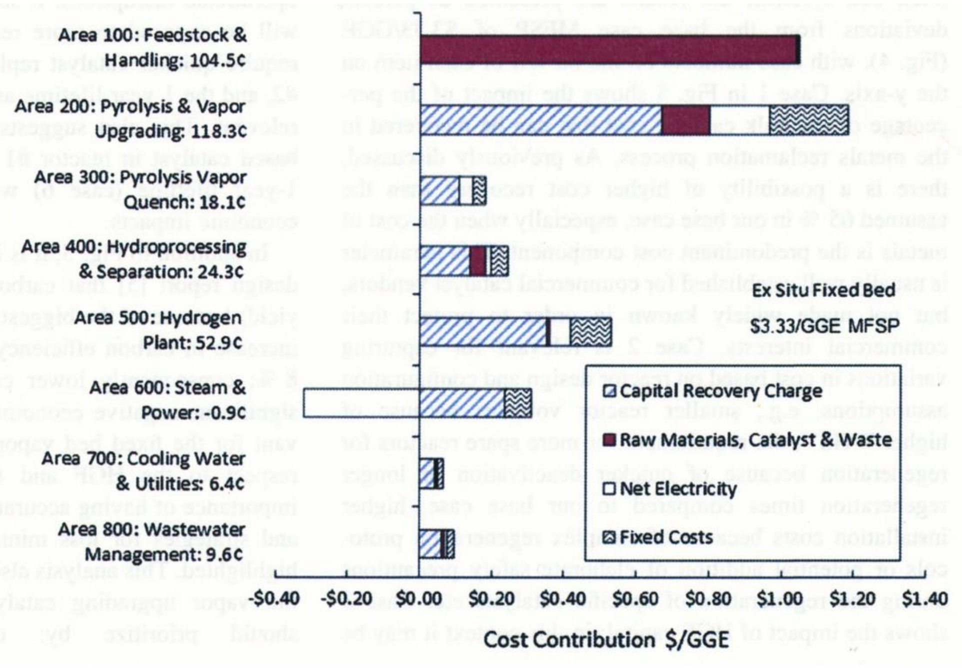


Source: Wong et al. (2016).

It is important to simulate sensitivity of each factor for producing biofuel. In the case of jet fuel production from Jatropha oil and residue, more than half of the direct capital cost is oil upgrading (Figure 3.4-7) (Wang, 2016).

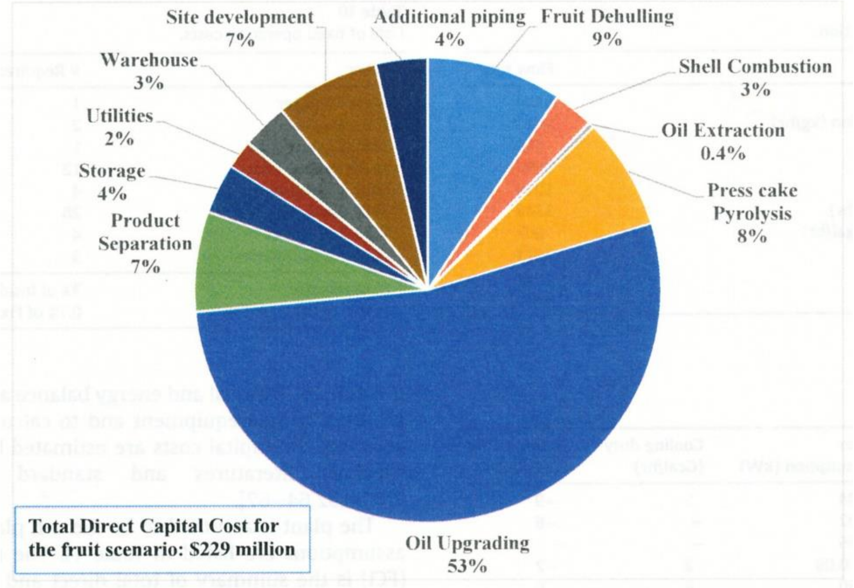
According to the simulation of cost sensitivity (Figure 3.4-8), the hydrotreating catalyst cost has a large influence on product price (MJSP or minimum jet fuel selling price). It can be concluded that the reduction of the catalyst price gives the largest effect to supply cheap fuel (Tijmensen et al., 2002).

Figure 3.4-6. Cost Contribution by Each Process



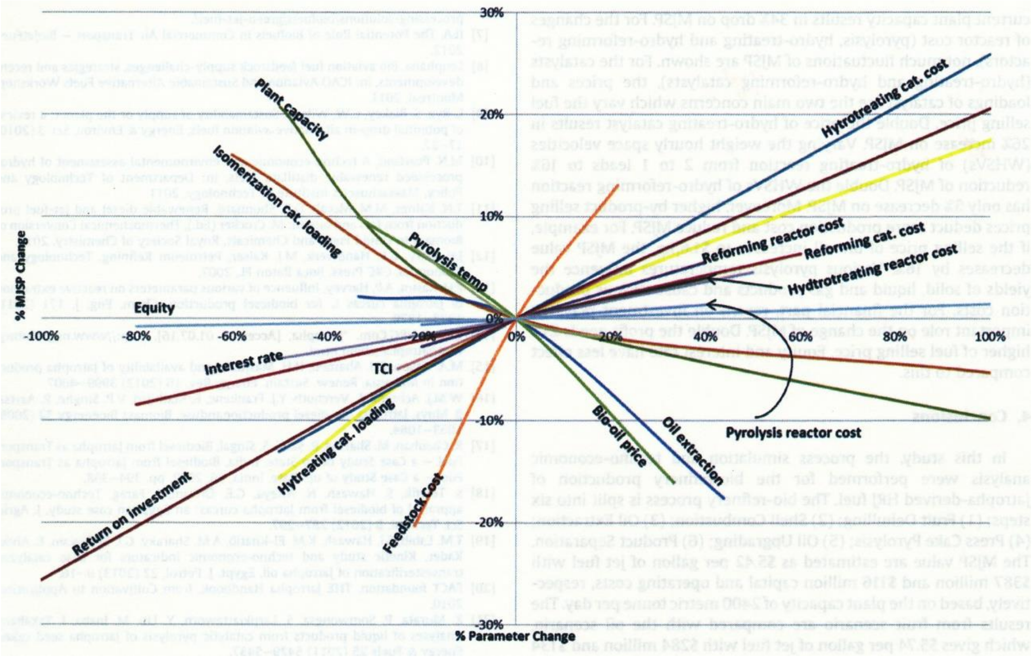
Source: Dutta et al. (2016).

Figure 3.4-7. Distribution of Total Direct Capital Cost



Source: Wang (2016).

Figure 3.4-8. Cost Sensitivity Analysis of Jet Fuel Production from Jatropha



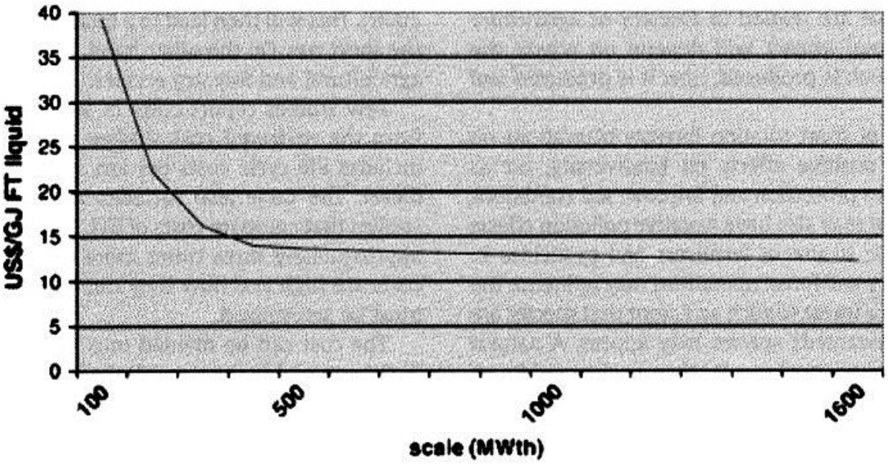
Source: Wang (2016).

Plant Scale

The scale of the biofuel manufacturing plant also has an influence on fuel price. An example of a biomass-to-liquids (BTL) process is indicated in Figure 3.4-9 (Tijmensen et al., 2002). The fuel price produced in a small-scale plant is high. The price decreases with increasing plant scale. However, the scale merit is sometimes denied by various factors such as transportation cost and productivity of raw materials when the scale becomes too large. Therefore, there is an optimal range in economical plant scale. If a cheaper raw material can be used, the cost performance of a small-scale plant may be improved.

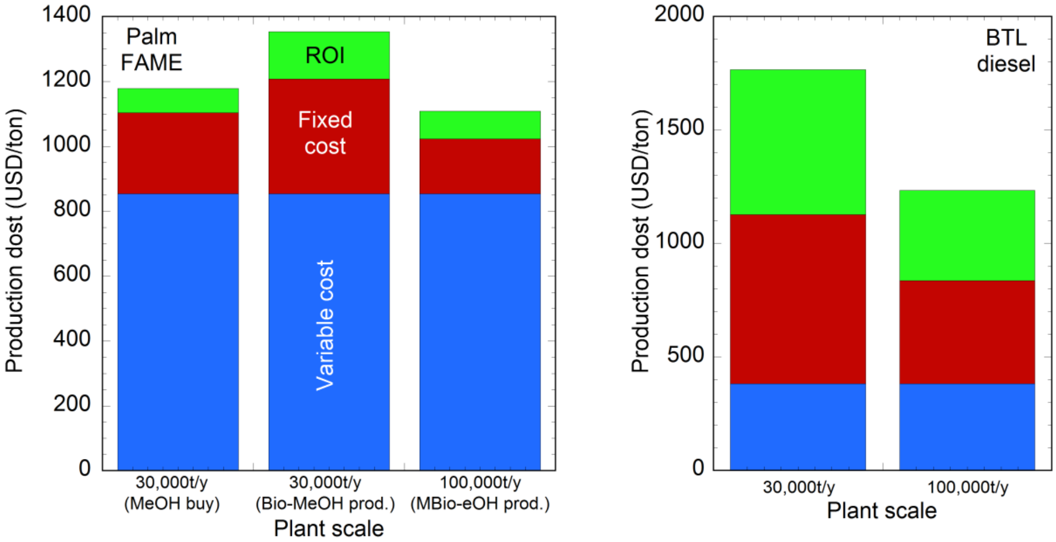
The production cost consists roughly of variable cost, fixed cost, and return on investment. The influence of the plant scale on these factors is shown in Figure 3.4-10. In the case of biodiesel (FAME) production, the variable cost per product weight is the same in all cases. The FAME production cost using methanol produced from biomass in the plant is higher than that using commercial methanol. This is mainly caused by an increase of fixed cost to construct a methanol plant. When the plant scale becomes larger, fixed cost per product weight decreases. A similar effect is observed in the manufacturing of BTL diesel fuel. Expansion of the fuel production scale is effective for reducing the fixed cost of fuel production.

Figure 3.4-9. Economy of Scale Effects for Biomass-to-Liquids Production from Poplar



Source: Tijmensen et al. (2002).

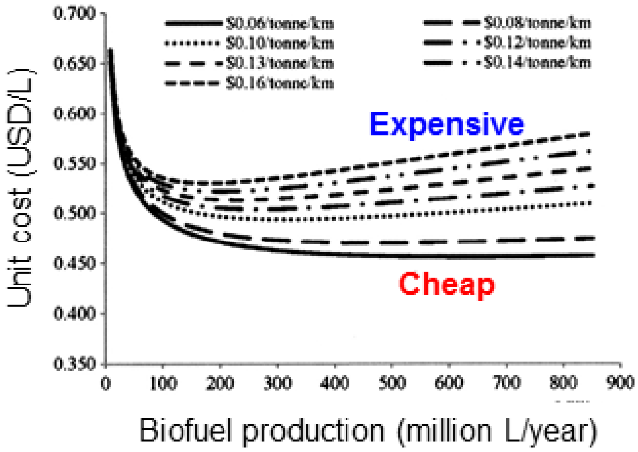
Figure 3.4-10. Feasibility Study of Alternative Diesel Production



Source: Waseda University (2011).

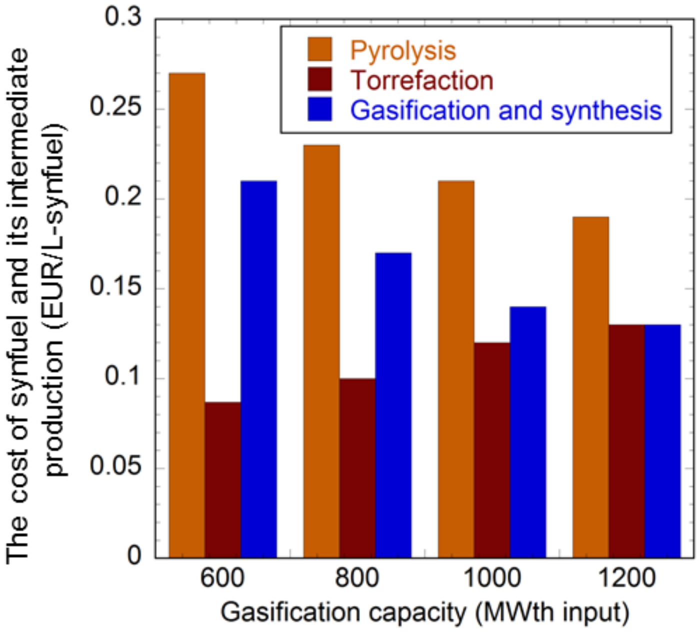
Scale merit is influenced by various factors. Jenkins et al. (2014) simulated the influence of the transportation cost rate of raw materials and intermediates on the relationship between plant capacity and ethanol production cost (Figure 3.4-11). The transportation cost usually depends on the distance from the place of raw material supply to the factory of intermediate and fuel production, as well as the shape and amount of the transported materials. If the transportation cost is too high, the scale merit is denied. The costs of the intermediate production and fuel synthesis by the BTL process are shown in Figure 3.4-12. The cost of synfuel production (gasification and synthesis) decreases with increasing gasification capacity. The cost of pyrolysis intermediate supply also decreases with increasing gasification capacity. On the contrary, the cost of torrefaction intermediate supply increases with increasing gasification capacity. The difference between pyrolysis and torrefaction causes transportation fee. The products of pyrolysis and torrefaction are liquid (tar) and solid, respectively. Liquid materials are less bulky and easier to carry to the fuel production factory by land transportation, ship and pipe line. This is an example of the shape effect of the transported materials on transportation fee.

Figure 3.4-11. Unit Cost as a Function of Biofuel Production for Various Delivery Rate Cost



Source: Jenkins et al. (2014).

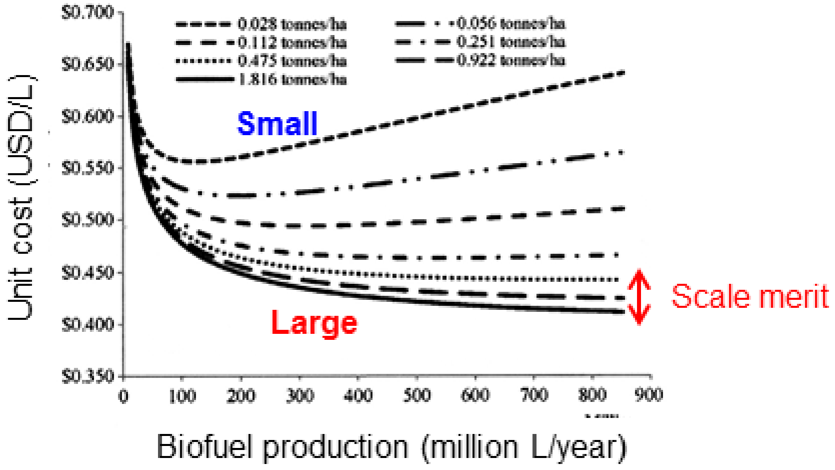
Figure 3.4-12. Synfuel Production Costs for Different Gasification Capacity



Source: Zimmer et al. (2017).

The productivity of the biomass also influences the scale merit. In the case of transportation of raw materials from farms with low productivity to a big factory, it is necessary to transport the materials multiple times. Consequently, an increase in total transport distance causes a cost increase and the scale merit to the fuel cost almost disappears (Figure 3.4-13).

Figure 3.4-13. Unit Cost as a Function of Biofuel Production for Various Equivalent Yields

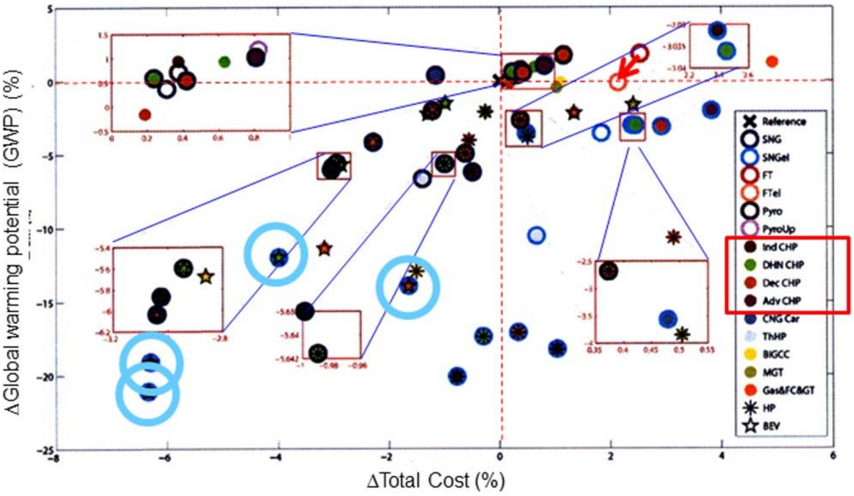


Source: Jenkins et al. (2014).

Energy Supply System

To reduce the influence on the cost and global warming, we have to consider measures based on a combination of the fuel manufacturing process, energy supply, and energy consumption by vehicles. Improvement of fuel efficiency of vehicles has been implemented by electrification. In addition, selection of an energy supply system is also an important factor that influences the cost and global warming. Figure 3.4-14 shows the annual global warming potential (GWP) impact and total cost relative values for various scenarios compared to the reference scenario. Light-blue plots indicate the influence of an energy supply system on the increase of GWP impact and total cost. In these cases, electricity is generated by substituted natural gas (SNG) produced with an electrolyser from biomass and the electricity was consumed by battery electric vehicles. The reduction of total cost depends on the combined heat and power supply systems. This result indicates that the optimum energy supply can contribute to the reduction of total cost and global warming.

Figure 3.4-14. Annual Global Warming Potential Impact and Total Cost Relative Values for the 56 Scenarios Compared to the Reference Scenario

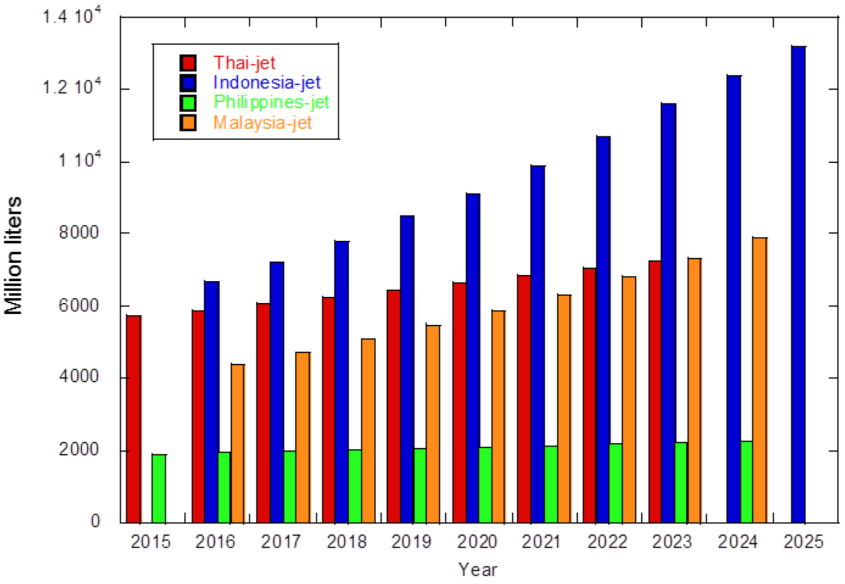


Source: Gironès et al. (2017).

5. Next-Generation Biofuel as Sustainable Aviation Fuel

Global demand for aviation fuel expands year by year. In particular, the demand for aviation fuel in developing countries will dramatically expand. In ASEAN, the demand in Indonesia and Malaysia will expand (Figure 3.5-1).

Figure 3.5-1. Aviation Fuel Demand Outlook in ASEAN-4 Countries



Sources: United States Department of Agriculture (2014; 2015).

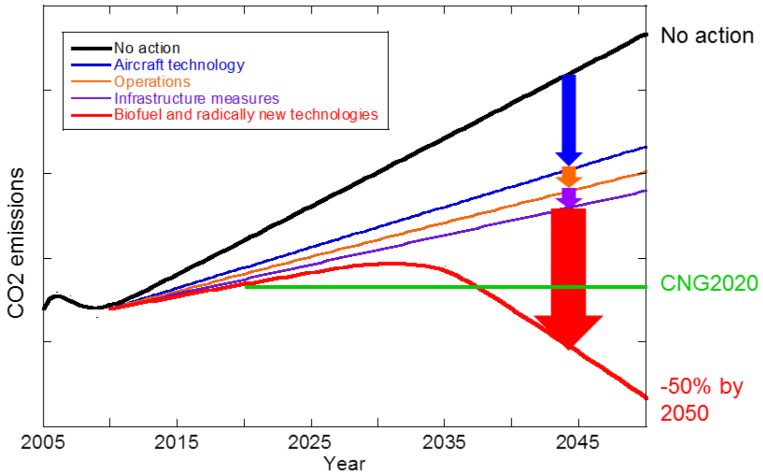
To correspond to the increase of aviation fuel and the reduction of fossil fuel consumption and GHG emissions, IATA decided the Sustainable Alternative Aviation Fuels Strategy. This strategy mentions three targets: (1) 1.5% fuel efficiency improvement from 2009 until 2020, (2) carbon-neutral growth from 2020, and (3) 50% reduction in carbon emissions by 2050 relative to a 2005 baseline. Automobile fuels are mainly used in domestic transportation. Each government can decide independently the policy such as quality and introduction of biofuel. However, aviation fuel is used for international transportation. Therefore, international decision applies to all countries.

It is predicted that international aviation net CO_2 emissions will increase 4.5 times from 2010 to 2040. Reducing GHG emissions involves several measures. Amongst them, the introduction of alternative aviation fuel is most effective (Figure 3.5-2).

Currently, there are only a few factories in the world that produce alternative aviation fuels and the products are used tentatively. According to the IATA outlook, the production of sustainable aviation fuel (SAF) will increase from around 2030. In the future, introducing alternative aviation fuel in earnest will require development and improvement of manufacturing processes of the fuel and the policy which promote the introduction.

In this study, we investigate manufacturing processes and product quality of alternative aviation fuels and clarify technological problems.

Figure 3.5-2. Greenhouse Gas Reduction in the Aviation Sector

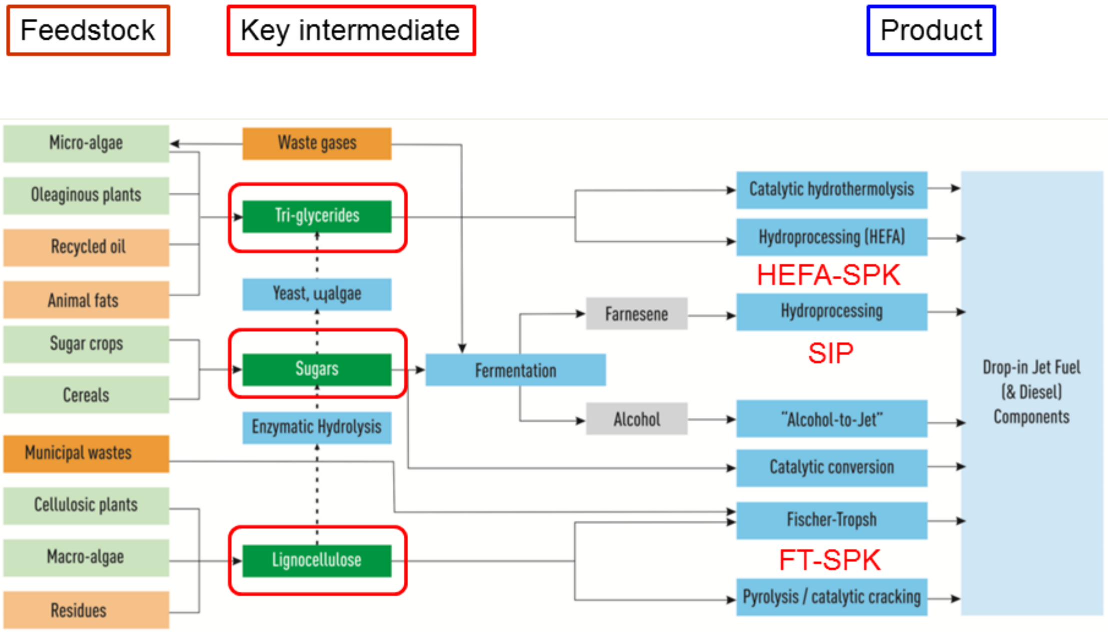


Source: IATA (2015).

Figure 3.5-3 gives a simplified view of pathways for alternative aviation fuel production (Novelli, 2014). Hydroprocessed ester and fatty acid synthetic paraffinic kerosene (HEFA-SPK), and FT synthetic paraffinic kerosene (FT-SPK) are the main alternative aviation fuels, which are produced by hydroprocessing (hydrodeoxygenation and isomerisation) and FT synthesis, respectively. Recently, a synthesised iso-paraffinic (SIP) fuel produced by a fermentation process was introduced. From the viewpoint of the diversification of resources, FT-SPK is more desirable because many kinds of resources such as solid biomass and waste materials can be used as resources.

The properties of HEFA-SPK and FT-SPK are close to those of HVO and FT-diesel, respectively. It is possible to produce alternative aviation and diesel fuels with the same raw materials and process. For example, FT-WAX, a product of FT synthesis is converted into FT-SPK by cracking and isomerisation, and FT-diesel by isomerisation and mild cracking. The key technology which enables each fuel to be produced selectively is catalyst technology. An example obtained in our laboratory is shown in Figure 3.5-4.

Figure 3.5-3. Pathways for Alternative Aviation Fuel Production

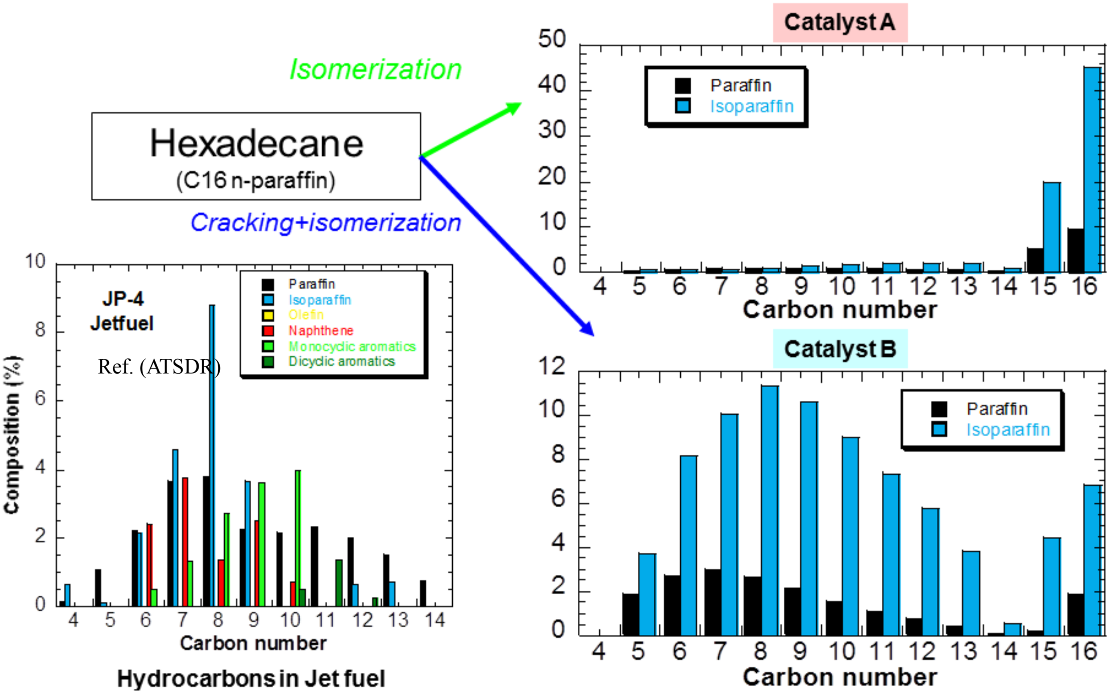


Source: Novelli (2014).

An alternative jet fuel standard has been established by the American Society for Testing and Materials ASTM D7566. The specifications are determined by mainly cold flow property and material compatibility. The remarkable item is aromatic hydrocarbon content. Because of fuel system material problems (sealing, etc.), aromatic hydrocarbons are required. HEFA-SPK and FT-SPK are usually a mixture of paraffinic hydrocarbons and they do not contain aromatic hydrocarbons (see Figure 3.5-5). Addition of aromatic hydrocarbons that are derived from petroleum fraction or produced by reforming paraffinic hydrocarbons is needed to meet the fuel standard.

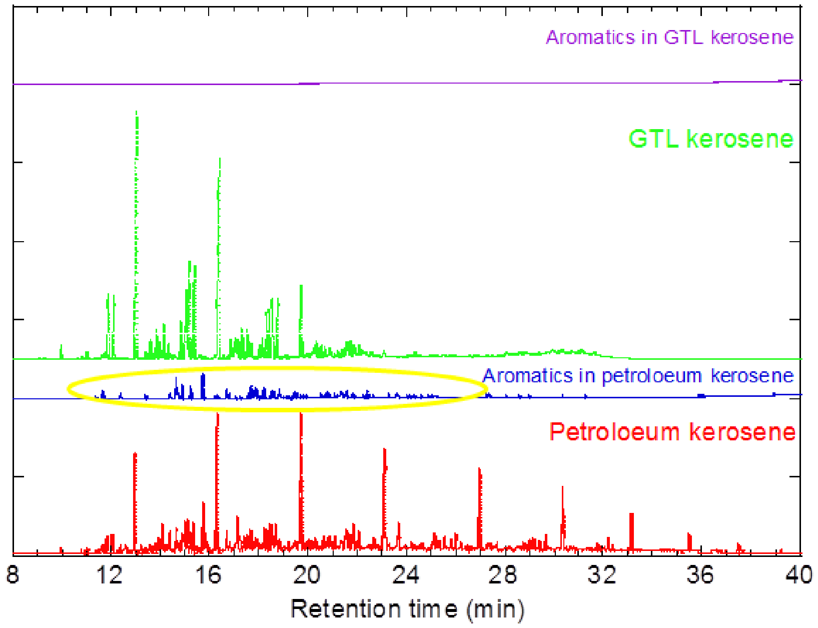
Recently, countries in East Asia have passed policies to introduce alternative aviation fuel. In Japan, a committee was established for the study of a process leading to the introduction of biojet fuel for the 2020 Summer Olympic Games and Paralympic Games in Tokyo. The Ministry of Land, Infrastructure, Transport and Tourism announced that use of biojet fuel (30 September 2015). Initiatives for Next Generation Aviation Fuels (INAF) plans a roadmap towards using nationally sourced aviation biofuels by 2020 (INAF, 2015). In Indonesia, the Directorate General of Civil Aviation has announced the Indonesian Alternative Fuels and Renewable Energy Initiatives for the reduction of GHG emissions (ICAO, 2017). In Malaysia, the Sustainable Fuel Centre of Excellence has been established by Airbus and key Malaysian partners to assess local solutions for sustainable biomass production (Airbus, 2014). The aim is to determine the most suitable feedstock to ensure any future jet fuel production.

Figure 3.5-4. Effect of Catalyst Species on Product Distribution in Hydrotreating of Hexadecane



Source: Authors.

Figure 3.5-5. Gas Chromatograms of Petroleum Kerosene and Gas-to-Liquids Kerosene



GTL = Gas-to-Liquids
Source: Authors.

The conclusions from this section are as follows:

(1) The demand for aviation fuel in developing countries will expand. In ASEAN, the demand in Indonesia and Malaysia will expand particularly.

(2) It is predicted that international aviation net CO_2 emissions will increase. The introduction of biofuel is effective for reducing GHGs. ASEAN Member States should consider the introduction of alternative aviation fuel produced from their own resources.

(3) FT-SPK and HEFA-SPK are the main alternative aviation fuels. They are produced by biomass gasification-FT synthesis and hydrodeoxygenation-cracking/isomerisation of oil and fat, respectively. Catalyst technology enables the production of both alternative aviation fuel and alternative diesel fuel for automobiles, selectively.

(4) The quality of petroleum-alternative mixed jet fuel and each blendstock should be controlled by standard specification (ASTM D7566).

(5) To introduce alternative aviation fuel, the decision of a national policy is needed. It is also necessary to consider cooperation between countries based on the resources.

6. Conclusions

Next-generation biofuels are expected to be sustainable transportation fuels, which contribute to energy security because they can be produced from various nonconventional resources such as woody biomass and waste materials. Various technologies have been developed such as the fuel manufacturing process from nonconventional raw materials. To choose an appropriate fuel production process, it is important to know the chemical and physical properties of the raw material sufficiently.

At present, some commercial plants are under operation. However, the price of the supplied next-generation biofuel is relatively high. Therefore, cost reduction is very important for accelerating next-generation biofuel introduction. Securing cheap resources, improving raw material productivity, and reducing the transportation cost are effective for variable cost reduction. The location of the manufacturing plant should be considered to reduce the supply cost of raw materials. On the other hand, selection of the fuel manufacturing process and its scale are also important factors for reducing the manufacturing cost. Cost reduction in the manufacturing process also depends on the measures of energy supply. In the future, it will be possible to supply next-generation biofuel more economically by optimising the combination of such factors as well as developing higher-performance manufacturing technology.

The electrification of small vehicles has been progressing, mainly in advanced countries. However, the electrification of buses, trucks, and airplanes has been difficult. The next-generation biofuel produced from sustainable raw materials will contribute to reduction of global warming in the transportation sector.

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