Chapter 5

Potential of Other Feedstocks

Benchmarking of Biodiesel Fuel Standardization in East Asia Working Group

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5. POTENTIAL OF OTHER FEEDSTOCKS

5.1 Jatropha curcas L.

5.1.1 Introduction

The term biodiesel that is nowadays understood by the industries and society at large is "a diesel engine fuel composed of fatty acids methyl ester (FAME)". It is made from vegetable oils or animal fats by a relatively simple chemical process called transesterification with methanol or methanolysis. As it is a relatively new but quite potential fuel, the industries in various regions of the world (in excitement) made biodiesel from the most readily available fat or fatty oil resource in their respective areas; understandably, most of these fats and fatty oils are edible. Thus, the current major biodiesel raw materials are :

- Soybean oil in the USA,
- Rapeseed (canola) oil in Northern Europe,
- Olive and sunflower oils in Mediterranean Europe, and
- Palm and coconut oils in Tropical Asia and the Pacific.

Recognizing the probable occurrence of food versus fuel competition, many attempts have been carried out to develop non edible raw material resources for biodiesel. Presently, physic nut (Jatropha curcas L) is undoubtedly the most popular oil-yielding tree identified for this purpose.

The initial, and rather euphoric, popularity of Jatropha curcas stems from the widespread general knowledge that it is a non-edible oil-yielding tree well adapted to marginal areas with poor soil and low rainfall, where it grows without competing with annual food crops, thus filling an ecological niche. In the last decade, therefore, extensive as well as intensive researches and developments on cultivation of Jatropha curcas, fatty-oil production from its seeds, conversion of the oil into biodiesel and engine tests of the fuel, started in many parts of the world.

Jatropha curcas (Linnaeus) is a small tree or large shrub belonging to the family of Euphorbiaceae. It grows wild in many tropical regions and is very adaptable as regards soil. It can reach a height of up to 7 m and has thick branchlets; on arid escarpments, however, its height does not exceed 2 m [19]. For planting, one can use a seedling, but the more usual practice is to use a stem cutting. Bushes begin to yield seed-containing fruits when they are 4 – 6 months old and can live up to 30 years or more. Each fruit contains 2 or 3 seeds which are separated from one another by the septums of an ellipsoidal, sparsely lobed capsule about 2 – 5 cm long. The ellipsoidal seeds are black, 13 – 19 mm long, about 10 mm thick, and each generally weighs 0.5 –

1.0 g [20]. Figure 39 shows flowers, fruits, and seeds of Jatropha curcas L. The seeds consist of 35–48% shell and 52–65% kernel [21]. The fatty oil is contained in the kernel and, on the average, the oil content is 52 % based on the kernel or 33 % based on the whole seed.

Figure 39 Various parts (i.e. flowers, fruits and seeds) of the tree Jatropha curcas L.

5.1.2 Characteristics of Jatropha curcas oil

The fixed or intrinsic empirical characteristics of crude Jatropha curcas oil (CJCO) are as follows: [22] :

- Specific gravity 15/15 ° C : 0.918 – 0.923
- Saponification value, (mg KOH)/g : 188 – 197
- Iodine value, (g I2)/(100 g) : 93 – 107
- Unsaponifiable matter content, % : 0.4 – 1.1

CJCO, which typically contains 1.45% phospholipids [23] or 290 ppm (mg/kg) phosphorus [24], has been reported with very high acid values [25], [26] and, consequently, investigated the biodiesel production processes from such acidic oils. It should be noted, however, that acid value is not a fixed or intrinsic character of a fatty oil but rather reflects the degree of correctness in seed handling prior to oil pressing. Oils obtained from properly dried seeds, and kept dry afterward, usually have low acid values, less than 1 (mg KOH)/g. Ensuring the production and delivery of low acid oils should be preferred to processing high acid ones as the former results in a much lower cost.

Table 13 shows the composition ranges of fatty acids in Jatropha curcas oil. As the table clearly indicates, Jatropha curcas oil belongs to the oleic or linoleic acid group, to which the majority of vegetable oils belong [27]. The usual method of biodiesel preparation should be applicable to this oil and many reports of its successful preparation are available in the literature (see e.g. [24]-[26]).

Table 13 Fatty acid composition of Jatropha curcas oil (%-weight)

Fatty acid	Eckey (1954) [22]	Gubitz et.al. (1999) [28]
Myristic acid, C14:0	0 – 0.5	0 – 0.1
Palmitic acid, C16:0	12 – 17	14.1 – 15.3
Stearic acid, C18:0	5 – 7	3.7 – 9.8
Arachidic acid, C20:0	0 – 0.3	0 – 0.3
Behenic acid, C22:0	-	0 – 0.2
Palmitoleic acid, C16:1	-	0 – 1.3
Oleic acid, C18:1	37 – 63	34.3 – 45.8
Linoleic acid, C18:2	19 – 40	29.0 – 44.2
Linolenic acid, C18:3	-	0 – 0.3

A potential major constraint in the widespread acceptance of Jatropha curcas as a source of biodiesel is the presence of phorbol esters, which, when consumed by human and animal, are toxic and also carcinogens [29]. Phorbol esters are defined as "polycyclic compounds in which two hydroxyl groups on neighboring carbon atoms are esterified to fatty acids" and occur naturally in many plants of the family Euphorbiaceae and Thymelaeceae. Due to the toxicity of the plant and oil, some special precautions need to be exercised during the processing of Jatropha curcas seeds and oils. The removal and degradation of phorbol esters during pretreatment and transesterification of Jatropha curcas oil has been thoroughly investigated [30]. The finding showed that during degumming, some phorbol esters were removed into the acid gums and wash water, which implies that the acid gums could not be used for animal feed and care should be taken when disposing the wash water into the environment. A silica treatment of Jatropha oil did not decrease the phorbol esters, whereas stripping/deodorization at 260 °C and 3 mbar pressure with 1% steam injection completely degraded phorbol ester. Further, phorbol esters were not detected in stripped oil, fatty acid distillate, transesterified oil (biodiesel) and glycerine. However, the presence of possibly toxic phorbol ester degradation products in these materials/products could not be ruled out [30]. The toxicity of phorbol esters has also prohibited the use of Jatropha seed meals as animal feed. Many researchers have attempted various chemical and physical treatments to extract or inactivate phorbol esters so that the protein-rich seed meals could be used as feed resources. However, not much progress has been reported so far [29].

5.1.3 R & D challenges

Contrary to the initial overly optimistic presumption that growing Jatropha curcas would, on one hand, supply non-edible raw material for biodiesel production while, on the other hand, provide employment, improve the environment, and enhance the quality of rural life. Most farmers in Indonesia (at least) are presently reluctant to grow it because, after widespread trial plantations instigated by irresponsible politicians, the farmers realized that cultivating the plant did not yield an adequate financial return. The principal problems are the relatively still low per hectare productivity of the seeds and high harvesting cost while the non existent of an established market is an extra obstacle. Although Jatropha is stated to have a potential seed productivity of up to 12 ton/ha/year, much research still has to be done to put that potential into practical reality. The non uniform (or non simultaneous) maturation of Jatropha's fruits lead to the need of frequent manual fruit/seed pickings resulting in high harvesting cost.

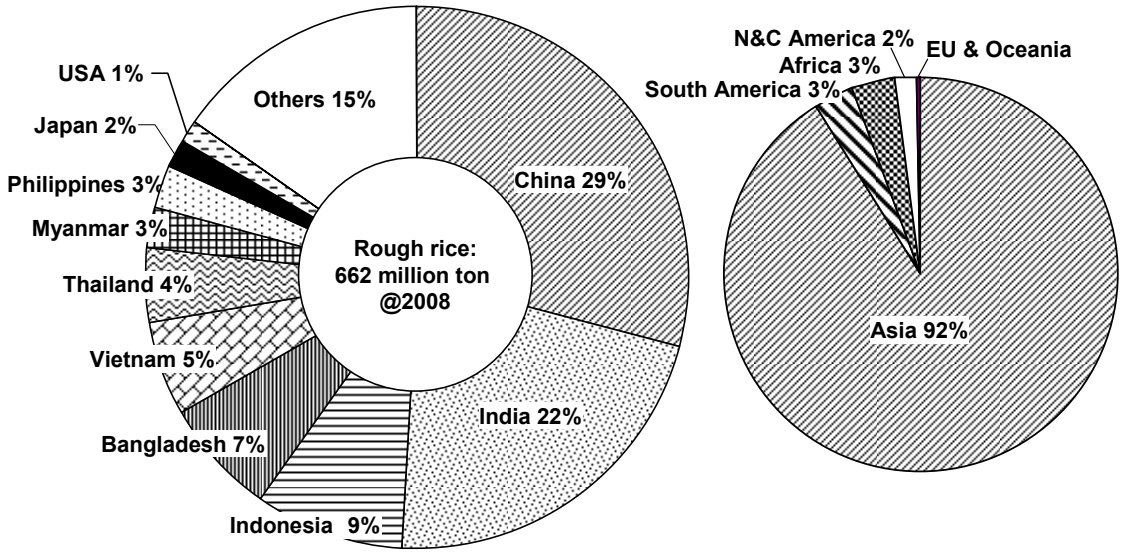
Among various institutions doing R&D on Jatropha curcas, the Pakuwon Jatropha Nursery and Experimental Plantation, which is operated by Indonesian Center for Estate Crops Research and Development (ICECRD) located between Bogor and Sukabumi in West Java, Indonesia, is presently carrying out R&D activities to solve the above problems. This Jatropha trial plantation site was established in 2005 by the Ministry of Agriculture with the purpose to improve yield of Jatropha seed production. Initially, nine Jatropha breeds were collected from all over Indonesia during the exploratory phase, and planted in a 50 ha area of the Pakuwon site. This original population yields about 25-30 capsules/shrub or average 1st year yield of 0.3-0.4 ton/. The first Improved Population (IP-1) was developed in 2006 with more than 200 capsules/shrub or average 1st year yield of 0.9-1.0 ton/ha ha (4 – 5 ton/ha/yr after the 4th year) in a 30 ha plantation area. Then, the second Improved Population (IP-2) was further developed in 2007 with more than 400 capsules/shrub or average 1st year yield of 1.9-2.2 ton/ha (6 – 8 ton/ha/yr after the 4th year) in a 25 ha plantation area. Recently (2009), they have launched the IP-3 seedlings capable of yielding 8 – 9 ton/ha/yr seeds after the 4th year. For each IP, there are varieties suitable for dry (e.g. IP-1A), medium dry (e.g. IP-1M) and wet (e.g. IP-1P) area. The Pakuwon site is also developing Jatropha breed with simultaneously maturing fruits for efficient harvesting. Other Jatropha research activities of the site include genetic control on number of seeds in Jatropha fruit, pest control, disease control, certification of distributed seed and inter-crop selection.

5.2 Rice Bran

5.2.1 Introduction

In the past, bio-diesel production has advanced with the help of price supports and an agricultural promotion policy utilizing surplus production of rapeseed in Europe and soybeans in the US. However, as biodiesel fuel demand has increased recently, the price of rapeseed oil, soybean oil, and palm oil for food has spiked, thus the competition of fuel and food has been a problem. On the other hand, from the viewpoint of national energy security, it is also important to possess the resources and/or crops that enable self-sufficiency. In Japan and the East Asian countries, rice crops are popular; however in Japan some rice fields are classified as "non-producing" and/or abandoned due to government policy. If industrial rice (not intended for food) is cultivated on the non-producing land, using low cost fertilizers and low-energy methods, it is possible to make rice into bio-ethanol and make rice-oil from the rice bran into a bio-diesel fuel feedstock.

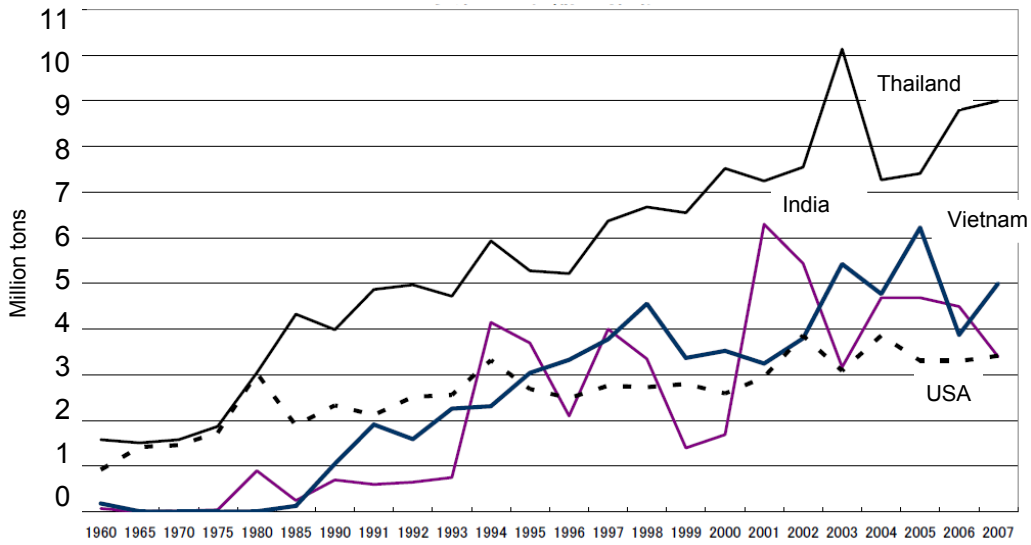
The amount of worldwide rough rice production was about 662 million tons in 2008. As shown in Figure 40, Asian countries; China, India, Indonesia, Bangladesh, Vietnam, Thailand etc., account for approximately 92% of annual production. Among the production leaders, India, China, Thailand, Vietnam, and Indonesia account for about 70%. Moreover, as shown in Figure 41(a), the main rice export countries are



(Source: USDA, PSD Online. June 10-2009 access data and International Rice Research Institute web-site "Facts and Figures-Rough Rice Production, by Country and Geographical region-USDA")

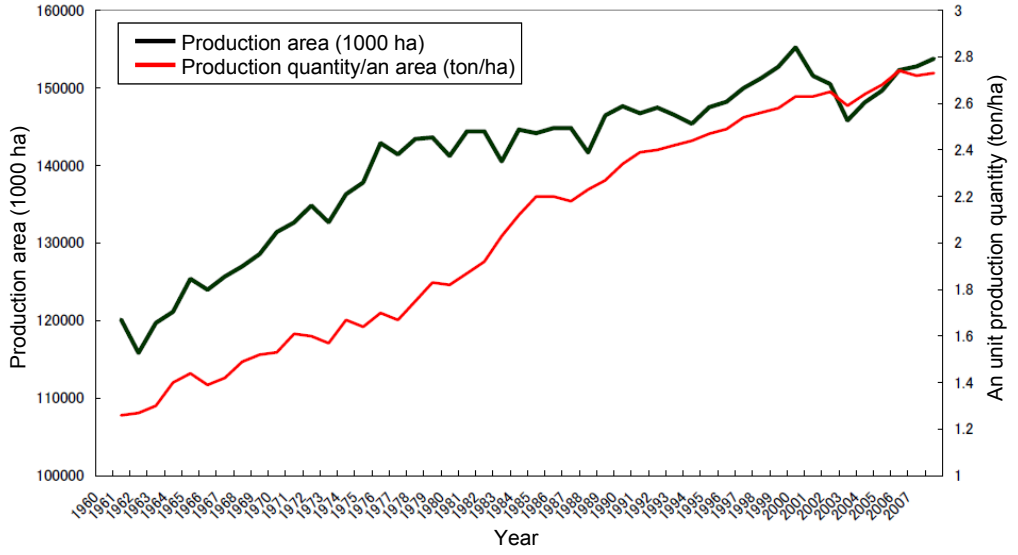
Figure 40 Estimated rice production in the world

Thailand, Vietnam, USA, and India. Although rice demand has been increasing worldwide, the production area and a unit price have been at a consistent upper limit, as shown in Figure 41(b). Thus at the present time the supply is well matched with demand, leaving negligible surplus. The largest importing countries of rice from the USA are Mexico and Japan. Japan imports about 2 million ton of rice annually, according to the World Trade Organization (WTO).



(a)

(Source: USDA, "World Agricultural Supply And Demand Estimates", 2007)



(b)

(Source: USDA, "World Agricultural Supply And Demand Estimates", 2007)

Figure 41 Historical plots of (a) export by main rice producing countries and (b) rice production area and an unit production quantity

5.2.2 Rice Bran Oil

Rice bran oil contains abundant unsaponificable matter that is not found in other vegetable oils. Figure 42 shows the process for which brown rice is made into milled rice, after which refined rice oil is made. Rice consists of a bran layer, the embryo, and the albumen. The albumen part of white rice is 91% of the total, while the remaining 9% is generally called the rice bran. About 18 to 20% of the rice bran is oil, and the rest is protein, fiber, carbohydrate, ash, and water. The embryo is a particularly high-quality medicinal supply ingredient, and has abundant antioxidants γ-oryzanol and tocotrienol, which are not found in other vegetable oils. Generally, oil from rice bran is extracted with a solvent (e.g. *n*-hexane) and goes through the following process.

(1) Heat up process, to make extraction easier.
(2) Solvent addition process to wash the oil from the bran.
(3) Separation process to remove the oil from the mixture of oil and hexane.
(4) Collection process to collect the solvent from defatted rice bran.

Rice bran oil that is obtained in this way is called rice crude oil.

Components of rice crude oil vary slightly, depending on the free-fatty acid. For example, about 80% is neutral oils (i.e. triglycerides), 10% is free fatty acids, 5% is unsaponificable matter, the remainder is wax, gummy matter, γ-orizanol, impurities, and water. Among these components we note that free fatty acids are created via fat and oil hydrolysis due to the lipase enzyme in rice bran, and these hydrolysis reactions vary depending on the temperature. In addition, the wax content also varies depending on the place of origin. It is known that rice produced in tropical regions has less wax, while that produced in cold regions has more wax. Purification of rice crude oil consists of degumming, de-acidification, dewaxing, wintering, bleaching, and deodorization. For good quality we point out that de-acidification, dewaxing, and wintering are important.

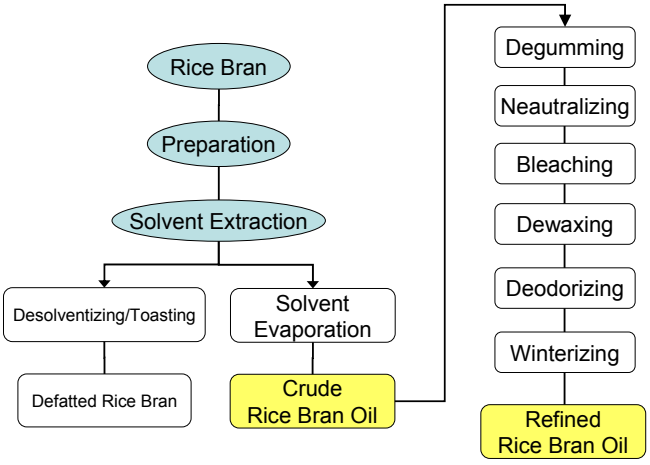


Figure 42 Process flow scheme of rice bran oil for cooking

5.2.3 Characteristics of Rice Bran Oil

Fatty acid components of rice bran oil consist mainly of oleic acid, linoleic acid, and palmitic acid. Very minor components are linolenic acid, which is an unsaturated fatty acid with three double bonds, thus rice bran oil's oxidation stability is relatively high. Moreover, compared to other vegetable oils, it contains relatively large amount of unsaponificable matter. For example, rapeseed (canola) oil has 0.87% unsaponificable matter; soybean oil has 0.46%, while rice bran oil has a relatively high 2.31% unsaponificable matter. This portion contains rice bran oil's unique components, such as the antioxidants γ-oryzanol and tocotrienol.

Rice crude oil contains 2% γ-oryzanol, and it has been reported that it aids in physiological processes like growth promotion and aging prevention, and for treatment of autonomic nerve ataxia, menopause, and for lowering blood cholesterol. It has been used as various forms of medicinal raw materials and food additives. Tocotrienol is contained only in rice bran oil and palm oil. It has been reported that it functions as an antioxidant, which helps lower blood serum cholesterol, and is effective for resistance to tumors.

Figure 43 shows the wide-ranging utilization of rice bran oil refinery byproducts. For example, the crude fatty acids generated in the deoxidation process are widely used for raw materials like soap, resins, and paints through another process of distillation and deodorization. Additionally, wax that is generated in the dewaxing and wintering processes contain behenic acid (C22), lignoceric acid (C24), ceryl alcohol (C26), octacosanol (C28), and myricyl alcohol (or triacontanol, C30). It is used for a molten type thermal printing ink ribbon, resin, and as an industrial lubricant.

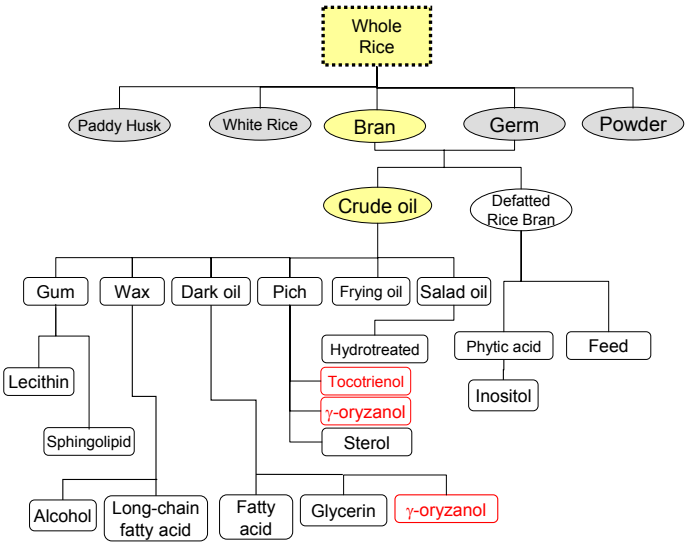


Figure 43 Utilization of rice and rice bran oil

5.2.4 Properties of Rice Bran Oil as a Biodiesel Fuel

Table 14 shows the main properties and components of RRBOME (Refined Rice Bran Oil Methyl Esters), CRBOME (Crude Rice Bran Oil Methyl Esters) that were produced with an alkaline catalyst method, as well as CJME (Crude Jatropha Oil Methyl Esters), RME (Rapeseed Oil Methyl Esters) and conventional petroleum based diesel fuel. Figure 44 shows a breakdown of the fatty acid content of these fuels. The Table and the Figure show that RRBOM and CJME have nearly identical fatty acid content, and they have a relatively high amount of saturated fatty acids (C16:0, C18:0). Because of this, both CJME and RRBOM have a slightly higher CFPP clog point, higher cloud point CP, and higher pour point, compared to RME. However, they do lack low temperature flowability. On the contrary, saturated fatty acids are relatively higher, thus compared to RME, the peroxide induction period IP is longer (with an oxidation acceleration test), and oxidation stability is excellent. Besides, since CJME and RRBOME have similar components, one may deduce that there will be no problems with mixing them together to use.

On the contrary, it is understood that CRBOME has a high acid value and low oxidation stability. This is because it contains impurities like bran in the feedstock oil, these impurities hamper reactions, and free fatty acids remain in the oil. Therefore, it is necessary to improve the refining process. For CRBOME one may add some type of preliminary treatment before doing the methyl ester exchange process.

Table 14 Biodiesel fuel specifications

		CJME	RRBOME	RME	Diesel fuel
Density	g/cm^3@15℃	0.884	0.886	0.885	0.833
Kinematic Viscosity	mm^2/s@40℃	4.8	4.7	4.4	3.5
Flash Point	℃	182.5	172.5	190	-
Pour Point	℃	0	0	-12.5	-
CFPP	℃	-1	-1	-13	-
Cloud Point	℃	5	7	-6	-
10% Carbon Residue	wt%	1.54	1.94	3.25	-
Lower Calorific Value	MJ/kg	36.1	37.7	36.7	42.7
Carbon	wt%	76.3	76.9	77.0	86.1
Hydrogen	wt%	13.1	12.8	12.0	13.7
Oxygen	wt%	10.5	10.2	10.3	<0.1
Sulfur	wtppm	<3	<3	1	<50
KF water	wt%	0.05	0.08	0.06	0
Oxidation Stability(IP)	hours	8.0	7.1	4.1	-
Peroxide Value	meq/kg	35.7	29.9	101.1	-
Acid Value	mgKOH/g	0.4	0.2	0.1	-
Iodine Value	gI/100g	93.2	101.2	111.4	-

CJME:Crude Jatropha Oil Methyl Ester, RRBOME: Refined Rice Bran Oil Methyl Ester
RME: Rapeseed Oil Methyl Ester, Gas oil(JIS 2#@2006)

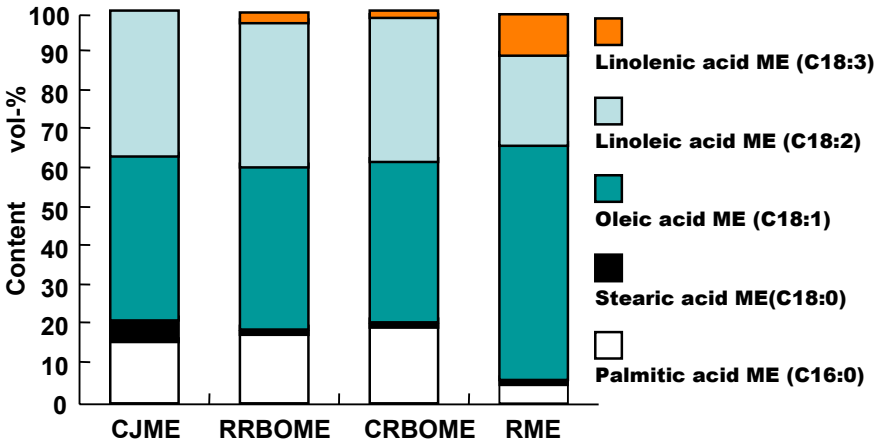


Figure 44 Fatty acid methyl ester components of raw materials

5.2.5 Potential of Rice Bran Oil

Table 15 shows the current production levels of food grade brown rice and rice bran in Japan. At present, non-cultivated land totaling about 380,000 ha exists as a result of the government production adjustment program for rice crops. Japan's annual production of brown rice for food was about 8.7 million ton in 2007. Of this amount about 870,000 ton is rice bran. Out of this total, about 20% can be obtained as oil (rice bran oil). Actually only about 63,000 ton per year is produced as edible rice oil, and about 111,000 ton is unrefined rice oil. If we could bring the non-cultivated land into production, it means that a rice oil production capacity of about 150,000 tons exists. This is equivalent to about 0.4% of the amount of light oil consumed annually in Japan. If it is assumed that from the annual 420 million ton yield of milled rice production worldwide, about 100 million ton of rice bran could be generated. From this it can be concluded that there is 20 million tons of potential rice bran oil production annually.

Table 15 Production situation of brown rice for food and rice bran in Japan

FY2007

	Crop of Rice ton/y	Planted area ha/y	Rice Bran ton/y	20% of rice bran ton/y
Total (food)	8,705,000	1,669,000	870,500	174,100
Abandoned cultivated land (Total)	1,981,965	380,000	198,196	39,639
Rice bran for food and refined rice bran oil			317,000	63,000

5.3 Microalgae

5.3.1 Introduction of Microalgae

(1) Microalgae basic characteristics and ecological functions

"Microalgae" (including blue-green algae or cyanobacteria) are group of photoautotrophic microorganisms comprising of a large, heterogeneous, and polyphyletic assemblage of relatively simple plants or thallophytes which lack differentiated roots, stems, and leaves. They have little in common except chlorophyll-a (primary photosynthetic pigment). Most microalgae usually occur in water, be it freshwater, marine, or brackish. They can also be found in almost every other environment on earth such as extreme environment e.g. snow, desert including hot springs. In most habitats, algae function as the primary producers in the food chain, producing organic materials from sunlight, CO_2, water (including nitrogen and phosphorus dissolved in water). They also produce the O_2 necessary for the other organisms, besides over 40% of atmospheric CO_2 is fixed by algae. About one third of the world plant biomass consists of algae. At present, more than 30,000 microalgal species have been reported from all parts of the world.

(2) Potential applications of microalgae

From the photoautotrophic growth of microalgae and production or accumulation of various valuable products, microalgae are potentially applied in various aspects as follows:

- Agriculture products e.g. biofertilizer, soil conditioner, plant growth regulator, pesticide and animal feed.
- Food products e.g. daily food, food supplements (neutraceutical), food colorant and thickening or binding agents.
- Medicinal products e.g. antibiotic, anticancer, antioxidant and diagnostic tag, etc.
- Environment e.g. secondary and tertiary treatment of wastewater, bioremediation of heavy metals and pesticides.
- Energy as renewable feedstock for bioenergy production (biodiesel, bioethanol and hydrogen, etc.).

(3) Advantages of biodiesel production from microalgae

Production of biodiesel from microalgae expresses advantages over "energy crops" as follows:

- No competition with food crop, therefore, no adverse effect on "food security".

- Using smaller foot-print (production area) of non-arable land to provide higher productivity due to their rapid growth rate with short growing cycle.
- Using smaller amount of water to obtain equal biomass productivity as energy crops.
- Co-processes with various kinds of industrial wastes e.g. wastewater, flue gas (CO_2) and waste heat, hence reduce the production cost (water and nutrients) and comply with CDM together with C-credit gain.
- Co-products with various kinds of algal left-over extracts thus make biodiesel production of biodiesel from microalgae feasible.

The production of biodiesel from microalgae with co-processes and co-products is shown in Figure 45

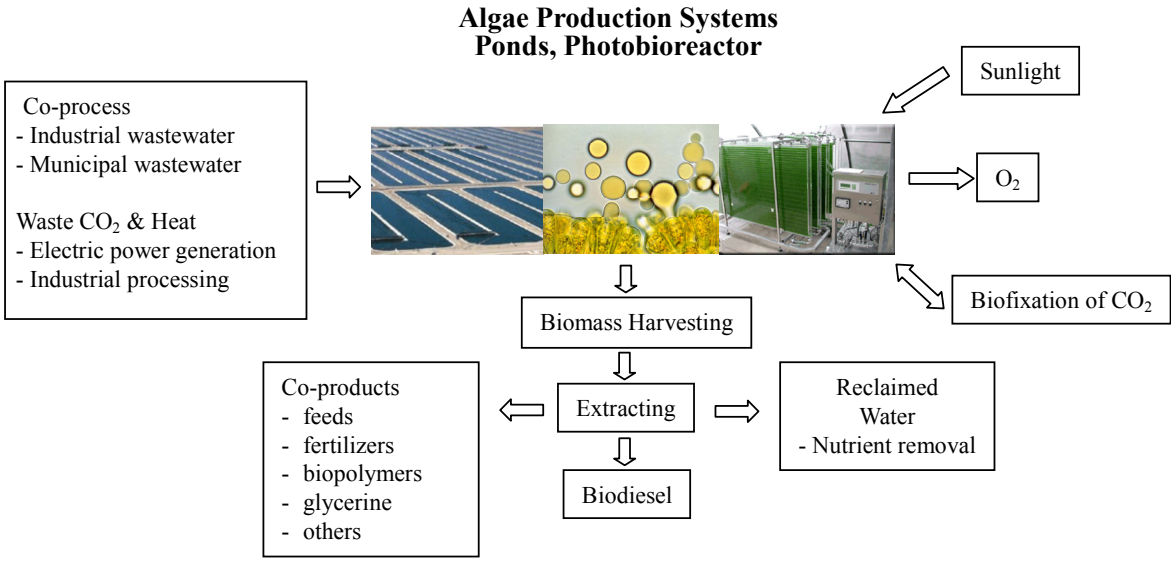


Figure 45 Production of biodiesel with co-process and co-products

5.3.2 Technology for Biodiesel Production from Microalgae

There are 5 steps in the process of biodiesel production from microalgae. The steps of which are:

(1) selection and preservation of selected oil-producing microalgal strains,
(2) preparation of inoculum for biomass production,
(3) cultivation for biomass production,
(4) harvesting of microalgal biomass, and
(5) extraction of microalgal oil.

(1) Selection and preservation of selected oil-producing microalgal strains

Currently, there are 3 microalgal groups of interest for biodiesel production. The groups of which are: (marine) diatoms (Bacillariophyceae), (freshwater and marine) green algae (Chlorophyceae) and freshwater blue-green algae (Cyanophyceae). The general criteria for strain selection are

(1) high growth rate and productivity,
(2) high oil content,
(3) suitable quality of oil (composition of fatty acids) and
(4) high (adaptation) ability to grow under the wide range of light intensity and temperature (of the cultivation location).

Apart from conventional techniques, a high-throughput screening (HTS) technique for target strains has been applied in advance laboratories. Not only had those mentioned criteria but various techniques including HTS also used for searching of other valuable substances for the production of co-products.

Besides the selection of target strains from natural sources, improvement of selected strains by genetic engineering has been done in some laboratories. However, stability of genetically modified strains is in daunted.

For the preservation of selected strains (to prevent the loss of their genotypic and phenotypic characteristics resulting from frequently sub-culturing of fresh strains), cryopreservation of strains under sub-zero temperature ($\leq$-20^{o}C in freezer to -196^{o}C in liquid nitrogen) using 5-10% dimethyl sulfoxide (DMSO) as cryoprotectant seems to be the most effective preservation technique.

(2) Preparation of inoculum for biomass production

To keep microalgal biomass production system under good condition for long cultivation period, high quality and quantity of inoculum (starter) are required. Starting the mass cultivation with suitable microalgal density can prevent the drop of microalgal growth by photooxidation and contamination. It is recommended using close-cultivation system (e.g. photobioreactor) to cultivate the strain under optimal growth condition to prepare high quality and quantity of inoculum.

(3) Cultivation for biomass production

There are 2 main microalgal production systems, so-called: (1) opened cultivation pond and (2) closed photobioreactor. The major technical challenges of these systems are how to:

(1) sustain highest photosynthesis and biomass productivity,

(2) reduce cell damage by hydrodynamic stress, photooxidation and grazer,
(3) reduce costs (fabrication, installation, maintenance), and
(4) increase the capability of the system to expand to an effective industrial scale.

Recently, various types of photobioreactors have been designed and developed e.g. hanging plastic bags and the most popular, tubular reactors (horizontal, vertical and inclined). Various types of clear plastic materials have been used to produce these reactors. The followings are advantages of closed photobioreactor over opened pond: 1) better control of algal culture, phyco-chemical culture parameters, and gas (CO_2) transfer, 2) larger surface-to-volume ratio, 3) less evaporation of water from growth medium, 4) better protection from outside contamination. (Less competition with natural microalgal species, infection by virus and bacteria as well as grazer by zooplankton), and 5) higher cell density can be obtained.

The weak point of photobioreactor is deterioration (cracking) of plastic surface (by UV) which leads to the reduction of light absorption. At present there are a few commercial microalgal products derived from photobioreactor production. The most important limiting factor to this is its high investment cost of construction and operation, especially in an indoor operation (to control light intensity and incubation temperature). In contrast to photobioreactor systems, there are many microalgal products obtained from opened cultivation pond systems located in various part of the world (Asia, Europe, America and Australia).

In the case of opened cultivation pond systems, there are 2 types of ponds designed, namely circular and race-way ponds. Race-way pond system is much more popular than circular one. Covering of race-way pond has been designed for improving of its performance. This new design does alleviate some of the disadvantages of opened pond in both quantity (biomass productivity) and quality (contamination). Semi-batch and continuous production of algal biomass can be conducted using an effective covering race-way pond system.

Apart from the selection of microalgal strains, “tailor-made design” of cultivation system suitable for the strain and growing (weather) conditions of the production area is also a vital key success factor to make the production of biodiesel from microalgae feasible. In addition, if marine phytoplankton has been used, special selection of material for constructing of the whole system should be considered to prevent the problem of corrosion.

(4) Harvesting of microalgal biomass

Harvesting method applied in the production system depends on the

characteristics of selected strain. Centrifugation and microfiltration are suitable for harvesting of phytoplankton (marine diatom and green algae and freshwater green algae of unicellular with small size). Simple filtering using plankton net is suitable for filamentous blue-green algae. Flotation is suitable for gas vacuole producing strains. Auto-flocculation is suitable for colony-forming strains, filamentous strains including unicellular strain of large size or high cell density. Harvesting using flocculants can be applied with all types of strains.

Combining of harvesting methods e.g. filtration + centrifugation, floatation + centrifugation + sand bed filtration also have been applied. Development of harvesting method of an effective simple process with low cost and large-scale feasible should be "tailor-made" for each selected strain because cost of harvesting is also significant for biomass production. In addition, if de-watering or drying microalgal biomass to a certain level is required, co-process using waste heat can be done after harvesting.

(5) Extraction of microalgal oil

In general wet microalgal biomass can be directly used for oil extraction. The same as extraction of vegetable oil, mechanical expression and solvent extraction are popularly applied for microalgal oil extraction as well. To derive over 90% of the total oil present in the biomass, combing extraction method of cold press and hexane extraction has been applied. Recently, supercritical fluid/CO_2 extraction also used to obtain 100% of the oil content; nevertheless this extraction process is very expensive.