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Microalgae Pioneering the Future – Application and Utilization –

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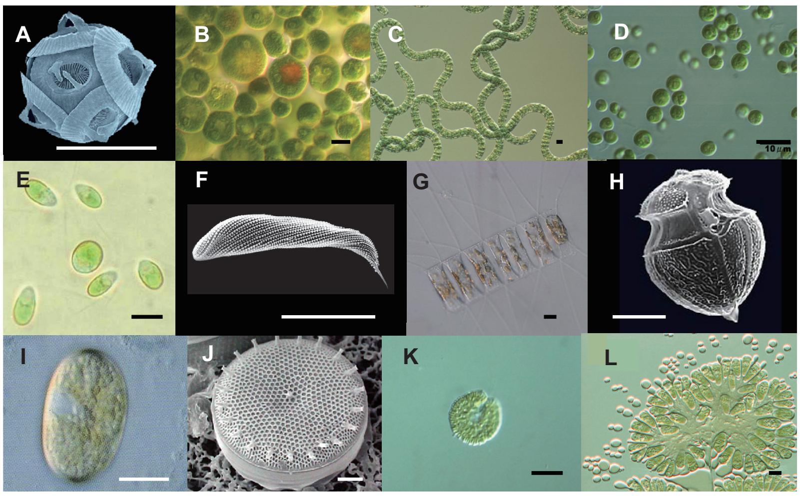
1 Microalgae

1-1 What are microalgae?

Microalgae were one of the first organisms to come into existence in the Earth's ocean more than 3 billion years ago, when the Earth's environment formed. They are also called phytoplankton. These unicellular organisms have chlorophyll and produce oxygen (O_2) by immobilizing carbon dioxide (CO_2) in the atmosphere through photosynthesis. There are about 100,000 different types of microalgae living not only in the oceans but also in fresh water (lakes, ponds, and rivers).[1]

Microalgae began growing proliferously in oceans about 3 billion years ago and ever since have displaced carbon dioxide, which had been the main component of the atmosphere, with oxygen through their photosynthetic capability, resulting in creating the current atmospheric composition. The oxygen produced by photosynthesis not only constituted the atmosphere but also raised the level of dissolved oxygen in seawater. As a result, iron in seawater was oxidized and deposited on the seabed, eventually forming the current iron ore layer. Large quantities of dead microalgae were also deposited on the seabed and, billions years later, they became oilfields. The *Gephyrocapsa*,(Figure 1, A) which is a kind of microalgae, produces calcium carbonate by causing carbon dioxide to react with calcium in water and thus forms the circular outer shell of a cell. This process formed limestone layers. A typical example is Chalk Cliff on the British side of the English Channel.[1] Microalgae form the bottom of the food chain — they are eaten by zooplankton, which in turn is eaten by small fish, then by big fish, and then by humans. In this way, microalgae form the current global environment and are feeding living organisms on the earth even now. Human beings are utilizing and enjoying the benefits from resources produced by microalgae.[1,2]

At the same time, however, pollution and disruption



A : *Gephyrocapsa*[4]
B : *Haematococcus lacustris*[5]
C : *Spirulina platensis*[6]
D : *Chlorella vulgaris*[7]
E : *Dunaliella tertiolecta*[8]
F : *Euglena gracilis*[4]
G : *Chaetoceros calcitrans*[9]
H : *Dinophysis acuminate*[4]
I : *Alexandrium*[10]
J : *Bacillariophyceae*[11]
K : *Raphidophyceae*[12]
L : *Botryococcus*[13]
A, F, H, and J are electron micrographs, the others are optical micrographs.

The length of the bar in each picture is 10 μm.

Figure 1 : Microalgae mentioned in this report (electron micrographs)

Prepared by the STFC based on References[4-13] of the water environment has caused excessive growth of microalgae, which is known as red tide. Red tide is believed to be caused by multiple factors, such as water being polluted with phosphorus contained in detergents and the breakdown in the balance of the food chain caused by a sharp decrease in clams, etc. due to the disruption of tideland ecosystems. Red tide depletes marine resources by lowering the concentration of oxygen in water. Moreover, some of the microalgae that grow excessively, such as Alexandrium,(Figure 1, I) produce toxic substances. Too much growth causes contamination of marine resources.[3]

1-2 Expectations for microalgae

Although human beings have been aware that the current global environment was formed by microalgae, they had not focused their attention on microalgae from the perspective of actively utilizing them. However, after problems connected to the existence of human beings came to the fore, such as the depletion of oil, higher crude oil prices, a rise in food prices, a food-supply crisis, and global warming caused by an increase in carbon dioxide, human beings have begun to pay attention to microalgae.

Due to the rapid population increase and industrialization, oil that was created by microalgae is expected to be exhausted by the middle of this century. This has prompted the idea that, since oil can be created by microalgae, we should make microalgae produce oil again. Since the production of bio-ethanol depends on cornstarch, demand for corn has increased, leading to a rise in food prices. Therefore, the idea has emerged that microalgae, which form the basis of the food chain, should be actively utilized and that, if the use of oil and other fossil fuels increases carbon dioxide in the atmosphere, microalgae should be used to immobilize carbon dioxide. Such an idea may have sounded far-fetched until recently. However, thanks to progress in biotechnology, it has become more possible for us to draw on the capability of microalgae to address the various problems we are facing.

One of the most feasible biotechnology fields is red biotechnology, an area concerning medicines and health, including drugs, bioactive substances and nutraceuticals. It focuses on functional substances produced by microalgae and aims at making use of them. The second field is green biotechnology, an area concerning agricultural, water and environmental biotechnology. It aims at producing feed for herbivorous livestock and bivalves and cleaning up the environment by making use of functional substances produced by microalgae. The third field is white biotechnology, an area concerning industrial biotechnology, such as biomass resources and biofuels. It is designed to use microalgae as a means of industrial production.(Figure 2)

This report focuses on the microalgae that may contribute to the enhancement of the quality of life of people in the future and that may lead to the solution of some of the problems we are currently facing. The report also looks at the value of utilizing microalgae in three biotechnology fields: red, green and white biotechnology.

2 Microalgae changing science fields

2-1 Red biotechnology: application to nutraceuticals

One of the challenges facing advanced countries in the 21st century is that various medical and health-related problems have increased. And many of them are diseases caused by people’s poor eating habits. To cope with this situation, people have come to pay more attention to preventing diseases and maintaining good health, rather than taking medicine after suffering from diseases. It has been scientifically demonstrated that some foods contain bioactive substances that fall between pharmaceuticals and nutrition. Such

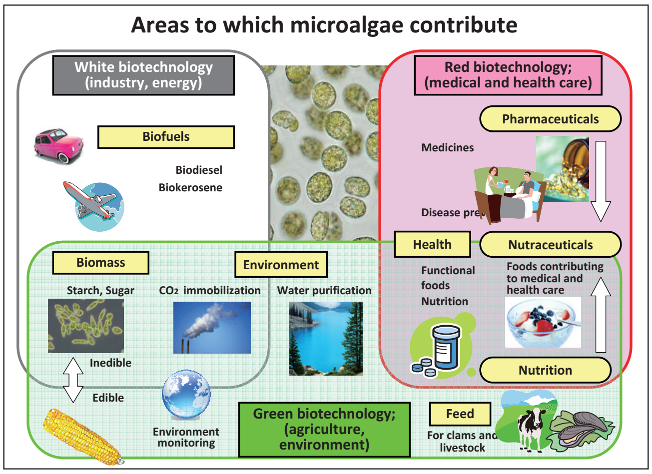


Figure 2 : Basic Concept of Biotechnology Fields to Which Microalgae Contribute

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substances are called nutraceuticals, and as they are effective for disease prevention they have come to draw attention.[14]

In recent years, it has been found that various substances produced by microalgae also have bioactive and other useful functions. This can be understood from the fact that microalgae have been the basis of the food chain. For instance, it is well known that blue fish, such as Pacific saury and sardines, contain docosahexaenoic acid(DHA), an unsaturated fatty acid also called omega fatty acid, which is said to be effective in preventing arteriosclerosis. However, these fish do not produce DHA in their bodies; rather they take in DHA from the food they eat. It is pointed out that the root of DHA in such fish can be traced to microalgae. In other words, DHA in fish is a substance ingested and concentrated along the steps of the food chain. Since DHA is essential for the cerebral development of infants, DHA obtained from refined fish oil has been used as a functional food ingredient. In recent years, concerns have been raised about higher prices of fish oil caused by a decrease in fish catches and oceanic pollution. This has prompted a study to develop a method to industrially cultivate DHA-producing microalgae and extract DHA from them.

Martek Biosciences Corp. of the United States (in Columbia, Maryland) has been cultivating microalgae in 80–260 m^2 tanks and extracting DHA oil from the microalgae. Unlike DHA derived from fish oil, microalgal DHA is said to have no fishy odor. Since DHA is necessary for the growth of the brain and eyes of infants, it has been used as an additive in infant foods.[15]

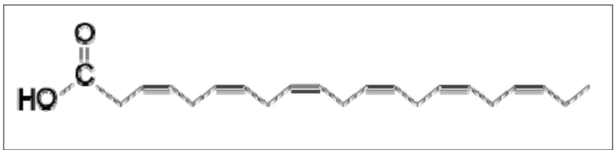

Figure 3 : Chemical Constitution of DHA

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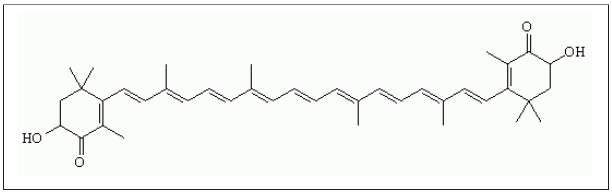

Figure 4 : Chemical Constitution of Astaxanthin

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Microalgae come in various colors. Chlorophyll makes some microalgae green. There are also many kinds of red, orange, and yellow microalgae. These colors are all derived from carotenoid or natural pigment. It has been proven that carotenoids have antioxidant and other bioactive effects. Studies are now under way to use them as functional food ingredients and cosmetics.

For instance, it has been reported that the astaxanthin produced by the orange-colored *Haematococcus lacustris* (Figure 1, B) has a high antioxidant effect that protects human bodies from ultraviolet light and excessive oxidation of fat in the blood. Therefore, astaxanthin has been drawing attention lately in such fields as the prevention of aging, easing of eye strain, relaxation of tired muscles, and prevention of arterial sclerosis. Already, several Japanese corporations have started operating microalgae cultivation facilities to produce astaxanthin.[16, 17]

Since microalgae are widely distributed in saline and fresh water and there are about 100,000 different kinds, it is believed there are many compounds with yet-to-be-discovered biological activities. Therefore, microalgae are promising treasure troves for researchers looking for candidate substances for medicines and functional ingredients.

2-2 Green biotechnology: application to food, feeds and environment

2-2-1 Application to food

People in the 21st century are facing challenges in terms of securing good-quality food and conserving the environment.

Living creatures on earth are enjoying the benefits of the sun. This is because the source of ecosystem evolution is sunlight. In other words, microalgae immobilize carbon dioxide and produce organic matters by making use of energy from sunlight. Microalgae are the primary producers of organic matter on the earth. They serve as prey for zooplanktons, shells and small fishes, which in turn serve as prey for bigger fish and animals on earth. Human beings stand at the top of this food chain. Viewed from this perspective, it is no exaggeration to say that microalgae are supporting all living creatures on earth. There is a big social need to provide safe food and food materials on a stable basis.

For instance, *Spirulina platensis*, a kind of microalgae

(Figure 1, C), has long been taken as a medicine in South America and Africa and studies are now under way on its nutrition and bioactive substances. *Chlorella vulgaris* (Figure 1, D), *Dunaliella tertiolecta* (Figure 1, E) and *Euglena gradis* (Figure 1, F) are being sold as health foods in Japan. Since substances produced by these microalgae are believed to be effective for health maintenance and disease prevention, studies are now under way to use them as new food materials and resources.

Meanwhile, toxic microalgae sometimes grow proliferously in the South Pacific. Since microalgae form the basis of the food chain, toxins concentrate in the bodies of fish that eat such microalgae. People eating such fish sometimes develop paralysis or other symptoms of food poisoning. A typical example of such toxins is ciguatera toxin. Until recently, poisoning cases related to ciguatera toxin were reported only in south Pacific regions. However, due to the recent global warming, microalgae containing ciguatera toxin have begun to move northward, raising the possibility of fish contaminated by the toxin being caught in seas near the coast of Japan.[18]

Professor Shoichiro Suda of the University of the Ryukyus has begun collecting toxic microalgae. From the standpoint of ensuring that it is safe to eat fish, it is necessary to promote research and collect information on microalgae in fishery waters.

2-2-2 Application to feed

Microalgae are good feed for clams. Gulf areas, where microalgae grow abundantly, are known as being good locations for the raising of oysters. However, oyster catches fluctuate wildly in line with climate changes. Therefore, a method of using cultivated microalgae as feed for the larvae of oysters, clams, mussels and sea urchins has been drawing attention as a stable cultivation method not affected by climate changes and environmental contamination. For instance, Akkeshi Town in Hokkaido has been engaged in nurturing young shells at an oyster nursery center. The center incubates oysters and feeds them with *Chaetoceros calcitruns* (Figure 1, G) and some other microalgae cultured in a sealed tank. This has made safe and stable cultivation of oysters possible without worrying about the risk of fluctuation in production volume caused by such factors as abnormal weather and the spread of oyster viruses.[19]

Moreover, the idea of using microalgae as feed can also be applied to raising cattle. At present, corn and other grains are used as feed for breeding cattle for meat, and about 11 kilograms of grain is used to get one kilogram of beef.[20] Amid concerns about food shortages caused by increasing population, it is questionable how long we can keep on feeding livestock with grains which can otherwise be used as food for people. Since microalgae contain a good balance of sugar, protein, fat and minerals and are suitable as feed for cattle and other livestock for meat, they warrant further study.

2-2-3 Application to environment

Microalgae have contributed to the formation of the earth's current atmosphere and are still parts of the mechanism whereby oceans absorb carbon dioxide from the atmosphere. Some of the carbon dioxide emitted into the atmosphere through animals' breathing and human industrial activity is absorbed into the oceans through ocean surfaces. Microalgae inhabiting ocean surfaces take in carbon dioxide dissolved by photosynthesis, resulting in lowering the level of carbon dioxide in the ocean surface and promoting the immobilization of carbon dioxide in the atmosphere. Furthermore, carbon dioxide is taken in by microalgae that are prey for zooplanktons and fish and then will be transported from the surface to the ocean's interior by dead fish and their feces. This is called a biological pump. In this way, microalgae are deeply involved in transporting dissolved carbon dioxide from the ocean's surface to the interior.

Over the last several decades, the technology to measure sea color with sensors mounted on artificial satellites has advanced, allowing global observation of microalgae in the ocean. For instance, the purpose of Sea WiFS (Sea-viewing Wide Field-of-view Sensor) on board the Orbview-2 satellite, which was launched by NASA in 1997, was to observe microalgae in the ocean on a global scale and study their distribution.[21] Chlorophyll-a in microalgae in the ocean absorbs blue light with wavelengths of around 443 nm and reflects green light with wavelengths of around 550 nm. For this reason, the sea becomes blue when there are few microalgae in it and green when there are many microalgae. If we analyze the light from the ocean by taking advantage of this nature of microalgae, we can understand the real-time conditions of microalgae development.[22]

The reproductive distribution of microalgae is mainly determined by environmental factors, such as light, water temperature and nutrient minerals. Therefore, many microalgae grow in such places as littoral areas, where nutrient minerals flow in from rivers; the subarctic area, where abundant nutrient minerals are already available; and the eastern equatorial area, where nutrient salts are provided due to upwelling caused by trade winds. However, few microalgae grow in the northern Pacific, the equatorial area and the Antarctic, despite the fact that these ocean areas are blessed with abundant nutrient minerals. Some people say this is because these ocean areas do not contain enough iron, which is essential for the growth of microalgae. Iron is provided to oceans either directly from rivers or through sands carried by wind currents, such as yellow sands carried by subtropical westerlies.[23, 24] A study project, called "Subarctic Pacific Iron Experiment for Ecosystem Dynamics Study (SEEDS)," was conducted in order to examine the hypothesis that when there is a lack of iron, few microalgae will grow. In the experiment, iron was dispersed in iron-deficient ocean waters to study its effect on carbon dioxide absorption and on marine organisms (Figure 5).[25] The results of the experiment confirmed that the iron distribution propagated microalgae.[26]

The experiment was intended to investigate the relationship between microalgae and nutrient minerals with regard to immobilizing carbon dioxide on a global scale. It was not intended to immobilize carbon dioxide in the atmosphere by actually dispersing iron. While such experiment may lead to immobilizing carbon dioxide, we have to be cautious about actually carrying out such an experiment, since it has a major impact on the marine ecosystem and environment.[27]

A study is also under way to purify water by utilizing microalgae's strong power to absorb nitrogen and phosphorus in water. Specifically, the study is aimed at absorbing and removing excess nutrients from shrimp-breeding water by using microalgae. It suggests that microalgae have a water-quality-purification function and that such function can be utilized.[28]

There is also an example of immobilizing carbon dioxide by using microalgae. For instance, euglena Co. Ltd., a company originating from the University of Tokyo and engaged in businesses related to *Euglena gracilis* (Figure 1, F), has been trying to immobilize carbon dioxide in exhaust gas emitted from thermal plants by directly connecting the gas to a *Euglena* culture tank for aeration in cooperation with Okinawa Electric Power Co.[29] Normally, if exhaust gas is directly aerated, the culture solution is oxidized by various oxides, making the solution unsuitable for culturing microalgae. However, the company was able to effectively culture euglena, even under acidic conditions, and immobilize carbon dioxide. At the

The whitish areas (whitish blue in a color image) are believed to be the areas where many microalgae grow.

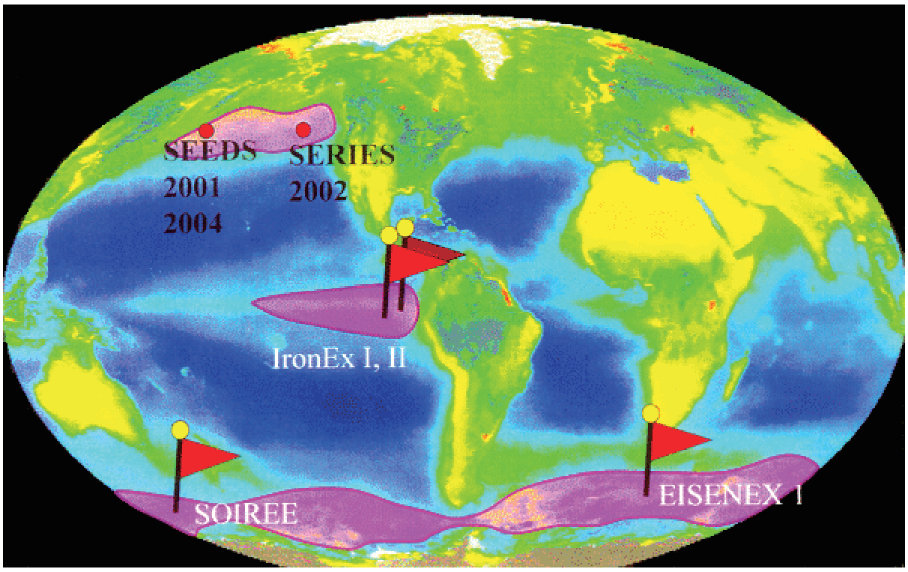


Figure 5 : Ocean Areas Where the Iron Dispersion Experiment was Conducted

Source: Reference[25]

same time, since culture solutions can be oxidized by aerating heavily-concentrated carbon dioxide, it can curb the growth of living organisms other than *Euglena*. In other words, it has been experimentally demonstrated that euglena is suitable for immobilizing carbon dioxide.

2-3 White biotechnology: application to biofuel and biomass

2-3-1 Application to biofuel

The depletion of fossil fuel is another major problem facing human beings as it appears imminent. As an alternative energy to oil, the development of bioethanol from starch, which is derived from corn and other grains, is now under way. However, this development has raised the problem of conflict between food and biofuel. It has resulted in increased prices of not only corn but also other grains, leading to the so-called international political issue of "eat or burn". Moreover, in addition to grains, the price of starch has also increased, raising doubts about the stable supply of starch. A study is also under way to produce bioethanol from the celluloses of unedible plants, such as switchgrass. Some say this may not compete with food. However, things are not that simple. This is because farmers decide which plant they grow — corn or switchgrass — depending on which one they can sell at a higher price. Therefore, it raises the problem of competition in terms of cropping acreage.

It is for this reason that the development of biomass has come to draw attention, as it does not pose competition with food and it is economically feasible. Microalgae basically require carbon dioxide, minerals and light for their growth. They do not require starch. Therefore, as long as water and sunlight are abundantly available, it is possible to cultivate microalgae, even on infertile land. Biomass has been drawing attention in the U.S. Sunbelt, a vast stretch of land where an abundance of sunlight is available.[30]

Oil consists of microalgal lipids that were deposited on the seabed several hundred billions of years ago. In particular, microalgae, such as *Gephyrocapsa* (Figure 1, A), *Dinophysis acuminata* (Figure 1, H), and *Bacillariophyceae* (Figure 1, J), are said to be the source of oil. Therefore, research is being conducted on culturing these microalgae in order to produce biofuels. At present, *Raphidophyceae* (Figure 1, K), *Botryococus* (Figure 1, L) and some other microalgae are drawing attention, as they produce a large volume of carbon hydride of carbon numbers 30 to 40. The volume of carbon hydride in some of these microalgae accounts for 75% of their dry weight.[31]

A problem common to biofuel production is that biofuel has to be produced in large quantities and that biofuel prices must be low. Since biofuel requires larger production facilities than other industrial area for microalgae and the cost needs to be kept low, it is necessary to always think of enhancing productivity.

Biofuels produced from microalgae are mainly used as alternatives to diesel oil. Palm, sunflower and rapeseed oil can also be used as biodiesel. However, microalgae can be cultivated throughout the year as long as light is available and, compared with such conventional plant oils, microalgae are less affected by seasonal changes. According to an estimate made by Professor Yusuf Chisti at Massey University (New Zealand), the production efficiency of microalgae is about ten times as high as palm oil, which is the most efficient producer of biofuel among plant oils (Table 1). Moreover, microalgae do not require fertile land and arable fields to cultivate and can be cultivated regardless of seasonal changes. It can be said that microalgae are far more productive than other biomass used to produce biofuels.[31]

Since the chemical structures of biodiesel produced from microalgae are similar to those of diesel oil, the existing infrastructure for diesel oil, such as existing refining and storage facilities, can be used for biodiesel, making it possible for diesel vehicles to run without their engines being modified. Therefore, it will be relatively easy to substitute biodiesel rather than to convert to bioethanol, while making use of the existing industrial infrastructure. In this way, it is highly possible to realize the application of microalgae to fuels.[32] In order to distinguish biofuels produced from microalgae from those produced from plant oils or cellulose, microalgae-derived fuels have recently come to be called photosynthetic biofuels or algal biofuels.[33]

In December 2008, the U.S. Department of Energy (DOE) sponsored Algal Biofuels Technology Roadmap Workshop to comprehend the actual state of the basic technology concerning the development of biofuels from microalgae and discuss their future prospects and target setting.[34] Later, the DOE invested $50 million to start and operate an algal biofuels workshop and prepare a specific roadmap to promote R&D concerning microalgae-based biofuels, out of the $786.5 million allotted for the research and commercialization of biofuels last fiscal year.[35] The DOE plans to provide $85 million to venture companies and universities to help them develop biofuels and examine the commercial viability of such fuels.[36]

Australia, which is also blessed with a vast expanse of land, has positioned algal biofuels as second-generation biofuels.[37] In August 2009, the country decided to form Algal Fuels Consortium, centering on Australia's Scientific Industrial Research Organization (CSIRO), with the aim of promoting algal biodiesel. The country said the consortium is expected to start developing a low-priced microalgae culture method.[37]

Meanwhile, Professor Rene Wijffels[38] of Holland's Wageningen University announced that he will establish a consortium-type microalgae research center (Algae PARC) in 2010 with funds to be provided by the farm ministry and related corporations. He said he plans to study a highly-efficient cultivation system by using a small-scale cultured layer.[39]

These efforts by various governments started only in 2008, led by the United States.

The research and development of microalgal biofuels is now being undertaken by many venture companies, mainly in the United States (Table 2). For instance, Sapphire Energy, a bio-venture company, announced in May 2008 that it has produced renewable 91 octane gasoline. Among Sapphire Energy's investors is Cascade Investment LLC, an investment firm owned by Bill Gates. The company said it has recently established a test and research site in New Mexico in order to expand its biofuel production capacity to 10,000 barrels per day. It aims to start commercial production within a few years.[40]

In addition to venture companies, oil majors have also begun efforts to produce next-generation biofuels from microalgae. In July 2009, Exxon Mobile Corp. formed a business tie-up with Synthetic Genomics Inc. with the aim of promoting the research and development of next-generation biofuels using photosynthetic microorganisms as the means of production. Exxon Mobile announced that it will spend more than $600 million on the project, aiming to develop a biofuel compatible with both gasoline and diesel fuels.[43]

As these announcements indicate, investment in the research and development of microalgal biofuels has picked up momentum since last year.

The United States is one step ahead of other countries in terms of experimental studies on the feasibility of using microalgae to produce an alternative to oil, but this does not mean that biofuels deriving from microalgae will be commercialized any time soon. Still, it indicates that the United States has put top priority on the development of alternate energies as a national strategy ahead of the expected depletion of oil. In particular, U.S. President Barak Obama's "green deal" policy has accelerated the move to develop alternatives to oil.

2-3-2 Application to biomass

New technologies for the future have also begun to emerge, such as one to produce necessary polysaccharide and other biomasses more efficiently by optimizing the metabolic system of microalgae with gene-recombination technology and one to make

Table 1 : Fuel Production Efficiency of Microalgae in Comparison to Plant Oils

Crop	Biofuel yield 1 ha (liter/ha/year)	Land area needed to produce oil meeting 50% of total transport fuel needs in the U.S. (million ha)	Percentage of land area needed to produce oil meeting 50% of total transport fuel needs in the U.S. (%)
Corn	172	1,540	846
Soybean	446	594	326
Canola	1,190	223	112
Jatropha	1,890	140	77
Palm oil	5,950	45	24
Microalgae*	58,700	4.5	2.5
Microalgae**	136,900	2.0	1.1

* 30% oil (by weight) in biomass
**70% oil (by weight) in biomass

Prepared by the STFC based on Reference[31]

Table 2 : Venture Companies Established to Produce Microalgal Biofuels

U.S.	・A2BE Carbon Capture ・Algae Floating systems ・AlgaeFuel ・Algae Fuel System ・AlgaeWheel ・Algenol Biofuels ・Algoil Industries ・AlgroSolutions ・Aquatic Energy ・Aurora Biofuels ・Bionavitas ・Blue Marble Energy ・Bodega Algae ・Cellana ・Chevron Corporation ・Circle Biodiesel & Ethanol Corporation ・Community Fuels ・Diversified Energy ・Energy Farms ・Global Green Solutions ・Greenshift ・Green Star Products ・HR BioPetroleum ・Imperium Renewables ・Infinifuel Biodiesel ・International Energy ・Inventure Chemical ・Kai BioEnergy ・LiveFuels ・Organic Fuels ・OriginOil ・PetroAlgae ・PetroSun ・Phycal ・Sapphire Energy ・Seambiotic ・Solazyme ・Solena Group ・Solix Biofuels ・Sunrise Ridge Algae ・Sunx Energy ・Texas Clean Fuels ・Valcent Products ・Vertical Algae Biofuel Growing ・W2 Energy
Europe	・AlgaeLink (Netherlands) ・Bio Fuel Systems (Spain) ・Enhanced Biofuels & Technologies (UK) ・Kwikpower International (UK)
Others	・Algae Fuel Systems (Canada) ・Algodyne Ltd (Israel) ・Aquaflow Bionomics Corporation (New Zealand) ・Enhanced Biofuels & Technologies India Ltd (India) ・Oil Fox (Argentina) ・Seambiotic Ltd (Israel)

Prepared by the STFC based on Reference[41,42]

microalgae produce biomasses that are not otherwise produced.

A group of researchers, including Professor Akihiko Kondo of Kobe University, has established technology to modify the metabolic pathways of microorganisms by using what is called arming technology, which is a genetic recombination technology. This technology gives a new metabolic capability to cells, such as yeast and grass bacilli, by making them produce enzymes that they do not inherently produce. The microorganisms produced in this way are called arming yeasts or arming grass bacilli. The research group has succeeded in experimentally producing ethanol, amid acid and lactic acid from celluloses, which are not inherently a resource. The technology has opened the way to utilize plants' unedible celluloses and simplify multiple enzyme reactions.[44]

If arming microalgae can be produced by employing this technology, it may be possible to cause fermentation by using sugar produced by microalgae. It is hoped that this method will lead to biomass production that does not compete with foods.

3 Toward industrialization

3-1 Industrial culture technique

Along with rising expectations for microalgae, it has become necessary to develop technology to industrially and efficiently produce the required amounts of microalgae. In particular, it is essential to establish culture techniques ranging from small to large-scale culturing. It is also necessary to enhance productivity based on individual culture methods and accumulate knowhow with regard to ensuring quality.

In the case of producing relatively small amounts of medicine, food and feed, which require purity and safety, an enclosed culture system (Enclosed System) (Figure 6 (a)) is used. In the case of biofuel and biomass, large-scale yet low-cost production methods are required. Currently, as a large-scale culture method, culturing in open spaces such as ponds (Open Pond System) has been employed (Figure 6 (b), (c)).

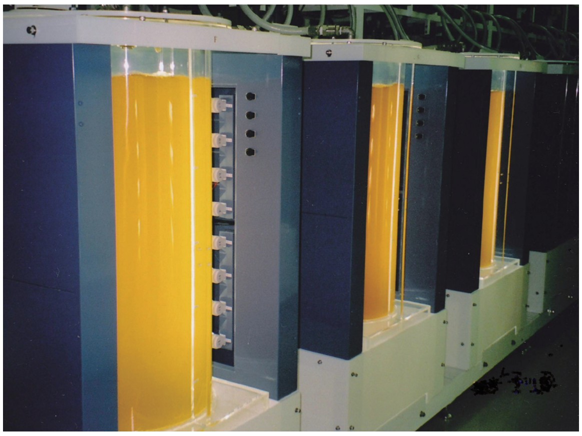
At present, such methods are a long way from being efficient. In particular, the development of a culture method to industrially produce low-priced products in large quantities is still at the study stage. A study is now under way to develop an enclosed culture system that utilizes light more effectively than open culture methods and is suitable for low-priced, mass culture.[46]

3-2 Value of products and production cost

According to Professor Rene Wijffels of Holland's Wageningen University, the cost of mass culturing microalgae with currently-available technology comes to €4.02/kg (about ¥520/kg) in the case of cultivation size of 100ha. He said the cost can be reduced to €0.4/kg (about ¥52/kg), if production technology advances in the future.[47]

As to the value to be obtained from 1kilogram of microalgae, Wijffels also assumed diversified products, such as those we mentioned earlier. He estimates the overall profits from various products, such as proteins, lipids, and sugars, come to €1.65/kg (about ¥210/kg). He said, with the current production cost of €4.04/kg, it is difficult to commercialize such products but that if the production cost is reduced to around €0.4/kg in the future commercialization will become possible.[47]

In order to reduce production costs, it is very important to sort out strains that produce specific substances in large quantities, and develop a low-



(a) Medium-sized enclosed culture system (Akkeshi Town Oyster Breeding Center[19]; Akkeshi Town, Hokkaido; Photo provided by Sumi). *Chaetroceros calcitrans* is produced and cultured automatically in 500-liter, slim containers.

(b) Large-scale open culture tanks (Yaeyama Shokusan Co.)[45]; Ishigakijima, Okinawa; Photo provided by Sumi)

(c) Large-scale open raceway culture system[46]

Figure 6 : Various Culture Methods for Typical Microalgae

cost cultivation technique and methods to extract and purify multiple products efficiently.

4 Challenges facing Japan in promoting study on microalgae

As we examined in Chapter 2, microalgae can be applied in a broad manner in the red biotechnology field (medicine and health), green biotechnology field (agriculture and fisheries, environment), and white biotechnology field (industry and energy). However, research on microalgae and moves to industrialize them in Japan are not yet active. Here we would like to discuss the reasons for the slow progress and the future challenges facing Japan.

4-1 Establishment of scientific and academic societies focused on microalgae biotechnology

First of all, microalgae research in Japan is being conducted only within segmentalized fields while basic or applied science fields centering on microalgae have yet to be established. Therefore, no academic association has been well organized. Existing academic associations are like hobby clubs dealing with only one microalga, raising no hopes of developing diversified technologies and knowhow common to microalgae. For instance, their activities are separated depending on fresh-water microalgae and marine microalgae. This seems to have narrowed researchers' vision.

The technology to assess, sort out and make use of microalgae that are useful for specific products from among the various microalgae possessing biodiversity can be called a common fundamental technology. Japan is blessed with diverse microalgae, both fresh-water and marine microalgae. Meanwhile, in each field, studies have been accumulated concerning individual microalgae. However, academic associations and researchers have no opportunities to make use of such studies in a comprehensive manner.

There are many microalgae-related biotechnologies that can be commonly used in various industries. Information fed back from other industrial fields should be greatly helpful. In order to share and make wide use of biotechnological information on research, development and technology in the fields of red bio, green bio, and white bio, it is necessary to treat the three biotechnology fields as a new comprehensive science discipline, for example, as microalgae utilization biotechnology, and reorganize researchers and academic associations.

Specifically, it is important to promote research activities that will form common bases for microalgae contributing in the various fields of medicine, health, environment, energy, agriculture and fisheries. For example, it is necessary to develop a technology to sort out microalgae for respective objectives, a highly-efficient culture technology for mass production, and recombinant technology using microalgae as hosts.

Table 3 : Value of Products Produced by Microalgae

Product (ingredient)	Use	Volume (kg)	Unit (euro/kg)	Value (€)
Proteins	Foods	100	5	500
	Feeds	400	0.75	300
Lipids	Chemical industry	100	2	200
	Biofuel	300	0.5	150
Sugars	Sugar biomass	100	1	100
Oxygen production	Immobilization of carbon dioxide	1,600	0.16	256
Removal of nitrogen	Water purification	72	2	140
Overall value			1.65	1,646

Assuming that it is possible to obtain 400kg of lipids, 500 kg of protein and 100 kg of sugar from 1,000 kg of microalgae, their respective value is calculated. From 400kg of lipids, 100 kg of chemical materials (€2/kg) (equivalent to biomass in this report) and 300 kg of biofuel (€0.5/kg) are obtained. From 500 kg of protein, 100 kg of food (€5/kg) (including nutraceuticals) and 400 kg of feed (€0.75/kg) are obtained. 100 kg of sugar (€1/kg) is equivalent to biomass in this report. In addition, 1,600 kg of oxygen (€0.16/kg) is generated. Since this is a result of the immobilization of carbon dioxide, it has a value in terms of CO2 emission rights. The value of the environmental purification effect is calculated as the removal of 70 kg of nitrogen (€2/kg). All this adds up to €1,646 (€1.65/kg), suggesting that profit could be made if production cost is reduced to €0.4/kg (€400 per 1,000kg).[47]

Prepared by the STFC based on Reference[47]

4-2 Establishing a collaboration system on the premise of industrialization

Industries concerned with microalgae cover a wide range of fields, including medicine, health, environment, energy, agriculture and fisheries. Therefore, it is necessary to establish a system to lead basic technologies developed in academia to effective utilization in development research, such as a system for collaboration among industry, academia and government.

As we described earlier, Algal Biofuels Workshop was inaugurated in the United States under the auspices of the Department of Energy. In Australia, moves to organize Algal Fuels Consortium, which is aimed at promoting algal-derived biodiesel, are expected to start under the leadership of the Scientific Industrial Research Organization (CSIRO). These moves demonstrate that governments and industries are working together to establish forums and an environment to foster a new industry concerning microalgae.

In Japan, a marine bioindustry cluster project is being conducted by Hakodate city, Hokkaido (the project started in fiscal 2009). The project is designed to foster new industries in such fields as acquiring bioactive substances, ensuring the safety of microalgae and other marine products, detecting toxic microalgae, forecasting oceanic environment, and securing oceanic biomasses, by utilizing the marine biotechnologies clustered in Hakodate city, such as 1) ubiquitous technology to forecast marine environment, 2) bioenergy sustaining technology, 3) bioactive compond-production technology, and 4) bio-farming technology. However, the project is not specifically focused on microalgae technology.

It is necessary to form an industry-academia-government consortium focused on fostering and supporting the three biotechnology fields described in this report as soon as possible by consolidating microalgae-related technologies. In particular, it is necessary to promote the application of cost-conscious culture methods and other basic technologies.

4-3 Drawing up road maps toward actual application of technologies

Microalgae biotechnologies have the potential to provide huge benefits to the industries of the 21st century and enrich human life. In order to realize it, it is necessary to draw up a comprehensive roadmap encompassing life science, environment, energy, etc. with the standpoint of promoting research activities ranging from basic-level research to industrialization, and put budget and manpower into research and development according to the roadmap.

Already, new products are being produced in two different ways on a trial basis. One method is to produce high-value-added products, such as medicines and nutraceuticals (small-scale production of high-priced products) and the other method is to produce commodity biofuels (mass production of low-priced products), which is being experimented with in the United States and Australia. In the United States, the Department of Energy has begun to draw up a roadmap based on the movements of venture companies focused on microalgal biofuels. In the Netherlands, the government is supporting a consortium to draw up a comprehensive roadmap to utilize multiple products to be produced by microalgae.

In Japan, the industry, academia and government have yet to come up with a specific idea of whether to promote basic technologies on an all-round basis or to take an approach focused on specific fields. For instance, a roadmap for the near future presented by the Ministry of Economy, Trade and Industry does not have "microalgae" in its items.

The new industry for the three biotechnologies described in this report comes under the jurisdiction of more than one ministry or agency. Therefore, it is necessary to draw up a roadmap from a broad standpoint going beyond the boundaries of ministries and agencies. It is a pressing issue for Japan to lay the groundwork for the application of microalgae, so that the microalgal technologies which Japan already possesses can be fully utilized.

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Profile

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Doctor of medical science. Professional discipline: Medical science and biotechnology.
I am convinced that microalgae are worth researching, as they hold promise for our future. If people in various fields join forces, I am sure Japan will become a world-leader in science and technology. Japan will create a sensation and change the world.

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