OFFSHORE MEMBRANE ENCLOSURES FOR GROWING ALGAE (OMEGA): A SYSTEM FOR BIOFUEL PRODUCTION, WASTEWATER TREATMENT, AND CO_2 SEQUESTRATION

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OMEGA is a system of photo-bioreactors (PBRs) filled with municipal wastewater, floating in seawater. It is constructed of flexible plastic with internal gas-permeable membranes diffusing CO_2 into the cultures and external forward osmosis (FO) membranes concentrating nutrients in wastewater and dewatering the algae for harvesting. The FO membranes also clean the water released into seawater. The OMEGA modules float at the sea surface. The surrounding seawater provides structural support, temperature control, and containment (the cultivated freshwater algae cannot survive in seawater). Waves and bubbling provide mixing. OMEGA produces biomass for biofuel, food, and fertilizer, while treating wastewater and sequestering carbon.

Keywords: microalgae, biofuel, wastewater treatment, photobioreactor, carbon sequestration

CHALLENGES WITH CURRENT BIOFUEL PRODUCTION METHODS

From Fossil Fuels to Biofuels

There are many strong incentives to replace fossil fuels with biofuels, among them are national security issues, sustainability of limited resources, and avoiding environmental disasters—the gradual disaster of climate change and the more imminent disasters caused by offshore oil spills.[1] While there are known species of plants that produce vegetable oil and well-established refining methods for transforming vegetable oils into biofuels, it is challenging to envision how adequate supplies of fuel can be produced from plants. The oil yield of soy plants, for example, is 50 gal/acre/year, Jatropha is approx. 200 gal/acre/yr, and some species of palm produce >600 gal/acre/yr.[2] The best oil producers are among the microalgae, which produce between 2,000 and 5,000 gal/acre/yr. In contrast, the 2008 average production from the 525,000 active oil wells in the USA was 144,102 gal/well/yr and all these wells provided only about 40% of the oil used domestically.[3] Thus it is clear that to replace a significant portion of fossil fuel with biofuels will require an enormous commitment of land—to replace production of a single average oil well requires 72 acres of algae or 2,882 acres of soy. This commitment of land, as well as water and fertilizer needed for growing biofuels crops, is the basis for the clash between biofuels and agriculture[4].

To avoid the "fuels vs. food" clash, it has been suggested that biofuels should be made from plants grown in deserts or on other non-agricultural land, using salt-tolerant or drought resistant plants, watered with seawater or municipal wastewater. Given the relatively high oil yields of algae, including marine algae that can grow in saltwater or freshwater strains that grow on municipal wastewater, it is generally agreed that microalgae are the most promising biofuels crop. The question is whether existing or new algae cultivation methods can be scaled up to meet the needs for biofuels and if these methods can avoid competing with agriculture.[5]

Raceways and Closed Photobioreactors

Microalgae are currently grown commercially in shallow open ponds called "raceways" or in sealed enclosures known as photobioreactors (PBRs).[6] These commercial systems grow algae that make high-value products, such as nutriceuticals, food additives, cosmetics, or pharmaceuticals, which means a small-scale algae cultivation system can be economically viable. Biofuels however, are a low-value commodity and to reach the economies of scale that will meet the demand for biofuels, will require raceway or PBR installations orders of magnitude larger than those currently in use. With sufficient motivation, huge raceways can be excavated and large numbers of PBRs can be built and these enormous installations can be located so as not to compete with agriculture, but the costs of infrastructure and logistics of water and product transport have made such ventures into algae biofuels impractical to date.

The Devil is in the Details

Indeed, while huge areas of raceways and large numbers of PBRs can be installed in remote locations that would not compete with agriculture, the actual use of these sites have been shown to be logistically problematic and prohibitively expensive.[6] Considering the volumes of water required for producing the quantities of algae need for fuels, an enormous infrastructure of pipes or roads will be needed for transporting the volumes of water, wastewater, and CO_2, as well as the harvested algae. Such an enormous algae cultivation system will require formidable amounts of energy for moving the large volumes of liquids and gas as well as for harvesting, processing, and transporting the tons of algae being processed. There is also the problem of water.

Raceways are open to the air, which means the water can evaporate. It is estimated that the replacement water required to grow freshwater algae and appropriate salinities for marine algae on a scale relevant to biofuels would be measured in the trillions of gallons of freshwater per year [7]. In addition, there are the energy requirements to move the volumes of water to deserts or remote cultivation sites and these consideration raise the question of whether fuel or food should be produced with this use of resources.

While evaporation may not be a problem for PBRs, which can be closed and sealed chambers, freshwater may still be a problem because many PBR systems use water for cooling. Why is it necessary to cool algae? Algae require light and if the light comes from the sun, there is also heat. Sealed PBRs are functionally solar-thermal collectors and to maintain temperatures suitable for growing algae, they need to be cooled and evaporative cooling using freshwater is a simple method. Here again, the system requires energy and competes with agriculture. Indeed, PBRs already use a lot of energy for mixing and circulating algae cultures. Even with the small-scale PBR systems used for making high-value products, it is the capital and operating costs that make them impractical.

Therefore, although algae have great potential as a source of biofuels, growing algae in raceways or in standard PBRs on a large enough scale to produce biofuels at a cost that can compete with fossil fuels remains as daunting challenge.

Is there another approach for growing oil-producing microalgae without competing with agriculture for land, freshwater, or fertilizer, without pumping water great distances, and in a way that benefits the environment?

OMEGA (OFFSHORE MEMBRANE ENCLOSURES FOR GROWING ALGAE)

Fig. 1: Schematic representation of OMEGA system

The OMEGA System

The OMEGA system consists of individual modules that are closed photo-bioreactors filled with domestic wastewater, floating offshore—just beneath the sea surface. Unlike PBRs on land, which have problems with heat and energy use, OMEGA modules transfer heat to the surrounding seawater, while mixing and circulating the algae is done using wave energy. The OMEGA system also uses buoyancy, gravity, and osmosis. Air and water filled bladders in the OMEGA structure provide buoyancy and structural integrity. Concentrated CO_2 from remote sources (wastewater facilities or power plants) diffuses into the algae culture through gas-permeable membranes. Patches of forward osmosis (FO) membranes on the bottom of the plastic enclosures allow water to diffuse out into the surrounding saltwater. This process is driven by the salt gradient and during an incubation period of 5-10 days, more than 65% of the bulk water can be removed from the culture. The FO process stimulates algal growth by concentrating nutrients in the wastewater and assists in harvesting by initiating dewatering of the algae. Furthermore, the water passing through the FO membrane is clean (bacteria, virus, and pollutants do not pass FO). This will help remediate dead zones in polluted coastal areas. The surrounding saltwater also prevents the freshwater growing inside the OMEGA system from becoming invasive species in the marine environment. In other words, if the OMEGA system catastrophically fails, it releases wastewater that is certified for release, freshwater algae that cannot grow and are completely biodegradable, and plastic that can be readily recovered.

OMEGA LOCATIONS AROUND THE WORLD

It is proposed that OMEGA farms will be located in marine (salty) environment in the vicinity of a source of nutrient-rich freshwater and a source of CO_2, such as a coastal power plant. Other conditions, including temperatures, light, water clarity, frequency and severity of storms, geography, boat traffic, wildlife conservation, will all influence how the OMEGA farm will be configured and what algae will be cultivated. The plan is to only cultivate freshwater algae and to use wastewater that meets regulations for release into the marine environment.

To accommodate sea birds and marine mammals, the OMEGA modules in a farm will be spaced to allow ample access. This also allows light to penetrate into the water column between the modules. The number of OMEGA modules in a farm will depend on the location, shipping lanes and the amount of wastewater to be processed in a given location.

Obviously, OMEGA farms will be easier to build in protected bays, in areas surrounded by breakwaters, or in places with existing marine infrastructure such as offshore platforms or wind farms. In the case of wind farms, OMEGA farms would use the infrastructure for anchorage and organization and could benefit from the source of local energy for pumping water, air, and CO_2, and well as producing artificial light. In turn, the wind-farm benefits by using the algal biomass as a way to solve the problem of long-term storage of wind energy.

As designs and methods for OMEGA farming develop, exposed open ocean locations may also be used. These will require robotic systems for transporting wastewater from the major sewage outfalls and for return algae biomass to shore. On the other hand, with global warming and rising sea levels, OMEGA farms may take advantage of flooded coastal zones, forming a new coastal infrastructure for algae production, wastewater treatment, and carbon sequestration.

LABORATORY TESTING OF OMEGA COMPONENTS

Algal Growth, Oil Production

Chlorella vulgaris was grown in lab-scale OMEGA modules and the growth and biodiesel production were monitored (Fig. 2). The growth conditions included using primary or secondary wastewater from the Sunnyvale wastewater treatment facility or using a standard laboratory medium for growing algae (BG11). We used constant light (177 ft candles), constant stirring, and added CO_2. The cultures grown in OMEGA modules 2 or 3 cm deep did not exceed 2 g/L dry wt, indicating the cultures were light limited. Cultures grown in 1 cm deep OMEGA modules achieved 6 g/L (data not shown), which is in agreement with previously published work on light limitation[4].

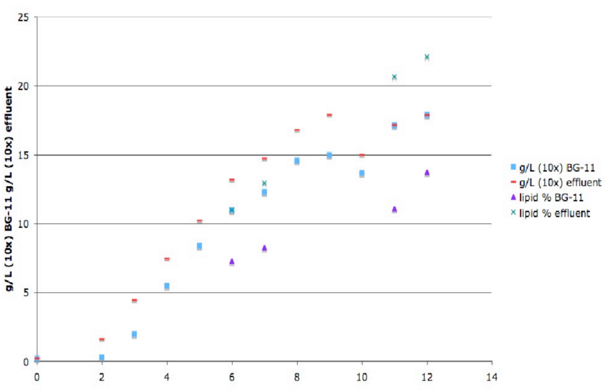

Fig. 2: Algal growth and % lipid results in simulated ocean with both primary wastewater and laboratory media. Note: biomass concentration scaled up 10X to correspond to % biodiesel.

Forward Osmosis and Biofouling

Chlorella vulgaris was grown in the laboratory in small OMEGA modules (20 cm x 20 cm x 1, 2, or 3 cm) made of clear polyurethane with or without forward osmosis (FO) membranes. Floating these modules in a seawater tank, the algal culture was dewatered up to 85% (range 65-85%) over a 4-day period (Fig. 3).

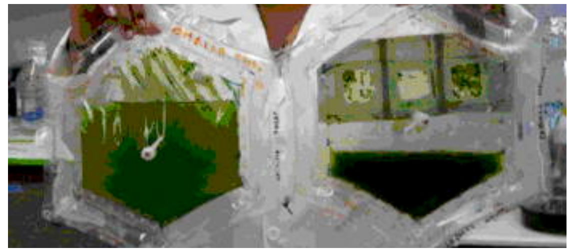

Fig. 3: Dewatering of algae culture in OMEGA module with FO membrane.

FO has the potential to concentrate nutrients and facilitate harvesting, if it could work under marine conditions. Nearly all surfaces in the marine environment are subject to biofouling and to determine the impact of biofouling on FO membranes, FO chambers were attached to a buoy in the ocean for 45 or 52 days (Fig 4).

(a) (b) (c)

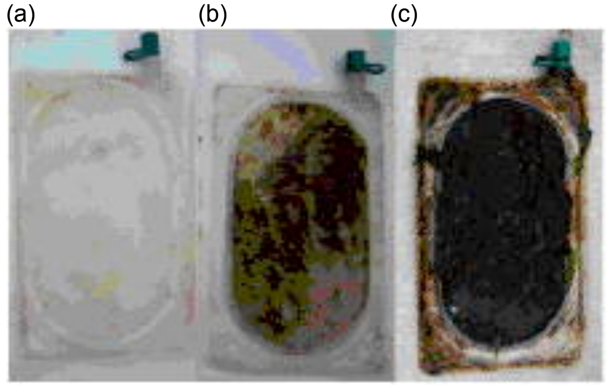

Fig. 4: FO chambers after exposure to the marine environment without dewatering. (a) FO chamber stored in artificial seawater in the laboratory for 45 days, (b) FO chamber off Capitola Pier, CA after 45 days, and (c) another FO chamber off Capitola Pier after 52 days.

As expected, compared to laboratory controls (Fig. 4a), the ocean exposed FO chambers accumulated thick layers of biofouling (Fig. 4 b&c). Surprisingly, however, the heavily biofouled FO chambers showed similar dewatering rates to the unfouled chambers, provided their membranes were not damaged by the encrusting material or by the added flexing due to drag on their surfaces (Buckwalter et al. in preparation).

OMEGA FEASIBILITY AND SCALABILITY

With the limits of fossil fuels on the horizon and ample evidence that their continued use will have catastrophic environmental consequences, the OMEGA project is an opportunity to be part of an international team to co-develop this alternative fuels technology. OMEGA is a novel approach to growing oil-producing, freshwater algae in offshore enclosures, using municipal wastewater that is currently discharged into the ocean. The technology is meant to produce sufficient quantities of algae to significantly contribute to the production of sustainable and carbon-neutral biofuels without competing with agriculture for land, water, of fertilizer. The OMEGA system uses solar energy, wave energy, the heat capacity of water, and the salt gradient between seawater and wastewater for forward osmosis. FO concentrates nutrients and stimulate algal growth, while facilitating the harvesting of the microalgae. OMEGA provides biofuels, as well as food, fertilizer, and other useful products, while processing wastewater released into the environment and removing carbon dioxide from the air. OMEGA was inspired by NASA's closed-loop life support systems and it represents an "ecology of technologies" in which waste products from one part of a system become resources for another. Like natural ecosystems, technology ecology is efficient, effective, and sustainable.

A team of scientists, engineers, ecologist, and economists supported by NASA ARMD and the California Energy Commission, are doing a demonstration project to determine if OMEGA is feasible and scalable. This demonstration is meant to determine if OMEGA is feasible: technically, biologically, environmentally, and economically, and if it can be done at a scale that impacts the current use of fossil fuels. Algae products from OMEGA could include biomass, oil, fertilizer, animal fodder and high-value products such as dyes, nutraceuticals, cosmetics, and drugs. Services could include wastewater treatment, dead-zone remediation, and CO_2 sequestration. The OMEGA system integrates solar, wave, and wind energy with gravity, buoyancy, heat capacity, and osmosis. The viability of the OMEGA system will be determined by prototype and pilot testing as well as energy return on investment and a detailed life-cycle analyses. The economics of OMEGA will be determined based on products and services as well as considerations of the consequences of not doing OMEGA.

OMEGA products and services do not compete with agriculture or damage marine ecosystems. Indeed, OMEGA is meant to improve the marine environment by removing nutrients that are currently contributing to the formation of dead zones and by sequestering CO_2 that is contributing to ocean acidification. The hope is that based on the results on the demonstration, people around the world will be motivated to develop OMEGA systems for their locations. Projects like OMEGA will require local experts supported by government agencies and private investors who all recognize the magnitude of global problems and the urgency of finding solutions. If such experts can be mobilized and openly share information, it is estimated that OMEGA technology can be developed to significant scales within 10 years. It is impossible to predict as yet if OMEGA is feasible and scalable, but having just emerged from the warmest decade on record, we enter a new era with the knowledge that it is imperative that civilization move without delay from hunting-and-gathering energy to sustainably and responsible cultivating and harvesting it. As we consider options for future energy "farms," the oceans emerge as the world's most promising energy frontier.

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