Sustainable Energy Education: Biofuels from Solar-Powered Algae Cultures

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Sustainable Energy Projects for Undergraduates: Biofuels from Solar-Powered Algae Cultures

Abstract

Renewable, Green, and Sustainable energy utilizing photovoltaics and wind power are well-established in educational laboratories and as topics for student projects. Biofuels are expected to be another cornerstone of future energy scenarios. The prospects for harvesting plants or microorganisms for biomaterial that can be processed into liquid or solid fuels, such as replacements for diesel fuel ('biodiesel") are continually improving and nearing feasibility for large-scale implementation. In this paper, we report student projects for solar-powered algae culture on desktop-sized demonstration systems built out of low-cost plastic materials for outdoor operation. Circulating algae culture (seeded with inexpensive (~ $10) algae purchased from educational laboratory supply houses) systems, equipped with consumer-grade pumps and instrumented with low-cost sensors, and powered by solar cells, can be monitored and optimized for biomass yield. In this report, we provide descriptions enabling schools to facilitate educational laboratories and student projects in solar biomass algae culture.

Introduction and Overview

Renewable and alternative energy, 'green' manufacturing, and sustainable technology are gaining increasing prominence in the Engineering Curriculum. Many schools offer courses in solar energy, wind power, fuel cells and batteries, smart power, and other emerging energy technologies in order to give students exposure to and experience in current and near-term renewable and alternative energy. Biofuels and aquaculture, on the other hand, are often neglected topic areas, unless the school has a bioengineering or chemical engineering program. The biofuels 'landscape' and the commercial prospects for biofuels and aquaculture are less familiar to most engineering students than some of the other technologies mentioned above. This may be due in part to the perception that biofuels and aquaculture require a certain level of expertise in biological sciences, and in effect, there may be an implicit bias against biotechnology as well as medical, agricultural and topics in mechanical and electrical engineering programs. Further, unlike mathematics, physics, materials science, and chemistry, biology is not usually a required subject for most engineers. This situation can be exacerbated by the perception that biology-based systems are unwieldy and erratic, lack reproducibility, and are less amenable to quantification, modeling, and optimization. The main purpose of this work is introduce a wider audience of engineering students to aquaculture as a renewable energy technology, and to demonstrate that such projects are feasible and instructive in mechanical and electrical engineering programs. We provide some descriptive details to show that these and similar projects are well within the means and expertise of most science, engineering and technology programs, and represent a useful exercise as an initial engineering scale-up and feasibility study of basic biological research for commercial applications.

With the advent of genetic engineering, microbes can be readily harnessed for industrial applications. Moreover, new sensors and image capture and processing can facilitate better quantification and control of systems such as cell cultures, and unit operations such as bioreactors, separation processes, mixers, can be modeled as engineering systems. Further, there is now a wide range of rapid prototyping tools to quickly and cheaply fabricate fluidic systems—from the nanoscale, through the microscale, and up to macro-scale (desktop and benchtop)—that can be used to implement biotechnological systems developed on the lab bench. These systems have many sensor and control issues which provide instructive case studies for electrical and mechanical engineers.

In this paper, we discuss simple experimental systems featuring a 'bioreactor' for growing algae as material for biofuels. These systems are based on experience with various undergraduate Senior Design and independent study projects. Broadly, this is a solar energy application for production of feedstock for be conversion into fuels and perhaps other food and industrial products. This project is suitable for course-based laboratory work, independent research, as well as Senior Design projects. A small fluid system is used to grow algae (a single cell photosynthesizing microorganism that can thrive with minimum nutrients) in sunlight as a raw feedstock for biofuels. The system is safe, portable, and relatively low in cost, and can be instrumented to serve as a platform for experimentation and modeling.

Students built table-top fluid systems that circulated water injected with algae. The system was constructed out of clear plastic (acrylic). The algae were exposed to sunlight and the algae population grew to a higher density, at which point the fluidic system is tapped and the algae are harvested. These systems generally incorporate solar cells, such that light penetrating the channels and suspension of algae will illuminate the underlying solar cells. The algae utilize the blue and red parts of the solar spectrum, and the unused (unabsorbed) green light can be converted to electricity by the solar cells positioned underneath the clear plastic channels in which the algae culture is circulated. Thus, the system provides a more efficient utilization of the sun's energy, by generating both algae feedstock for biofuel and solar electricity. Further, the solar cells can be used to run the pump and other supporting equipment and electronics, creating an autonomous system.

Biofuels are attractive as a locally produced and locally refined substitute for gasoline and diesel fuels. There are particularly of interest in rural areas and farm economies. Biofuels offer prospects for energy independence, mitigation of CO_2 emissions, and revival of economically-depressed areas of the US.

Biofuels are commonly produced from lipids (fats) derived from vegetable oils (rapeseed, soybean, mustard and sunflower), animal fats (tallow, lard, yellow grease, and poultry products), waste vegetable products, and certain types of microorganisms such as algae. Fatty acids can be extracted from these materials. Biodiesel is processed from these extracts by a transesterification reaction, where fatty acids are mixed with methanol and a catalyst (such as alkali metals or acids) to yield a mixture of methyl esters (biodiesel) and glycerol (a useful byproduct). The National Renewable Energy Lab (Golden Colorado) Aquatic Species Program conducted studies identifying over 300 algae species that could produce lipids amounting to 20 to 50% of biomass. High growth rates of algae will in general lower lipid production per cell.

There are good prospects that genetic engineering may be able to produce species of algae and other microorganisms that grow fast with a high lipid content.

Biofuels derived from plants have benefit that the growth of such plants reduces atmospheric CO2, a greenhouse gas. In the case of algae culture, basically sunlight, CO2, and water (plus micronutrients) are used to produce oxygen, polysaccharides, proteins, and fatty acids. The polysaccharides and proteins can be used as food for animals and people. The growth of algae in areas with high human activity might be used to mitigate CO2 production.

Algae reproduce fast, have a comparatively small use of land, and have minimal nutrient requirements. Algae can be cultured in open ponds, tubular and flat reactors, and plastic sacs or barrels. Reactors in sunlight can overheat, reaching temperatures where algae are inefficient. Too intense sunlight can photobleach algae, in which case they cease photosynthesis. Ponds and reactors can become contaminated with bacteria and other unwanted organisms. Other issues include optimal orientation toward the sun, clogging, optimal algae density, flow rates, modulation of sunlight (on and off cycling for solar exposure), gas (oxygen and CO2) concentration and ease of degassing, micronutrients, and light intensity as function of depth in liquid. Clearly, there are many parameters to optimize in algae culture. Bioreactor systems can be better optimized than growing algae in ponds. Further, the algae culture system can be combined with photovoltaic cells for electricity generation. Conventionally, 1 hectacre of algae culture (e.g., in ponds) can produce about 2700 liters of biodiesel per year. Research to improve algae yields is ongoing. A figure of merit is the production of algae (dry weight per day). One interesting observation is the report that flashing sunlight improves algae yield, probably by reducing photobleaching effects.

There are many species of algae including *Anabaena, Closterium, Volvox, Chlamydomas, Eugenia Gracilis, Chlorella, Oedogonium*, and *Synedr*a that are good candidates for biofuel applications. Algae have varying tendencies for clumping and optimal growth density and temperature. Chlorella appears to be the most favored species for biofuel algae culture. Test tubes of algae can be purchased from Carolina Biological Supply for about \$5 to \$10. They can be stored at room temperature for long periods (months). Preliminary experiments on growing algae using halogen lamps to simulate sunlight can be performed in petrie dishes. The algae yield can be measured by completely drying out the algae with a hot air blower or sunlamp, and weighing the residue (dry weight). Care must be taken not to overheat the algae. Optimum temperatures are Aanbaena is 40 to 45 °C and for Chlorella is 25 °C. Concentrations of algae (which can be determined with a microscope) typically range from 10^6 to 10^8 cells per ml. Algae cells range in size from 2 microns to 10 microns.

Engineering Design and Prototyping

Very simple and unsophisticated solar algae systems (**Figure 1**) can be built, but these are of limited value in exploring process optimization. A more useful system is shown in **Figure 2**. Students at several schools built several algae aquaculture systems with pumps, control, and solar cells (**Figures 4** through **8**). The system is made out of clear acrylic plastic sheet (3 to 5 mm thick). The sheet is cut with a Universal Laser Systems 40W CO2 laser using AutoCAD or SolidWorks source files. The acrylic is bonded with acrylic cement (Weldon 4052), but in general, all adhesives and materials should be checked for toxicity to algae.

The channel height (normal to incident sunlight) is about 1 cm. The widths of the channels ranges from 4 to 8 cm, and can be up to 1-2 m long. Flow rates range from 1 to 10 ml/s, which corresponds to a Reynolds Number of about 20 to 500, and a flow velocity of 1 cm/s, indicating laminar flow. Syringe pumps are gentle to the algae, and peristaltic pumps were considered as an alternative. Centrifugal pumps (as used for pumping coolants in electronic systems) were also utilized. These operate on 12 volts (convenient for interfacing with solar cells), draw about 1 A (for 8 to 12 W power), produce a head of 3.3 m of water, with a flow rates up to 100 GPH (440 liters per hour = 120 ml/s). The pump can be connected to the channels with ¼ inch Tygon® tubing. The density of the algae can be monitored by measuring optical absorption in the algae culture using a red LED light source and a silicon solar cell as a detector. The current of the solar cell can be calibrated against cell density. This provides a sensor for the most important process control variable, algae cell density in culture. An Arduino Microcontroller is used to control the pump speed and records algae density data. A tap in the circulating loop allows harvesting of algae, which is dried and weighed (**Figure 9**). Some representative data are shown in **Figure 10**.

Summary and Discussion.

The system serves as an experimental test bed to optimize algae growth conditions. There are still many fundamental issues to resolve in optimizing the growth of algae, their specific production of fatty acids (lipids), and their utilization of the solar spectrum. The system can also be regarded as a pilot plant in a step toward scale-up for high-volume production.

This project does not burden school resources, and the materials costs for a small system are several hundred dollars. The system can be compactly stored when not in use, and does not present any hazardous waste or disposal problems. The algae culture system described here is a low-cost, safe, and portable system. The small systems can be placed on a cart and wheeled outdoors for testing. Moreover, many schools have greenhouses that can be used for experiments in the winter, which may also serve as an expedient for more collaboration between agriculture schools and engineering departments. The basic principle of the algae aquaculture is simple and intuitive, and will not intimidate engineering students. Perhaps simplistically, this project might be regarded as a mixture of gardening, aquariums, home brewing, and cooking, in search of engineering expertise for process development and optimization. In summary, our aim was to show that algae culture for biofuels, utilizing solar energy, is a feasible, accessible, instructive area for engineering students, imposing only modest costs in resources for schools.

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Figure 1: "Home-Brew" mini-algae culture system.
(http://www.instructables.com/id/Solar-powered-algae-bioreactor/)

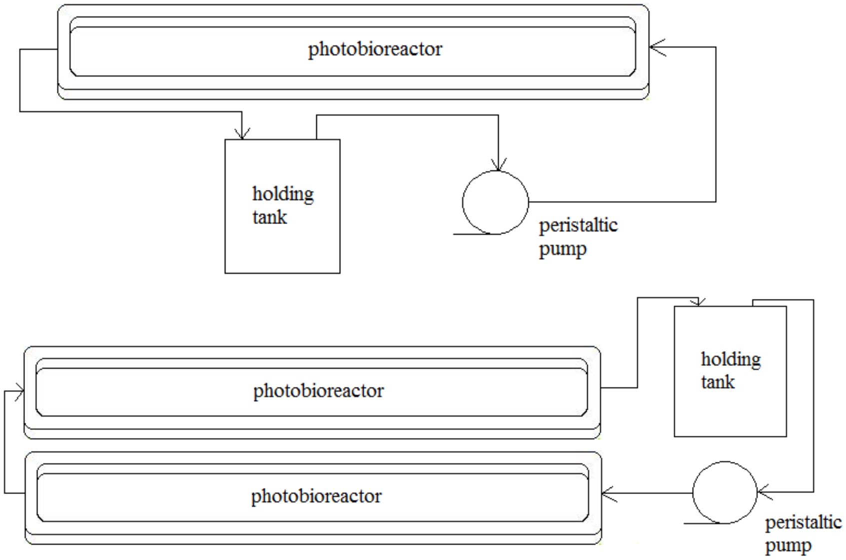

Figure 2: Algae Bioreactor System. From Narkeviciute and McLaughlin [2].

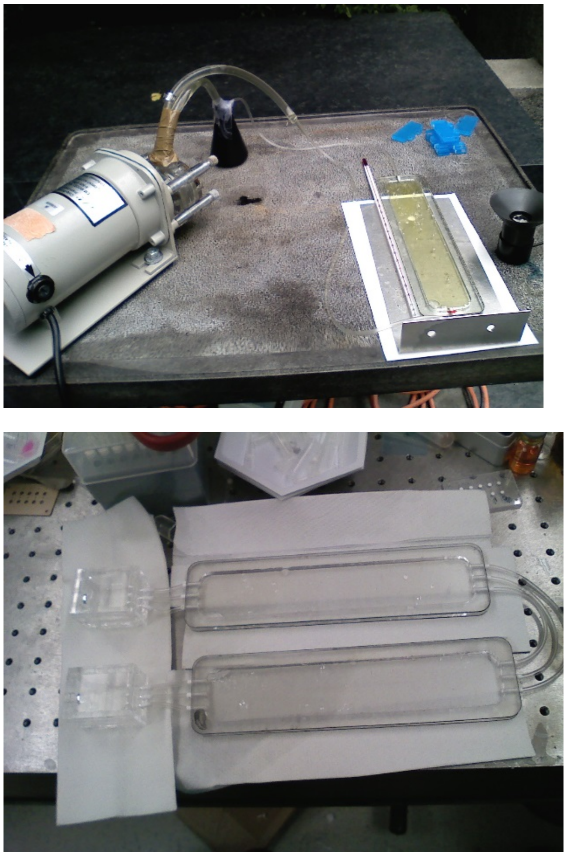

Figure 3: Constructing the Algae Bioreactor system. From [2].

Figure 5: Small Algae Bioreactor system. From [2].

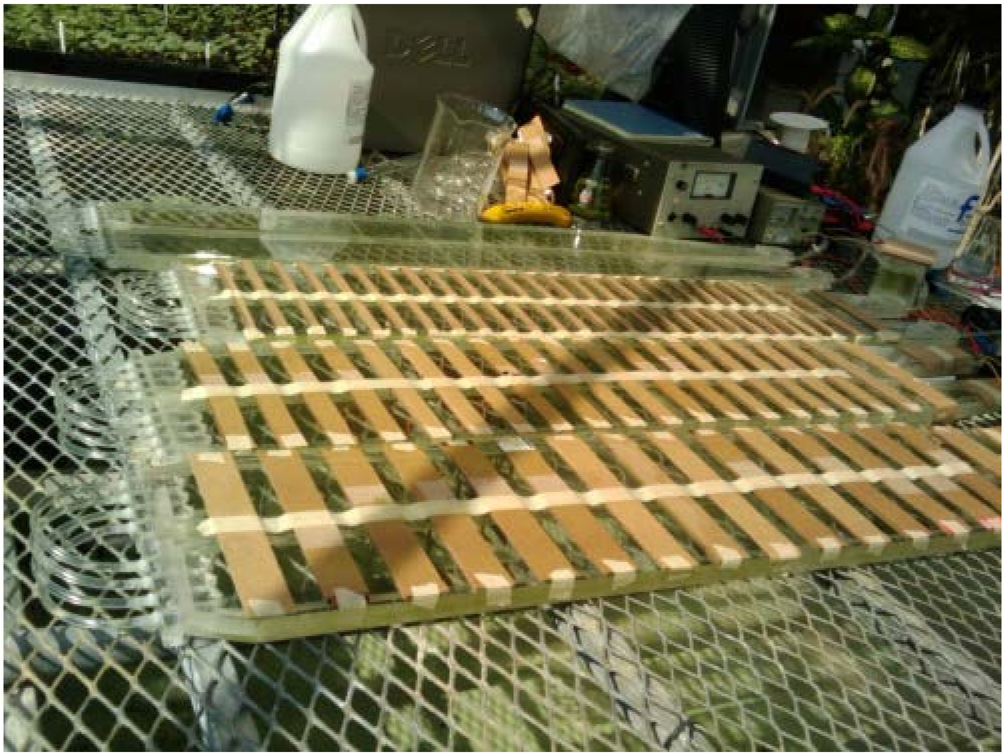

Figure 6: Larger Algae Bioreactor system. From [1].

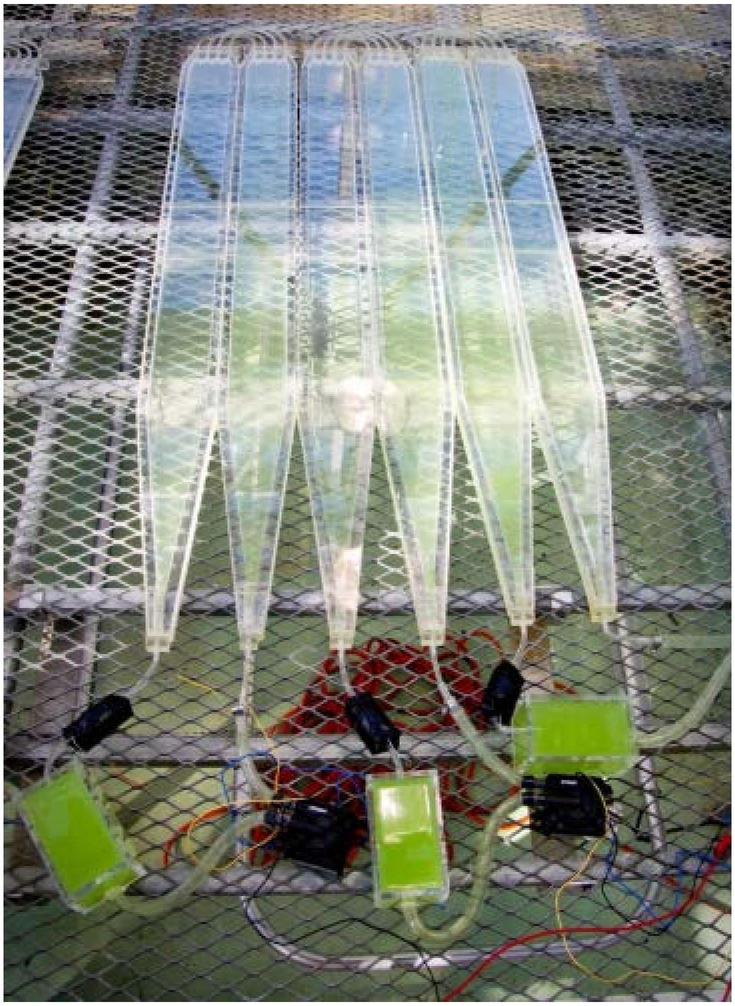

Figure 7: Alternative larger Algae Bioreactor system. From [1].

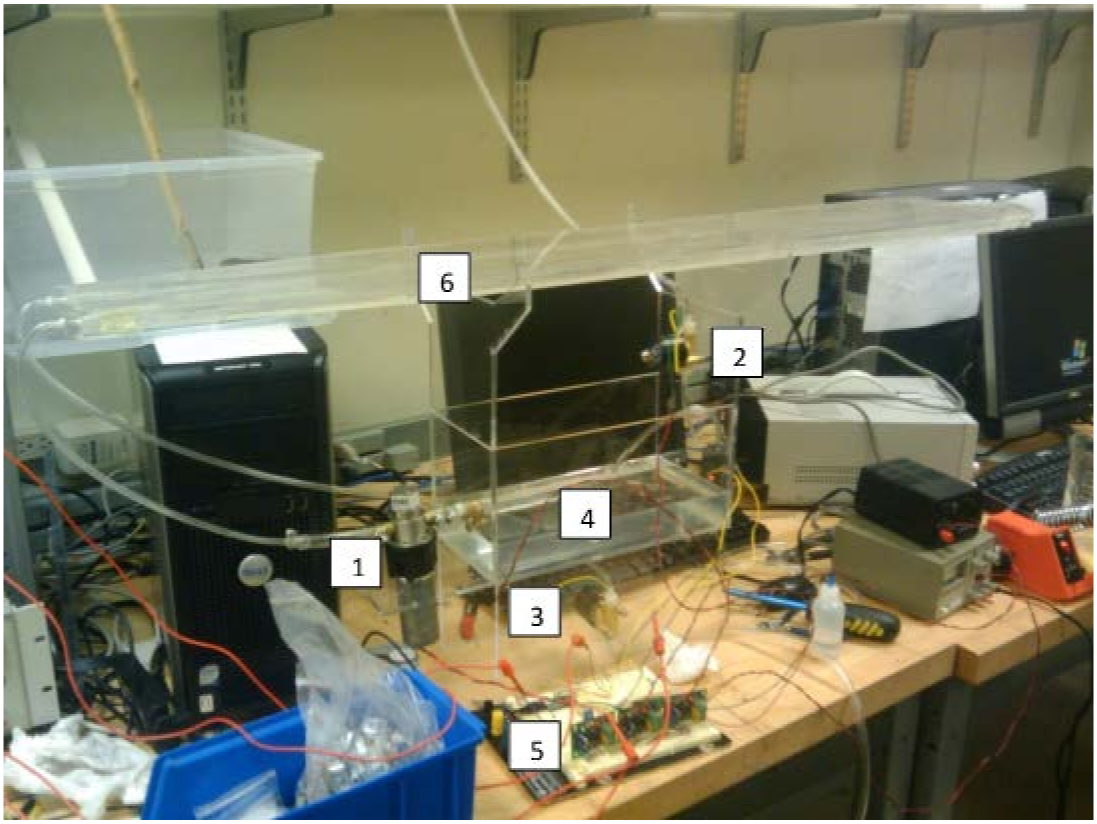

Figure 8: Algae Bioreactor test bed and system development bench showing gasifier (1), sensor (2), pump (3), flow controller (4), microcontroller (5), and channel (6). From [1].

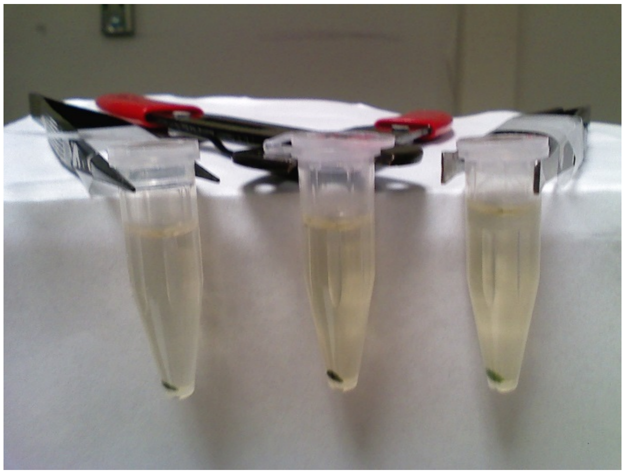

Figure 9: Harvesting Algae in 200 microliter tubes.

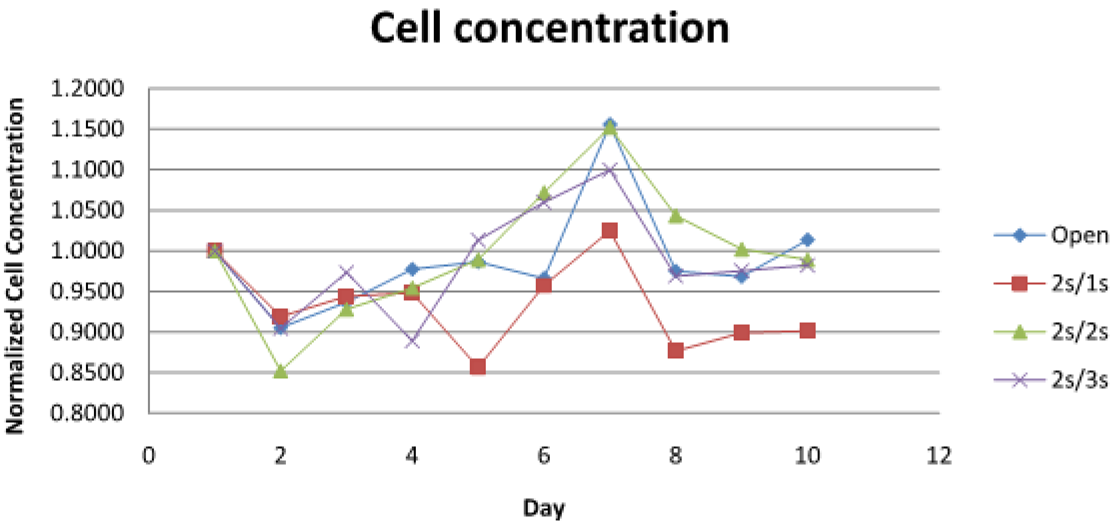

Figure 10: Measuring Algae density in the aquaculture system. From [1].