Photobioreactors for microalgal cultivation

Sergei A. Markov, PhD

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About myself

• Started research on **algae** more than 30 years ago

• Lomonosov Moscow State University, Russia

• King’s College London, University of London

• National Renewable Energy Laboratory (U.S. Department of Energy)

• Currently:
  • Professor at Austin Peay State University, TN, USA
What is microalgae?

- Microalgae (microscopic algae) are mainly photosynthetic microorganisms similar to plants.
Algae bloom: nuisance, pond scum
Algae bloom again: algae in news
Here Comes Algal Power
Practical use of algae

• Microalgae can be used as animal feed, medicine, and fertilizer.
• They also are used in production of chemicals.
Microalgae as a food
Applications of algae in our lab

- Biofuels generation (H₂ and biodiesel)
- Wastewater clean up
- CO₂ mitigation
What are biofuels?

- Biofuels are renewable fuels generated from living things or by living things.
- Algae can be used to generate a number of biofuels, including biodiesel, hydrogen ($\text{H}_2$), and methane.
Hydrogen as biofuel

• Molecular hydrogen is an ideal fuel to be used for transportation.

• Energy content of hydrogen is three times greater than in gasoline and four times higher than in ethanol.

• The hydrogen power was running NASA’s space rockets for many years.

• Hydrogen-powered cars.
Customers are willing to pay for hydrogen cars
Why algal H₂ production?

The problem is to find a way to produce H₂ cheaply and environmentally friendly. Algal hydrogen could be an alternative to the industrial methods of H₂ production.

Algae produce H₂ from water using solar light as an energy source.

\[ \text{H}_2\text{O} \rightarrow \text{H}_2 + \text{O}_2 \rightarrow \text{H}_2\text{O} \]
Biodiesel from algae?

• Biodiesel is a diesel substitute currently being obtained mainly from vegetable (crops plant) oil.
• It is produced by transesterification of oils and lipids.
Biodiesel from algae

- Biodiesel from crops cannot realistically satisfy even a small fraction of the existing demands for fuels.
- It is possible to make biodiesel from oil extracted from algae.
- **Algae use oil** (lipids) as a storage material.
Growing algae in ponds

• You can grow algae in ponds, but be aware. This creates several problems: contamination by other microbes, predators, vulnerability to temperature fluctuations, inefficiency, etc.

• Only few algal species can be successfully grown in ponds
Mass Cultivation of algae in ponds

- The most widespread industrial microalgal cultivation system currently in use is the open raceway pond.
- Its low volumetric productivity of about 0.08 g biomass per liter per day is due to the rapidly decreasing light supply with increasing culture depth and density.
Photobioreactors

• Photobioreactors are various types of closed systems made of an array of transparent tubes or even plastic bags, in which microalgae are cultivated under controlled conditions.

• The main purpose of a photobioreactor is to improve growth of algae for practical applications.
Photobioreactors for algal biomass production (*Chlorella and Spirulina*)

1. Lipid concentrate was used as a biologically active additive to shampoos, medical preparations for the treatment of wounds and burns,

2. Protein concentrate was used as biologically active additive to creams and hair and skin lotions,

3. The third product contains up to 25% of nitrogen compounds and was used as feed for fish, poultry and cattle.

Photobioreactor in Russia in 80s
Photobioreactors

• The photobioreactor should be simple, inexpensive, with high volumetric productivity, energy efficient, and scalable to industrial applications.
Algal photobioreactor needs

- Light
- CO$_2$
- Optimal temperature
- Mineral nutrients

The main **challenge** in photobioreactor design and development is to achieve the efficient supply of CO$_2$ (carbon source for algae) and light (energy source for algae) which are both needed for algal growth.

The temperature control is another issue which needs to be deal with.
Bubble column photobioreactors for algal $\text{H}_2$ production

- They are generally tubular vessels. Other than a sparger for entry of compressed air/$\text{CO}_2$, bubble columns have no internal structures.
- Perforated plates are sometimes installed in bubble columns to break up and redistribute bubbles.
- Advantages of bubble columns include low capital cost, lack of moving parts, and *satisfactory mass-transfer performance*.  

Spiral PVC tubular photobioreactor (popular in 90s) for $\text{H}_2$ production by *Anabaena variabilis*

The photobioreactor’s algal suspension can be bubbled with a mixture of $\text{CO}_2$ and air to supply the cells with a carbon source and remove $\text{H}_2$.

Schematic diagram of a PVC spiral tubular photobioreactor for $\text{H}_2$ photoproduction by an *A. variabilis* mutant
Two-stage photobioreactor with computer control (from Sartorius AG)
Computer-controlled algal bioreactors

The productivity of a bioreactor might be increased by varying of the concentration of supply gases including CO₂, N₂, and O₂. Continuous H₂ photoproduction by cyanobacterium *Anabaena variabilis* PK84 was shown in a stirred tank bioreactor in which gas delivery is controlled by computer.
How much $\text{H}_2$ can algae produce?

- Algae: up to 20 ml $\cdot$ g dw$^{-1} \cdot$ h$^{-1}$
- Purple bacteria: up to 700 ml $\cdot$ g dw$^{-1} \cdot$ h$^{-1}$
- Hydrogen by fermentation: up to 1600 ml $\cdot$ g dw$^{-1} \cdot$ h$^{-1}$
Making biodiesel from... algae?
Algal biodiesel: scope of our work
Tubular PVC photobioreactor

Made from clear PVC 10 feet tubes (6’ diameter) with a small slope (10%). Volume 100 L. Inexpensive (under $300).
Tubular PVC photobioreactor
Plastic bag photobioreactor

Photobioreactors to grow green microalgae *Neochloris oleoabundans* (Neo) under artificial and natural illumination. CO$_2$ was supplied under elevated pressures. We exceeded our expectations by obtaining higher volumetric productivity values (3-4 g dry weight per L per day) compared to volumetric productivity data from other microalgae reported in the published papers.
Carbon dioxide and algae

Figure 2  $H_2$ and $O_2$ photoproduction and net CO$_2$ uptake (CO$_2$ uptake minus CO$_2$ production) by 33-day-old *Anabaena variabilis* as a function of CO$_2$ concentration in the gas phase of reaction vials.
The floating-type, plastic bag photobioreactor
The floating-type, plastic bag photobioreactor
Algal photobioreactors for water depollution

• The pollution of streams and rivers by inorganic nitrogen and phosphorus ions is increasingly posing an environmental concern.
  • Ammonium ion
  • Nitrate
  • Phosphate
• High level of inorganic nitrogen and phosphorus in water can cause a negative environmental impact through the process of eutrophication
The use of algal cascade-type systems in wastewater treatment in 80s.
Ammonium and nitrite ion uptake by immobilized alga *Anabaena variabilis* in a photobioreactor.
Ammonium and nitrite ion removal from water by alga *A. variabilis*

- Ammonium ion uptake efficiency in the photobioreactor was found to be 88% after 20 days.

- Nitrate uptake efficiency by microalgae in a photobioreactor was found to be 70% after 8 days.
Conclusion

• Microalgal photobioreactors can be used simultaneously for different practical applications:
• From CO$_2$ mitigation to waste water treatment to production of food and chemicals and for generation of energy
Sustainable biorefinery for generation of an array of biofuels and other products by sequential use of photosynthetic microorganisms in photobioreactors.

CO$_2$ Floating-bag photobioreactor on a surface of a pond

Recycle nutrients/water

Biodiesel

H$_2$

Animal feed cosmetics

biogas

Solvent recycling

Austin Peay State University
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