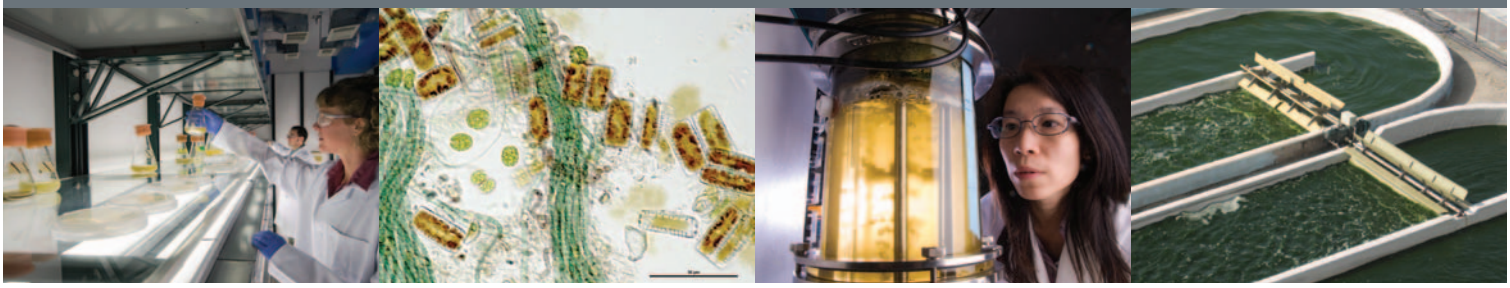
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Algal Biofuels R&D at NREL

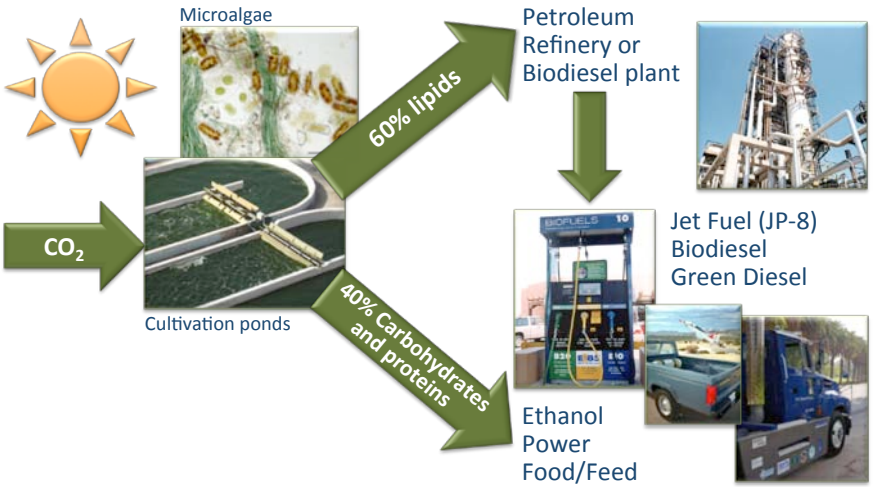


Algal Biofuels

NREL is aggressively pursuing algal biofuels projects with national and international partners, as well as a number of internally funded projects through its Laboratory Directed Research and Development (LDRD) program. With these projects, NREL is addressing challenges that are critical to achieving an economic algal biofuels production process.

Algal Biofuels

Microalgae, photosynthetic microorganisms capable of converting atmospheric CO_2 to biomass and oil, offer great promise to contribute a significant portion of the renewable fuels mandate. Soaring energy demand in developing nations is beginning to create intense competition for the world's dwindling energy resources. The current algal biofuels program at NREL builds on expertise and knowledge acquired during the Aquatic Species Program, a U.S. Department of Energy (DOE) funded research effort established in 1978, specifically investigating microalgal biofuels. Despite significant progress, the program was discontinued. In the last four years, NREL has continued this algal research.



Summary of the current algal biomass-to-biofuels product streams (adapted from Pienkos and Darzins, 2009)

Promises

Microalgae offer great promise to contribute a significant portion of the renewable fuels mandate. The main advantages of algal biomass-derived biofuels include:

- High per-acre oil productivity
- Use of non-arable land
- Use of a wide variety of water sources
- Mitigation of GHG emissions
- Production of both biofuels and valuable coproducts.

Challenges

Despite the huge potential of microalgae as biomass feedstocks for advanced biofuels, the technology is still facing major challenges associated with technical and economic barriers:

- Feedstock supply; developing suitable algal strains and cultivation parameters
- Feedstock logistics; harvesting and extraction of the oils from algal biomass
- Techno-economic analysis of different algal biofuels processes.

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Algal Biofuels Projects and Partnerships

NREL is currently involved in several algal biofuels projects addressing different aspects of algal biofuels research and development.

Establishment of a Bioenergy-Focused Microalgae Strain Collection Using Rapid, High-Throughput Methodologies

C2B2 Profit From Our Synergy Colorado Center for Biorefining and Biofuels

- University of Colorado
- Colorado State University
- Colorado School of Mines
- National Renewable Energy Laboratory

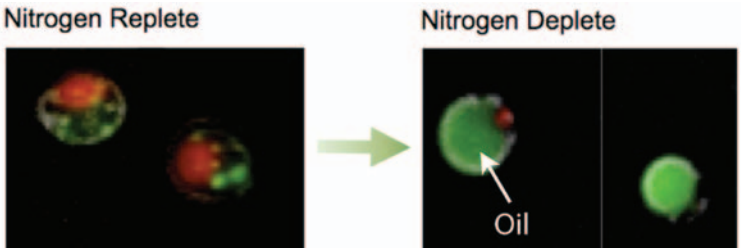
A seed grant from the Colorado Center for Biorefining and Biofuels (C2B2) is being used to discover new novel microalgae strains that can be used for biofuels and bioproducts applications. This project has isolated novel microalgal strains using high-throughput methods and generated a culture collection that is now being screened for isolates with high growth and lipid accumulation properties. Partner: Colorado School of Mines.

Development of Algal Strains

NREL and Chevron Corp. are collaborating to develop techniques to improve the production of liquid transportation fuels from microalgae.

Molecular Foundations of Algal Biofuel Production: Proteomics of Algal Oil Production

NREL is working with the U.S. Air Force Office of Scientific Research (AFOSR) to perform a proteomics analysis of an oil accumulating green algal strain. This basic research will answer fundamental algal biology questions regarding oil production that could lead to the development of cost-effective, algal-based jet fuel. Partner: U.S. Air Force Office of Scientific Research. For more on algal-based jet fuel, see the proceedings and presentations from the February 2008 NREL/AFOSR Workshop on Algal Oil for Jet Fuel Production: www.nrel.gov/biomass/algal_oil_workshop.html.



Development of a High-Performance Computational Framework for Combinatorial Systems Biology

NREL is constructing chemically detailed metabolic models and parallel software to sample, fit, and optimize network behaviors of algae in the space of model parameters such as enzyme concentrations and kinetic constants. The modeling is focused on biofuel production in the green alga *Chlamydomonas reinhardtii*. Partners: Colorado School of Mines, Carnegie Institute (Stanford), with support from the DOE Office of Advanced Scientific Computing Research and Office of Biological and Environmental Research.

Techno-Economic Assessment of Algal Biofuels Processes

Several projects study the viability of algae as a biofuels feedstock in the context of resource availability and techno-economic barriers and opportunities. Partners: DOE, Environmental Protection Agency (EPA), Sandia National Laboratories, Solix, New Mexico State University.

Identification of R&D Activities to Accelerate Commercialization of Algal Biofuels

NREL and Sandia National Laboratories worked with DOE to identify and prioritize R&D needs for commercialization of algal biofuels. The labs and DOE hosted the Algal Biofuels Workshop in December 2008 and invited experts in biology, systems and process engineering, modeling and analysis, algae cultivation, algal oil extraction and conversion, algal-based co-products, water and land use, and policy and regulatory issues. Participants helped draft the roadmap by identifying activities needed to work toward commercial-scale algal biofuel production. The roadmap is now published and can be downloaded from www1.eere.energy.gov/biomass/pdfs/algal_biofuels_roadmap.pdf.

Sustainable Algal Biofuels Consortium (SABC)

NREL is part of a DOE-funded consortium that will focus on testing the acceptability of algal biofuels as replacements for petroleum-based fuels. Specific tasks include investigating biochemical conversion of algae to fuels and products and analyzing physical chemistry properties of algal fuels and fuel intermediates. NREL is currently negotiating with DOE about the scope of this work and the partners involved. The Core Team consists of Arizona State University, NREL, and Sandia National Laboratories. Details can be found at apps1.eere.energy.gov/news/progress_alerts.cfm/pa_id=359.

Integrated Biorefinery (IBR)

NREL is part of a collaborative agreement with Algenol Biofuels and the Dow Chemical Company as part of an integrated pilot scale biorefinery project for the production of ethanol directly from microalgae. Similarly, NREL is collaborating with Solazyme to investigate the pilot scale production of heterotrophic algal biofuels.

Development of Novel Microalgal Production and Downstream Processing Technologies for Alternative Biofuels Application

NREL and Sandia National Laboratories are working under a DOE funded project with the Israel-based algal cultivation company Seambiotic, which is using flue gas from a coal fired power plant for algal growth. In this project, a full life-cycle analysis of the algae-to-biofuels process will be performed. Furthermore, this project is designed to develop, test, and evaluate cost-effective oil extraction methods as well as to determine the feasibility of using proven thermochemical conversion technologies to transform algal biomass into fuel (or related intermediate products).

Isolation, Characterization, and Preliminary Assessment of Scale-Up Potential of Algae for the Production of Biofuels in the United States and Canada

NREL, Sandia National Laboratories, Pacific Northwest National Laboratory and the National Research Council of Canada are working together on this DOE-funded project to further the development of algal-based biofuels in northern latitudes. NREL is using high-throughput fluorescence activated cell sorting capabilities to isolate algal strains from water samples taken from a variety of northern marine and freshwater habitats.

Efficient Use of Algal Biomass Residues for Biopower Production with Nutrient Recycle

NREL is investigating the optimization of biogas production from algal residues via anaerobic digestion. In this project, researchers want to understand effluent treatment requirements and the fate and bio-availability of nitrogen and phosphorus following anaerobic digestion as well as test the ability of recycled nutrients to support algal growth. Partner: Washington State University.

Algal Biofuels LDRD Projects

Each year, following a competitive process, NREL awards Laboratory Directed Research and Development (LDRD) funding to in-house projects designed to advance NREL's technical competencies. Among the recent LDRD projects are several focused on algal biofuels development.

Development of a Comprehensive High-Throughput Technique for Assessing Lipid Production (2008)

There is a need for a fast and non-destructive method to measure lipids in algae, for example to select improved strains or identify high-lipid-producing strains in a bioprospecting project. NREL researchers have demonstrated the application of infrared spectroscopy (NIR and FTIR) for algal lipid quantification in dried biomass as well as in growing cultures. Using multivariate calibration models we can now estimate lipid levels in algal strains in a matter of seconds as opposed to days of wet chemical analyses.

Development of a Genetic Model for Biodiesel from Cyanobacteria (2009)

NREL is working to establish a genetic model in a cyanobacterium for solar biodiesel production. The goal of this project is to redirect carbon fixed in photosynthesis toward lipid accumulation. This approach involves blocking glycogen synthesis and other non-essential carbon utilization pathways to focus metabolism primarily for triacylglycerol synthesis.

Use of Digital Gene Expression: Tag Profiling for High-Throughput Transcriptomics in Microbial Strains Involved in Advanced Biofuel Production (2009)

NREL is evaluating the utility of high-throughput transcriptomics analysis of microbial strains relevant to advanced biofuel production using the Illumina Genome Analyzer, a novel gene sequencing technology. Transcriptomics is the study of gene expression patterns that vary with external environmental conditions. This technology will provide NREL with information that can be used for the identification of genes and pathways involved in biofuel production.

Evaluation of Regulated Enzymatic Disruption of Algal Cell Walls as an Oil Extraction Technology (2010)

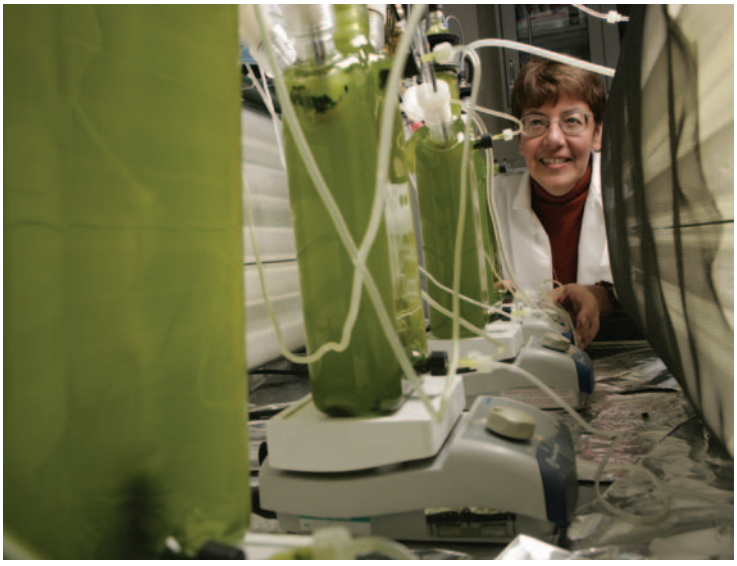
This project evaluates cell-wall-degrading enzymes that can disrupt algal cell walls sufficiently to allow internal oil bodies to escape and be easily harvested. This technology could be a simple and economic option for recovery of lipids from algal biomass, currently a major economic hurdle.

Identification of Novel Promoters in Green Algal Species (2010)

NREL is working to identify promoter gene sequences isolated from a green algal species and is taking advantage of the sequencing information of the chloroplast genome to increase lipid production. This work will expand the genetic tool box for green algal systems.

Development of Novel Cyanobacterial Biofuels (2010)

NREL researchers are studying metabolic pathways in a model unicellular photosynthetic microbe to establish strategies to enhance the synthesis of next-generation renewable biofuels. This project is designed to develop a comprehensive understanding of carbon pathways and their regulation in photosynthetic organisms.



Investigation of Biomass Productivity and Lipid Content in Green Algae Constitutively Expressing a Novel Lipid-Producing Pathway (2011)

One of the major limitations for biodiesel production is the fact that green algae can either grow or accumulate lipids, but are unable to do both simultaneously. NREL researchers are investigating the effect of introducing a novel metabolic pathway on biomass production and concomitant lipid accumulation.

Developing Compositional Analysis Methods to Compare Microalgae-to-Biofuel Processes (2011)

NREL researchers are developing methods for the analysis of biofuel process-relevant components in algal biomass. These methods will allow researchers to assess the efficiency of the overall algal biofuels production process through the use of techno-economic analyses of commercially proposed processes. This will keep NREL at the forefront of compositional analysis of novel feedstocks.

Conclusions

Past work has provided a solid foundation for algal biofuels research, making it possible for NREL to rebuild the Aquatic Species Program, though in a very different form.

Production of fuels from algae has been demonstrated.

- Algae can be grown and harvested
- Lipids can be extracted and converted to transportation fuels.

However, can algal biofuels be made economically and sustainably at a scale to help contribute to U.S. fuel demand?

What's needed:

- Greater understanding of the underlying biological and engineering principles before commercial scale-up is feasible
- Fundamental/applied R&D
- Coordinated support from relevant government agencies, private sector, academia, and stakeholders.

Sheehan et al. (1998) presaged the current revival in this field, concluding the ASP close-out report with the following:

" … this report should be seen not as an ending, but as a beginning. When the time is right, we fully expect to see renewed interest in algae as a source of fuels and other chemicals. The highlights presented here should serve as a foundation for these future efforts."

Selected Publications

Sheehan, J.; Dunahay, T.; Benemann, J.; Roessler, P. (1998). "A Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from Algae." Close- Out Report. Golden, CO: National Renewable Energy Laboratory.

Hu, Q.; Sommerfeld, M.; Jarvis, E.; Ghirardi, M.; Posewitz, M.; Seibert, M.; Darzins, A. (2008). "Microalgal Triacylglycerols as Feedstocks for Biofuel Production: Perspectives and Advances." *The Plant Journal* (54); pp. 621-639.

Pienkos, P. T.; Darzins, A. (2009). "The Promise and Challenges of Microalgal-Derived Biofuels." *Biofuels, Bioproducts and Biorefining* (3:4); pp. 431-440.

Weyer, K. M.; Bush, D. R.; Darzins, A.; Willson, B. D. (2010). "Theoretical Maximum Algal Oil Production." *BioEnergy Research* (3:2), pp. 204-213.

Laurens, L. ML.; Wolfrum, E. J. (2010). "Feasibility of Spectroscopic Characterization of Algal Lipids: Chemometric Correlation of NIR and FTIR Spectra with Exogenous Lipids in Algal Biomass." *BioEnergy Research*; DOI: 10.1007/s12155-010-9098-y.

Greenwell, H. C.; Laurens, L. ML.; Shields, R. J.; Lovitt, R. W.; Flynn, K. J. (2009). "Placing Microalgae on the Biofuels Priority List: A Review of the Technological Challenges." *Journal of the Royal Society Interface* (7:46); pp. 703-726.

Radakovits, R.; Jinkerson, R. E.; Darzins, A.; Posewitz, M. C. (2010). "Genetic Engineering of Algae for Enhanced Biofuel Production." *Eukaryotic Cell* (9); pp. 486-501.

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Algal Biofuels R&D
www.nrel.gov/biomass/proj_microalgal_biofuels.html

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