

# BIOMIMETIC NANOTECHNOLOGIES

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## Abstract

Examples are given of work underway within the Center for Sustainable Ecosystem Nanotechnologies that is using biomimicry as the method for applying nanoscale materials, structures and devices to problems involving sustainable systems. Specific applications of biomimicry are given in the areas of artificial photosynthesis and the bio-fouling of surfaces. Future work using biomimetic nanotechnologies is described.

**Keywords:** Sustainability, ecosystems, nanotechnology, biomimicry, artificial photosynthesis, anti bio-fouling

## Introduction

Sustainable ecosystem nanotechnologies, or nanotechnologies designed to ensure the sustainability of ecosystems, must be "eco-logical". They should be designed and adapted to make certain that they are sustainable within the ecosystem to which they are applied. Logically, if they are designed on the basis of natural counterparts, mimicking nature, they are sustainable.

The term for this ecological design is biomimicry, the art and science of mimicking nature's way of performing similar functions. Janine Benyus, one of the early thought leaders and champions of using ecological design, describes biomimicry as "a way of seeking sustainable solutions by borrowing life's blueprints, chemical recipes, and ecosystem strategies." Biomimetic products and processes mimic not only nature's forms and function, but also their adaptation to the environment in which they will be created, sustained and retired.

Examples of biomimicry abound. Hulls of boats imitate the thick skin of dolphins. Some current sonar, radar and medical ultrasound imaging technologies imitate the echolocation of bats. In the field of computer science, the study of bionics has produced artificial neurons, neural networks and swarm intelligence. Evolutionary computation took the idea of biomimicry even further by simulating evolution using computers, and producing well-optimized solutions that have not yet appeared in nature.

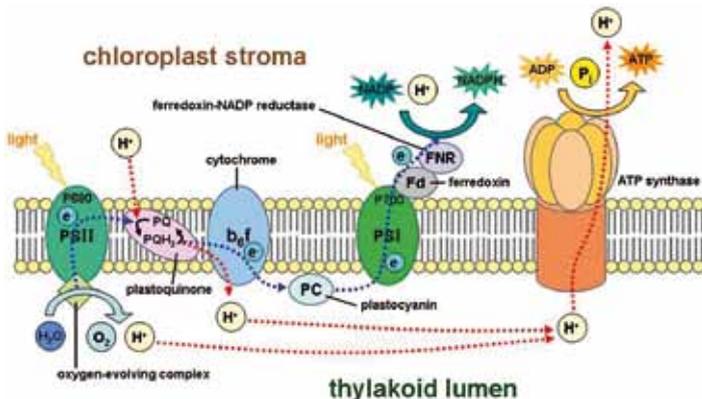


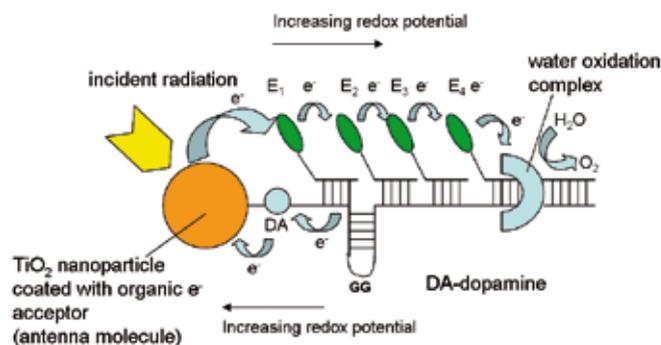
Figure 1. Light-dependent reactions of photosynthesis

It is becoming increasingly clear that the greatest opportunities for applying biomimicry are found at the nanoscale, where the properties of materials differ greatly from those in bulk form, and where the majority of nature's physical, biological and electrochemical processes occur.

In photosynthesis, for example, two processes occur: the so-called "light-dependent reactions" in which light energy is converted into chemical energy in the form of the energy carriers ATP and NADPH, and the "light-independent reactions," in which these formed products help sequester CO<sub>2</sub> from the atmosphere in the form of organic compounds such as glucose.

In the light-dependent reactions, illustrated in Figure 1, photons are absorbed through proteins containing pigments ("light harvesting complexes") which bundle different pigments together to enable absorption over a wide part of the spectrum. This absorption puts electrons into an excited state, thereby allowing them to transfer from one molecule to another through an electron transport chain. The rate of this electron transfer process ("resonance energy transfer") depends strongly on the distance between each donor and acceptor in the chain. In order to have charge separation, nature designs it so that the next electron acceptor is within one nanometer of the previous link.

In this process, the final electron acceptor is NADP and the first electron donor is water.



**Figure 2.** Schematic of the self-assembled oxygen evolution complex (OEC). Arrows indicate the direction of electron transfer. The orange component represents the light absorber, the green components represent the series of electron acceptors conjugated to short DNA strands, and the water oxidizing complex is shown assembled onto the long charge transfer DNA sequence.

The process by which water is split in the oxygen-evolving complex to release electrons, protons and oxygen is the subject of intense research.

### Development (Methods/Results)

Work within the Center for Sustainable Ecosystem Nanotechnologies (CSEN) at the College of Nanoscale Science and Engineering (CNSE) of the University at Albany is employing biomimicry in a variety of applications. For instance, one of our most interesting efforts to date is the work of CSEN's Dr. Tulika Dalavoy in the development of microscale energy production by mimicking the process of photosynthesis described above.

This work at CSEN is through a collaboration with, and under the leadership of, the Engineer Research and Development Center (ERDC) of the U.S. Army Corps of Engineers. The overall effort focuses on generating hydrogen at the microscale using only sunlight and water to provide power to small portable devices.

"Production of hydrogen from protons will be accomplished using hydrogenase enzymes and synthetic mimics."

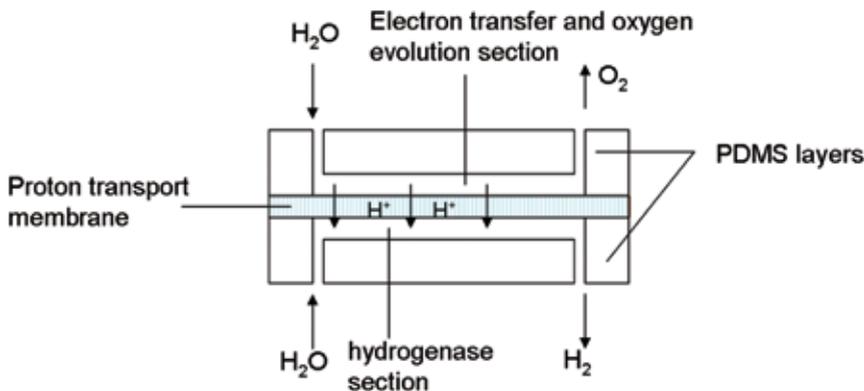
The project uses fundamental chemistry principles to design an artificial biological photosynthetic system for controlled generation of hydrogen fuel. It can also be used to convert atmospheric CO<sub>2</sub> to liquid fuels. The overall approach is to construct an artificial photosynthetic system based upon existing knowledge of the photocatalytic water splitting process (Photosystem II). The program fabricates novel electron transfer and oxygen evolution complexes (OECs) using self-assembling DNA-chromophore systems. The idea is to replicate the independent yet interactive biochemical steps in photosynthesis as a model system to parse complex functions into discrete units that can be fabricated, studied independently, and then integrated into a complete micro-fluidic system on a chip. A schematic of the self-assembled oxygen evolution complex is shown in Figure 2.



**Figure 3.** Using a Rotating Ring Disk Electrode, Adam Lemke conducts leading-edge research at CNSE's Center for Sustainable Ecosystem Nanotechnologies.

topography on bio-fouling. By using photo-lithographic patterning techniques, Dr. Cady has formed topographic features, including pillars, holes, lines and trenches, on silicon wafers. These features were then used as a template to imprint silicone-based poly dimethylsiloxane (PDMS). These PDMS molds, in turn, are used as templates to form replicas in other materials, or used directly for bio-fouling studies. Dr. Cady and his researchers have found that the attachment of bacteria such as *E. coli* to polymeric surfaces is drastically reduced as the topographical feature size is reduced, as shown in Figure 5.

These preliminary results have led to the development of a high-resolution molding method to fabrication of features in biologically relevant polymers and to incorporate them into microfluidic devices to enable the evaluation of bacterial adhesion



**Figure 4.** Schematic of microfluidic artificial photosynthesis device.

In addition to the OEC, a biomimetic proton transfer interface will be developed so that it can be self assembled in a microfluidic platform. The device will serve as a pump for protons generated by the OEC. A simplified schematic of the microfluidic artificial photosynthetic device is shown in Figure 4. Production of hydrogen from protons will be accomplished using hydrogenase enzymes and synthetic mimics.

Another CSEN activity involves addressing the development of anti-bio-fouling surfaces. Preventing bacterial adhesion and attachment to surfaces is critical for the reduction of the spreading of disease and infections. It is well documented that bacterial adhesion to surfaces is mediated by the physical and chemical properties of the substrate, as well as the surface characteristics of the organism. CNSE Professor Nate Cady's group is conducting a systematic study of the effect of surface

topography dramatically alters bacterial attachment, which could lead to the development of low adhesion, anti-fouling surfaces for biomedical applications. Research in multiple laboratories has shown that the skin, scales and shells of marine organisms have innate bio-fouling properties that can prevent the settling and attachment of microorganisms<sup>[1,2,3,4]</sup>.

Consequently, using a biomimetic approach, Dr. Cady and his team plan to

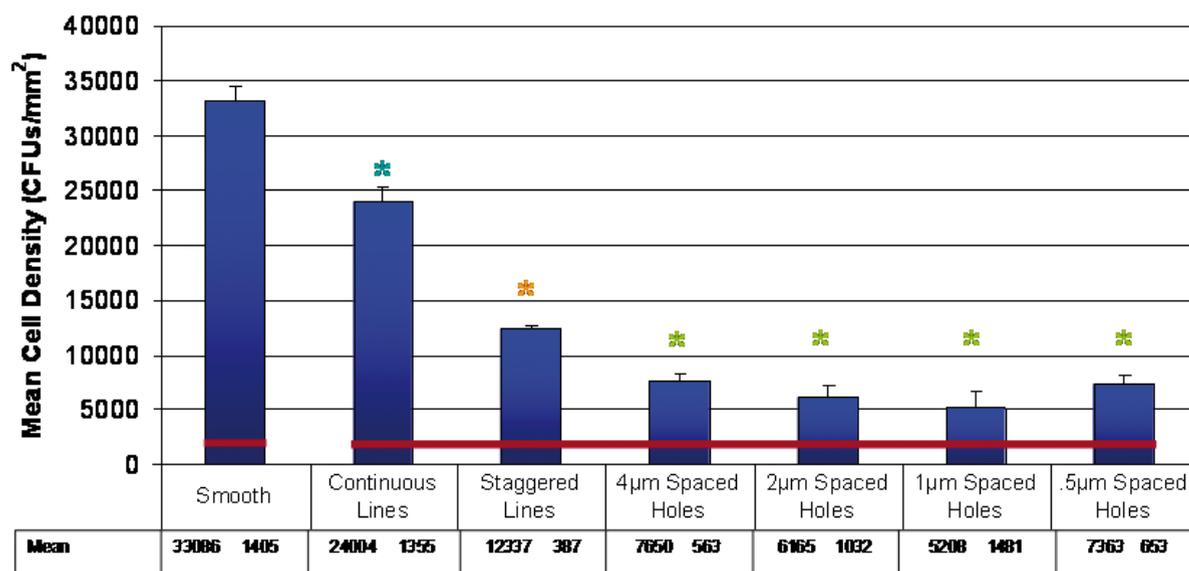


Figure 5. Cell attachment to PDMS surfaces of varying topography.

further study the micro- and nanoscale topography of both marine and freshwater organisms for continued development of anti-fouling surfaces.

Additional CSEN research projects include addressing sustainable ecosystem nanotechnologies for solar cells, batteries, and fuel cells. One solar project is a funded grant to examine the feasibility of very low-cost, large-scale manufacturing of dye-sensitized solar cells, a biomimetic approach to harvesting light by attempting to mimic the light reactions mentioned above. Another CSEN solar project is studying the photophysics of carbon nanotubes, attempting to mimic the efficiency of light-harvesting machinery in photosynthesis.

By making the most sensitive photovoltaic diode using a single carbon nanotube CNSE Professor Dr. Ji Ung Lee is trying to attach light-harvesting molecules that will capture photons and funnel their energy to the nanotube, which converts electrical power. Research has recently begun on rechargeable Zinc/Air batteries, examining nature in order to gain insights on how to improve the bi-functional performance of the air electrode.

## Conclusion

It is important to note that work has been going on in laboratories around the world using “bio-inspired” approaches to address a wide array of design challenges.

For instance, scientists continue to search for earth-abundant, low-cost catalysts for fuel cell reactions involving the oxidation of hydrogen and the reduction of oxygen. Gewirth<sup>[5]</sup> and co-workers are trying to develop non-precious metal catalysts by mimicking the active site of laccase, a protein found in nature that performs near thermodynamic four electron reduction of oxygen to water. Likewise, DuBois, Bullock and others<sup>[6]</sup> are examining the use of nickel, cobalt and manganese complexes for hydrogen oxidation – guided, if not inspired, by the ability of nature to perform these functions efficiently and under mild conditions.



**Figure 6.** Researchers Tulika Dalavoy and Phil Chow use a Scanning Electrochemical Microscope as part of CNSE's Center for Sustainable Ecosystem Nanotechnologies.

Bio-inspired design represents an exciting trend toward respecting nature and our environment. Using biology as design inspiration, bio-inspiration is a step toward appreciating nature's 3.8 billion years of design expertise.

Using nature as a model, mentor and measure, as Janine Benyus defines biomimicry, is a leap toward true sustainability. **e**

## References

1. Carman, M. L., T. G. Estes, A. W. Feinberg, J. F. Schumacher, W. Wilkerson, L. H. Wilson, M. E. Callow, J. A. Callow, and A. B. Brennan. 2006. Engineered antifouling microtopographies—correlating wettability with cell attachment. *Biofouling* 22:11-21
2. Schumacher, J. F., M. L. Carman, T. G. Estes, A. W. Feinberg, L. H. Wilson, M. E. Callow, J. A. Callow, J. A. Finlay, and A. B. Brennan. 2007. Engineered antifouling microtopographies - effect of feature size, geometry, and roughness on settlement of zoospores of the green alga *Ulva*. *Biofouling* 23:55-62.
3. Granhag, L. M., J. A. Finlay, P. R. Jonsson, J. A. Callow, and M. E. Callow. 2004. Roughness-dependent removal of settled spores of the green alga *Ulva* (syn. *Enteromorpha*) exposed to hydrodynamic forces from a water jet. *Biofouling* 20:117-22.
4. Callow, M. E., Jennings, A.R., Brennan, A.B., Seegert, C.E., Gibson, A., Wilson, L., Feinberg, A., Baney, R., Callow, J.A. . 2002. Microtopographic cues for settlement of zoospores of the green fouling alga *Enteromorpha*. *Biofouling: The Journal of Bioadhesion and Biofilm Research* 18:229-236.
5. Gerwith, A.A., Kenis, P.J.A., Martinez, T., Nuzzo, R.G. Rauchfuss, T.B., DoE Annual Merit Review Meeting, BES007, 2010. ([http://www.hydrogen.energy.gov/annual\\_review10\\_bes.html](http://www.hydrogen.energy.gov/annual_review10_bes.html))
6. Rakowski DuBois, M., DuBoise, D.L., A Modular Approach to the Development of Molecular Electrocatalysts for H<sub>2</sub> Oxidation and Production Based on Inexpensive Metals, In *Catalysis Without Precious Metals*, Bullock, R.M.,(Ed), Wiley-VCH, Weinheim, Germany, to be published in 2010.