Progress and Plans of National Nanotechnology Initiative (NNI) Agencies

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U.S. Department of Agriculture (USDA)[1]

National Institute of Food and Agriculture (NIFA)

Summary

The NIFA nanotechnology portfolio will continue providing national leadership and investments in research, education, and extension activities through its extramural funding instruments. NIFA advances nanoscience and nanotechnology for addressing significant societal issues such as sustainable agricultural production, food and nutrition security, food safety and biosecurity, the bio-based economy, water and other natural resources, and environmental and ecological systems. The program also supports risk assessment and management, as well as public engagement and communication about nanotechnology and nanotechnology-enabled products.

Plans and Priorities by Program Component Area (PCA)

PCA 1. Nanotechnology Signature Initiatives (NSIs) and Grand Challenges

1a. Nanomanufacturing NSI

NIFA's sustainable nanomanufacturing effort will continue to focus on nanobiomaterials derived from crops, woods, and other biomass-based agricultural by-products. The program supports novel uses and high-value-added uses of nano-biomaterials from agricultural and forest origins for food and industrial applications. There are ongoing efforts in synthesis of carbon-based nanomaterials, development of cost-effective production methods, functionalization and characterization of nanobiomaterials, and exploration of applications of nanocellulose.

1d. Sensors NSI

NIFA will continue to support development of nanoscale sensing mechanisms and smart sensors for reliable and cost-effective early detection of pathogens, allergens, insects, diseases, toxins, and other contaminants in food, plant, and animal production systems, and in water, soil, and the agricultural production environment. The program also supports research in monitoring physiological biomarkers for optimal crop or animal productivity and health. The program seeks to develop cost-effective, distributed sensing networks for intelligent and precise applications of agricultural inputs (e.g., fertilizer, water, and agrochemicals).

1e. Water NSI

NIFA invests in integrated research, education and extension efforts to address the significant problem of irrigation water shortage for sustainable agricultural production. Agricultural water shortage problems arise from deteriorating water quality, groundwater depletion, uncertainties in precipitation, and unsustainable freshwater usage. Food producers are under growing pressure to increase crop production, but also are pressed by issues such as soil salinization, groundwater overdraft, and over-allocation of available surface water. The NIFA effort aims at developing novel detection and treatment technologies, using advanced data-driven decision tools and the "Internet of Things" to enable new smart irrigation systems for broad farming operations, including small and mid-size farms. The goal is to significantly improve agricultural water quality and use efficiency, and to increase the use of alternative water sources for irrigation of fresh produce, decreasing freshwater withdrawals, and closing water use gaps. The effort will train a cohort of transdisciplinary graduate and undergraduate students.

PCA 2. Foundational Research

NIFA continues to advance interdisciplinary nanoscale science, engineering, and technology for solving significant societal challenges facing agriculture and food systems. The scope of investigation ranges from discovery and characterization of novel nanoscale phenomena, processes, and properties relevant and important to agriculture and food; the development of new nanotechnology applications platforms; the exploitation of bio-nano interfaces, hybrid bioinorganic systems, systems biology, and additive manufacturing technology; and the investigation of broad social, ethical, legal, and other implications that major emerging nanotechnology applications may pose for society, agricultural markets, consumer preferences, and other spaces.

PCA 3. Nanotechnology-Enabled Applications, Devices, and Systems

NIFA nanotechnology efforts support a variety of innovative and applied research to develop nanotechnology-enabled applications, devices, and systems for a wide range of national priorities. The application scope includes early detection and effective intervention technologies for ensuring food safety and biosecurity, more effective therapies to improve animal health and wellness, development of bio-based novel products, and protection of natural resources, the environment, and agricultural ecosystems. Applications, especially those with potential near-term commercial impact, are encouraged to include socioeconomic analyses of anticipated benefits to agriculture, food, and society, and to identify the factors that may contribute to, or hinder, adoption and commercialization. Systems approaches are emphasized, with the convergence of agricultural sciences with engineering, nutritional and food sciences, social sciences, and other disciplines (including nanotechnology, computational sciences, and advanced manufacturing) to generate new scientific discoveries, new products, new markets, and consequently new high-skilled jobs.

Following two previous successful conferences in 2015 and 2018, NIFA is supporting the third Gordon Research Conference on Nanoscale Science and Engineering for Agriculture and Food Systems, to be held June 21–26, 2020. The conference will bring together visionary leaders, scholars, and students from academia, government, and industry around the world to exchange new discoveries and knowledge, inspirational ideas, novel analytical techniques, and new experimental approaches that balance the applications and implications of nanotechnology for sustainable agriculture and food systems. In conjunction with the conference, a Gordon Research Seminar will again be provided as a unique opportunity to foster interactions between graduate students and post-docs and to present and exchange results and cutting-edge ideas in a familiar atmosphere for young scholars. In addition, NIFA is providing support for the 2019 Environmental Nanotechnology Gordon Research Conference and Gordon Research Seminar, to be held June 2–7, 2019.

PCA 4. Research Infrastructure and Instrumentation

NIFA will continue supporting universities to develop new curricula, and develop the future workforce. NIFA's higher education programs support competitive grants to universities for developing nanotechnology curricula for undergraduate and graduate students in agriculture and food science and technology. NIFA's Education and Literacy Initiative (ELI) programs will continue to focus on building institutional capacity and enhancing the pipeline for producing more STEM graduates to meet the projected shortfall in agriculture-related fields.

PCA 5. Environment, Health, and Safety

NIFA supports environmental, health, and safety (EHS) research relevant to agricultural production and food applications. Appropriate EHS assessments of engineered nanoparticles applied in food and agricultural systems include characterization of hazards, exposure levels, and transport and fate of engineered nanoparticles or nanomaterials in crops, soils (and soil biota), livestock, and production environments. The program also supports research on transport and fate of engineered nanoparticles or nanomaterials associated with food production and processing, and on interactions with microbiota in the human gastrointestinal tract.

Key Technical Accomplishments

The following are some selected examples of accomplishments arising from NIFA's nanotechnology research and development investments.

Nanomaterial-Based Platform for DNA Delivery in Plants Without Transgene Integration

Genetic engineering of plants is at the core of sustainability efforts, natural product synthesis, and crop engineering. Unlike most cells, the plant cell has a cell wall, which is a rigid barrier that limits the ease and throughput of exogenous biomolecule delivery to plants. The presence of the cell wall therefore greatly limits the ability to deliver the "tools" of molecular biology: DNA, RNA, and proteins, into plant cells. Existing delivery vehicles cause integration of DNA into the plant genome, yielding a genetically modified organism (GMO). Researchers at the University of California, Berkeley, with support from USDA/NIFA, have demonstrated that carbon nanotubes can be loaded with DNA to deliver genes into intact plants of several agriculturally relevant species (Figure 1). Efficient DNA delivery and strong protein expression was accomplished in tobacco, arugula, wheat, and cotton, without transgenic DNA integration into the plant host genome. This latter result is important because it shows that expression of a foreign protein is possible without GMO labeling of the transformed crop. Furthermore, the researchers found that nanomaterials not only enable non-GMO transport of DNA into plant cells, but the nanomaterials also protect DNA from degradation in the cellular environment. This work provides a tool for species-independent and passive delivery of genetic material, without transgene integration and GMO labeling, into plant cells for diverse biotechnology applications. The work was published in *Nature Nanotechnology*.[2]

[2] https://www.nature.com/articles/s41565-019-0382-5

Figure 1. Carbon nanotubes loaded with DNA to deliver genes into intact plants.
Image credits: Ella Marushchenko (left); Landry Lab, UC Berkeley (right).

Next-Generation Water Quality Sensors

Recent news from Flint Michigan and other areas has raised concerns about water quality. Researchers at the University of Utah, with funding from USDA/NIFA, have developed next-generation water quality sensors using nanostructured materials. Through the design and synthesis of tailored nanostructured polymer composite materials, they were able to interface toxicant-sensing proteins to electrode surfaces (as shown in Figure 2). These electrodes were incorporated in an electrochemical cell to make a portable, self-powered sensor for arsenic in water samples. These sensors harvest energy from the local environment and use it to power the sensor, so battery replacement or electrical re-charging is not needed.

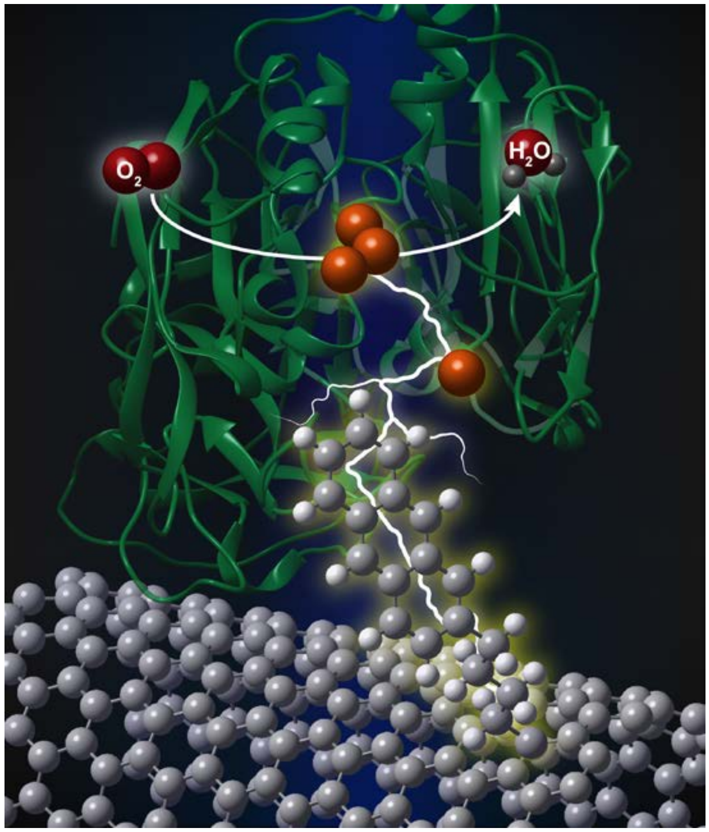

Figure 2. Toxicant-sensing proteins interfaced to nanosensor electrode surfaces.
Image credit: David Hickey, University of Utah.

Engineered Water Nanostructures for Antimicrobial Delivery

A novel nanotechnology-based antimicrobial delivery platform using engineered water nanostructures (EWNS) was developed by researchers at Harvard University. The project was funded by USDA and NIH. These EWNS nanoparticles are synthesized using electrospray and ionization of aqueous suspension of nature-inspired antimicrobials such as citric acid, lysozyme, hydrogen peroxide, etc. The EWNS nanoparticles have unique tunable physico-chemical properties. They have a size in the nanoscale, are highly mobile, and carry an electric charge that can be used to target them on surfaces in order to achieve disinfection by delivering minuscule quantities of nature-inspired antimicrobials and reactive oxygen species (at the nanogram level). They leave no chemical byproducts, nor cause any negative sensory effects. The antimicrobial potency of these EWNS nanoparticles across a variety of microorganisms, including *E. coli*, *Listeria,* and *Influenza* H1N1 virus, to mention a few, was demonstrated using various EWNS-based nanosanitizers synthesized using mixtures of nature-inspired active ingredients. Beyond food disinfection, this technology is has great potential for air disinfection, wound healing, and hand hygiene.

Graphene-Enabled Pesticide Sensing

Researchers from Iowa State University and the Naval Research Laboratory (supported by funding from USDA/NIFA) have developed a scalable manufacturing route of patterning graphene with high resolution while simultaneously constructing multidimensional pores in the graphene surface. In this process, referred to as salt-impregnated inkjet maskless lithography (SIIML), microscale pores (25–50 µm in size) are formed in the graphene surface by using salt crystals as porogens that are incorporated directly in the solution-phase graphene ink. The researchers have demonstrated the use of these graphene electrodes in both electrochemical biosensing and energy storage (supercapacitor) devices. For an agricultural application, the research team demonstrated how this platform can be functionalized with an enzyme for sensitive and selective detection of organophosphate pesticides. The sensor was able to detect concentrations of organophosphates as low as 0.6 nM, well below the tolerable drinking water equivalence levels established by the U.S. and Canadian governments (24 nM and 170 nM, respectively). Hence, the sensor could be used in the farm field or at water treatment facilities to ensure that excessive levels of these insecticides are not found on produce or in drinking water. The manufacturing steps presented in this work can also be performed on virtually any substrate, both flexible and chemically/thermally sensitive. Consequently, this new fabrication technique presents a possible wide-reaching platform technology, with a wide variety of other potential applications including batteries, biofuel/fuel cells, wearable biosensors, or even dye-sensitized solar cells. The work was published in *Nanoscale Horizons*.[3]

Polyviologens as Electron-Transport Material in Photosystem I-Based Photovoltaic Cells

Photosynthesis, the conversion of solar energy into chemical energy, created the ancient organic matter responsible for today's fossil fuels that have sustained our increasing energy consumption. However, the associated greenhouse gas emissions have resulted in several problems such as climate change and environmental pollution. Solar cells made from biological nanomaterials could become a low-resource-intensive and environmentally friendly alternative to traditional solar panels for the production of clean energy. Photosystem I (PSI), one of the two main protein complexes that drive photosynthesis, can be easily extracted from plants, algae, and cyanobacteria. Due to its vast abundance in nature and remarkable photoelectric properties, PSI can serve as the active component within a host of low-cost biohybrid solar cells. In this work, Vanderbilt University researchers supported by NIFA prepared novel PSI-based solar cells by using polyviologens to transport electrons between a layer of PSI proteins and an indium tin oxide (ITO) anode. Polyviologens are a unique class of cationic polymers that can rapidly accept electrons from a primary donor such as PSI and subsequently donate them to another material or electrode. This device exemplifies the direct use of extracted PSI proteins to create photoactive biohybrid electrodes, and represents one of few reported methods for incorporating PSI proteins into a solid-state device. The device maintains its photocurrent for at least a month after fabrication, demonstrating that PSI proteins can exhibit high stability in this solid-state architecture. The work was published in *Langmuir*.[4]

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[3] https://pubs.rsc.org/en/content/articlehtml/2019/nh/c8nh00377g

[4] https://pubs.acs.org/doi/abs/10.1021/acs.langmuir.8b02967