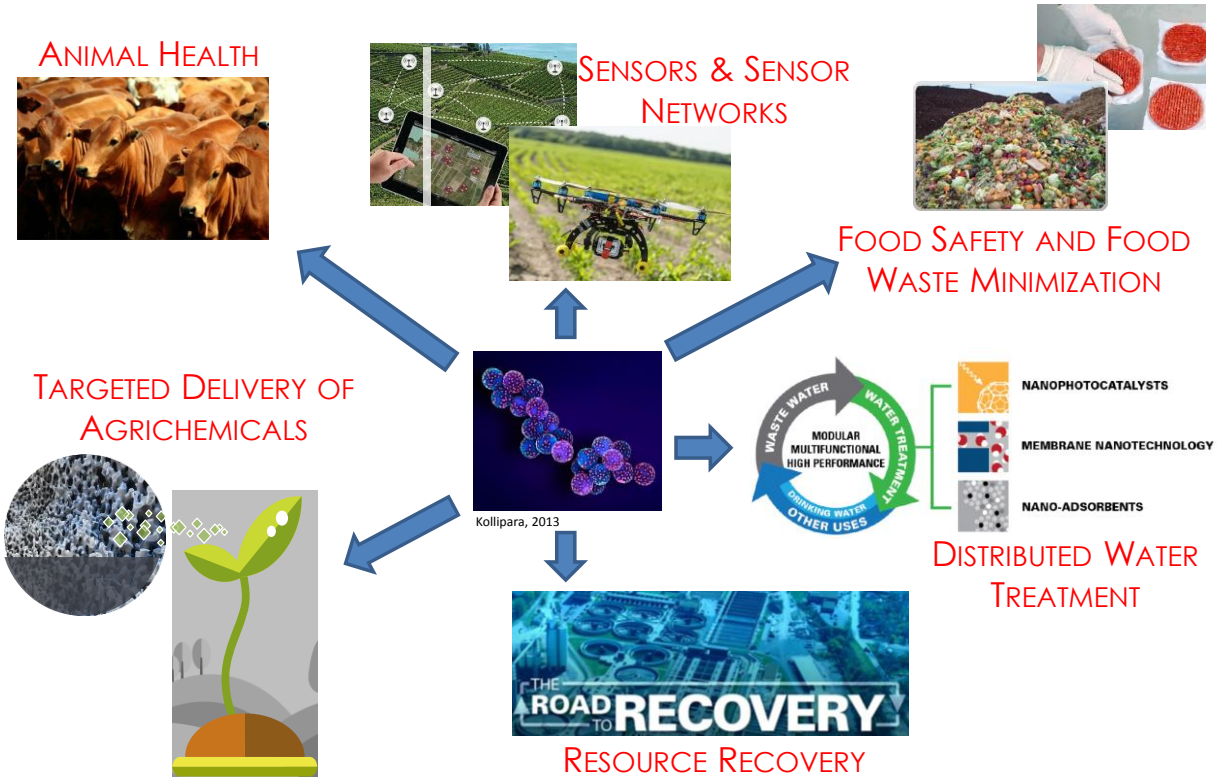
# NSF Workshop Report

## Role of Nanotechnology in Achieving Sustainability at the Food-Energy-Water-Nexus




## December 15, 2015

**Executive Summary**

Nanotechnology could play a critical role in sustainably meeting societal demand for energy, water, and food. The potential of nanotechnology to improve sustainability at the Food-Energy-Water (FEW) nexus, particularly in agriculture and food safety has not been fully explored. An interdisciplinary workshop conducted at Carnegie Mellon University October 19-20, 2015 gathered ~50 experts from the U.S. and the EU in the areas of nanotechnology, energy, water, agriculture, systems engineering, data integration and analysis, and social science to identify the greatest systems-level opportunities for minimizing resource inputs and waste, and for maximizing crop productivity and food utilization. The scientific, engineering, and social and regulatory challenges to realizing the full potential of nanotechnology at the FEW nexus were discussed.

Workshop participants identified seven key areas where nanomaterial applications can be used to provide system-wide optimization opportunities at the FEW nexus.

- Nano-enabled sensors and analytics
- Treating and recycling agricultural wastes
- Nanomaterials for improved efficiency and performance of water systems at the FEW nexus
- Minimize food loss and waste; detection and intervention approaches
- Food safety detection and intervention approaches
- Nanomaterials for efficient fertilizers and pesticides
- Plant and animal health protection and intervention approaches

Applications of nanomaterials in each of these areas can lead to lower overall water and energy inputs for food production. The use of multifunctional nanomaterials and nano-enabled sensors in agriculture can increase the spatial and temporal granularity of monitoring crop and livestock health, and revolutionize the delivery of pesticides, vaccines, and nutrients to improve yields while lowering overall inputs and environmental impacts of agriculture. Nanotechnology also offers opportunities to recover energy, water, and nutrients from agricultural waste streams. These opportunities come primarily from the ability to provide more controllable membrane geometries for separations, greater selectivity and reactivity of the nanomaterials for target analytes, and the ability to produce multifunctional materials.

Nanotechnology can improve water treatment by enabling more efficient and more selective materials for separations and contaminant removal. This enables the use of alternative impaired water sources (e.g. wastewater) for agriculture or for emergency response, opens opportunities for distributed treatment systems (lowering the energy footprint from

distribution), and provides greater ability to match treated water quality to the intended use. Nano-based systems for detection of pathogens and toxins in food, or as an intervention to prevent spread of these organisms, can reduce food waste. Reducing food waste will decrease energy and water inputs of food production (on a per unit consumed basis). There is also significant opportunity for nanomaterials, nano-coatings, and nano-enabled packaging to improve food safety. Pesticide and nutrient management can be improved through the use of multifunctional nanomaterials that incorporate the ability for specific targeted delivery at a specific delivery time. Finally, nanotechnology may improve detection and protection of animal health, thereby reducing the resources required to care for them. This can be realized through e.g. targeted delivery of drugs, detection of biomarkers that will enable more timely and effective decision-making on disease intervention and breeding, and development of technologies to modify animal environments.

While there are significant opportunities for nanomaterials and nanotechnology to improve sustainability at the FEW nexus, manufacturing these nanomaterials cheaply and safely, and designing them as selective, sensitive and durable for use in highly complex matrices (e.g. soil or food) is a significant challenge. Performing a technoeconomic gap analysis on proposed nano-enabled solutions will be critical to identify the highest value opportunities for nanotechnologies at the FEW nexus. Managing risk perception by consumers and manufacturers, and overcoming the regulatory challenges to implementing these new technologies is also essential to having them adopted. All stakeholders should be brought into the process early on to maximize public benefit of this new technology while minimizing undue hardship on agricultural producers.

The workshop recommends investments in basic science to support the 1) development of nanosensors for agriculture, animal health and husbandry, and pathogen detection. This includes development of the infrastructure required to distribute and power the sensors, and the analytical tools needed to analyze the data. 2) Development of multifunctional and environmentally responsive nanomaterials to enable targeted delivery and timed releases of important agrichemicals. 3) Development of nano-enabled platforms for pathogen detection and intervention along the farm to form continuum. 4) Development of nanomaterials for antimicrobial surfaces, disinfectants, and vaccines. 5) Development of multifunctional nanomaterials and with high selectivity (adsorbents, reactants, or membranes) for use in water treatment, recovery of high value materials in wastewater and food waste. Also, fundamental research is still needed to determine the relationships between specific material properties and the elicitation of a desired response. Finally, there is a pervasive need for tools to support regulatory and social acceptance of nano-enabled technological solutions for food and water applications, including approaches for effective communication to manage expectations of

technological impact (without associated behavioral changes) on achieving sustainability at the FEW nexus.

## Introduction

Rapid population growth, climate change, and increasing soil erosion rates are placing enormous stress on our ability to reliably provide food, energy, and water (FEW) to society in an equitable manner. This is a historic inflection point, with an unprecedented need for more sustainable approaches to food production, energy generation, and supplies of fresh potable water.

Zero hunger is the second of the Sustainable Development Goals adopted by the United Nations Sustainable Development Summit on 25 September 2015[1]. An important aspect of combating hunger is to increase food production, a goal which is dependent on water and energy availability. Historically FEW systems have been examined independently of one another, and system-level opportunities for more efficient agriculture are overlooked. Fundamental research is needed to understand the principles underlying the connections between FEW systems and how new technologies and engineering solutions can be applied to enhance productivity and sustainability of the food supply.

Associated with the UN Goals are three guiding principles for sustainability at the FEW nexus extracted from the 2011 Bonn FEW Nexus report[2]: Investing to sustain ecosystem services; Creating more with less; Accelerating access, integrating the poorest. These principles were kept in mind as the workshop discussions progressed.

*Potential of Nanotechnology to help*

Nanotechnology will play a critical role in sustainably meeting societal demand for energy, water, and food. The role of nanotechnology in enabling the transition from fossil fuels to renewable energy sources and for improving energy efficiency of built infrastructure is well documented[3, 4]. The use of nanomaterials in water treatment and disinfection has been studied for several decades and has resulted in significant improvements in water treatment[5-7], and is the focus of a recently funded NSF Engineering Research Center (ERC), Nanotechnology Enabled Water Treatment (NEWT). The role of nanotechnology for food security and improved sustainability at the FEW nexus has been discussed[8-10], but to date these opportunities for nanotechnology are less well explored than the applications to energy and water. The opportunity to leverage nanotechnology across the domains of food, water, and energy that

will yield the greatest improvements in sensing, efficient use of agricultural inputs (e.g. water and fertilizer), and performance required to optimize future Food-Energy-Water (FEW) systems have not been significantly explored.

Food, energy, and water are inextricably linked. For example, electricity powers groundwater pumping for irrigation in certain areas (often semi-arid places). Water is exported in the form of food from wet places to dry places. Over-watering and over-fertilization of crops has energy costs as well as water pollution costs. Food, energy, and water are wasted when food is not consumed. Therefore, the greatest opportunities for the sustainable development of agriculture will likely result from systems level optimization at the food-water-energy nexus. For example, nano-enabled sensors combined with wireless sensor networks (precision agriculture) can optimize agriculture systems to minimize the water consumption to crop productivity ratio by providing data on crop performance at high spatial and temporal resolution. Opportunities exist to improve food safety and to minimize food waste across the farm to fork continuum. For example, nanotechnology may enable the gathering of temperature-time information (TTI) at low cost, thus providing the information needed to better manage food handling and storage.

*Purpose of the Workshop*

While individual research communities surrounding the food-water-energy nexus have independently made great strides in the last decade, the potentially transformative role of nanotechnology to improve sustainability at the FEW nexus has not been fully explored. The highly interdisciplinary workshop conducted at Carnegie Mellon University October 19-20, 2015 gathered ~50 experts from the U.S. and the EU in the areas of nanotechnology, energy, water, agriculture, systems engineering, data integration and analysis, and social science to identify the greatest systems-level opportunities for minimizing resource inputs and waste, and for maximizing crop productivity and food utilization.

*Workshop Goals/Objectives*

The overarching goal of the workshop was to enable a higher appreciation, visualization, and understanding of food systems and their couplings to energy and water systems. This was done through debate, discussion, and visioning by researchers and stakeholders across nanotechnology research communities in the energy, water and hydrology, sensors, data integration, agroecosystem, and social science research communities. We used a variant of the nominal group technique (NGT) to 1) identify the most promising areas where nanotechnology

may help to improve sustainability at the FEW nexus, and 2) to identify the science, engineering and data challenges, and societal impediments that currently limit the use of nanotechnology to optimize food systems, water treatment, and energy consumption. The results of these discussions are summarized in this white paper. This will inform research organizations and future solicitations for research at the food-water-energy nexus.

A complete list of opportunities for future work on nanotechnology are found in Appendix A. Detailed outputs of the discussion groups about key opportunities for nano at the FEW nexus are listed in Appendix B. A list of workshop participants is provided in Appendix C. What follows is a compilation of the priorities from the workshop aimed at using nanotechnology in improving food production and security at the FEW nexus along with the scientific and engineering challenges to being able to realize those benefits.

## Workshop Findings

The following seven opportunities were identified as those with the greatest potential for nanotechnology to improve sustainability at the FEW nexus. These priority areas represent overlap areas between the initial NGT groups (Appendix A) focused on food, energy, or water. In each key opportunity, the concept is introduced, followed by the key opportunities for nanotechnology and its potential to improve sustainability. The key scientific, engineering, and social challenges are then presented, followed by a brief conclusion of that opportunity.

## Critical Opportunity 1.

## NANOSENSORS and ANALYTICS

Nano-enabled sensors (nanosensors) have the potential to enable highly distributed, real-time sensing of key performance metrics (e.g. variability of soil properties and nutrient availability at high spatial resolution) or other parameters of interest. The following opportunities for nanosensing were seen as the having the greatest potential impact on sustainability at the FEW nexus.

- Nano-enabled sensor networks to enable precision agriculture; i.e. to provide soil properties and plant health information at high spatial and temporal resolution.

- Development of integrated, robust and highly sensitive/selective nanosensors for pathogens, nutrients, pheromones, moisture, and pH for multiple media (water, soil, air, plant tissues)
- Development of corresponding sensing network infrastructure, data management, and analytics needed to maximize the benefits of ubiquitous sensing.

Great improvements in agricultural productivity while decreasing water and energy inputs and the environmental impacts can be achieved with real-time information about soil properties and crop health that is collected on-the ground at high spatial resolution. Such an approach will enable delivery of nutrients and water only when and where they are needed, i.e. precision agriculture. Nanosensors have broad applicability to meet this need by enabling cost-effective and robust methods for detecting parameters of interest in a diverse array of environments, with potential applications in food, energy, and water. Nanosensing techniques are already being developed for the detection of a variety of parameters (pathogens, nutrients, moisture, pH, etc.) in a variety of environments (air, water, soil, pore water, plant/animal tissue, etc.)[11-19].

Sensors networks will require the associated infrastructure to transmit and interpret their results. As such, any nanosensor-based improvements will need to consider the entire sensing system, which includes: (1) the sensor, which performs the sensing and reports; (2) the power and transmission system, which relays the output from the sensor to the user and/or network; and (3) the data analysis system, which translates the raw data into a form that can be used to answer questions about the system under study.

The National Nanotechnology Initiative (NNI) describes two types of nanosensors: those that incorporate nanomaterials to enhance sensor performance, e.g. sensitivity and selectivity; and those that are used to detect nanomaterials themselves across the substance lifecycle[20]. In this workshop, participants focused on the former. Two primary visions emerged from the discussion, distinguished primarily by how the sensors are deployed. The first technology is nanosensors which utilize nanoscale materials to detect important phenomena with a high level of accuracy and sensitivity to be deployed in traditional sensor arrays at discrete locations and linked via wireless networks. The second technology discussed in the workshop was distributed nanosensing, which involves the dispersion of nanomaterials and/or nanosensors directly and ubiquitously into FEW systems in order to measure parameters at high-density over large spatial scales. The advantage of this approach would be the high density of information that could revolutionize how agroecosystems are managed. However, the participants agreed that this approach was still far from realization.

*Key opportunities, technology, and impact on sustainability*

Sensing systems can be defined and compared based on a number of criteria (e.g., cost, spatial resolution, sensitivity, robustness, temporal resolution, and time to report). Nanosensing systems may offer substantial improvements over traditional sensing systems in each of the above criteria.

Nanosensors can be deployed in locations inaccessible to traditional sensors (e.g. in the canopy of plant/environmental systems or directly in plants)[21], can measure new parameters undetectable by traditional sensors (e.g. pH in confined spaces), can provide higher selectivity and sensitivity for analytes of interest, can enable more compact sampling designs, and can use smaller amounts of materials. When deploying nanomaterials for sensing in FEW systems, nanosensing is a logical first step to bridge the gap between the current successes in the medical field and their application in highly variable FEW systems.

*Significant scientific and engineering challenges*

Much of the research in the nanosensor field has been conducted by the medical community. This valuable research has provided support for the general utility of nanosensors to the FEW nexus, but the applicability and use of these existing sensors in highly variable water, soil, plant, and animal environments must be critically assessed. Complex soil and water matrices may cause sensing systems to behave in unexpected ways, and a key engineering gap is to create systems that are sufficiently robust to deal with varied environments, and that provide the required sensitivity and selectivity to detect a broad range of low concentration analytes.

Challenges to the implementation of on-ground sensors in FEW systems are dependent on the method of deployment. Principle challenges include the development of agriculturally relevant probes, the need to enable sufficient sensor density at low cost, and the need to power these systems. In many cases, nanosensor systems can be enclosed and isolated from the system at large, and as such, suffer less from concerns over life-cycle, use-phase human health impacts, and environmental toxicity. Nanomaterials in these systems are concentrated and contained, which offers the possibility of reclaiming materials for increased efficiency. As data density increases, corresponding changes will be needed within systems to make use of the information (e.g. moisture sensors in agriculture are best used with variable-rate irrigation systems).

*Conclusions*

The application of nanosensing to the FEW nexus has the opportunity to increase spatial resolution, decrease costs and waste, and improve crop quality. . Increases in spatial and temporal data granularity have the potential to revolutionize how agriculture systems (fine-scale measurement of field moisture and nutrients) and environmental systems (broad

measurement of ecosystem health indicators) are managed. As these data are collected and managed, key questions will arise surrounding collaboration and data-sharing. Stakeholders should be brought into the process early on to clarify in what ways data will be used to maximize public benefit of this new technology while minimizing undue hardship on agricultural producers.

## Critical Opportunity 2.

## TREATING AND RECYCLING AGRICULTURAL WASTES

Agriculture waste streams exist across the entire supply chain and contain valuable embodied resources. Workshop participants considered four primary stages where waste recovery has a high potential payoff: 1) 'in the field', which includes overproduction, crop residues, animal waste, leachates, and runoff, 2) 'processing, transportation and distribution', which includes waste trimmings, contamination, and products not suitable for human consumption either due to spoilage or not meeting mandated standards, 3) 'consumer inefficiency', which primarily includes waste from spoilage (or anticipated spoilage), and 4) 'end of life' which includes the ultimate fate of agricultural waste in either a landfill or incineration plant. These greatest opportunities for nanotechnology to reduce net life cycle resource inputs and impacts on the environment are the following.

- Nutrient recovery from leachates and runoff using highly selective membranes, adsorbents, and magnetic materials.
- Water recovery from leachates and runoff using membranes selective for specific cationic and/or anionic species, and reactive adsorbents for pesticide removal.
- Energy recovery from plant residues and animal wastes using novel catalysts to remove oxygen from biomass and more resilient membranes and new membrane geometries for selective separations.

*Key opportunities, technology, and impact on sustainability*

As with water treatment, there is already a significant arsenal of biological and chemical processes available for performing the separations and conversions required to treat these waste streams. The role that nanotechnology might play in improving these separations and conversions builds from key attributes of nanoscale objects that primarily include:

- The ability to place materials at precise locations at the nanoscale;
- Controlled access and selectivity of solutes or macromolecules to tailored surfaces;

- Specificity of catalytic reactions that may occur on surfaces;
- Photocatalytic and redox-active materials that may be used to transform materials of interest or inactivate pathogens;
- Magnetic properties;
- The ability to combine two or more of the above attributes on a surface.

An essential question is whether or not these properties can be exploited to yield reductions in cost, or improvements in performance over currently available technologies. Workshop participants considered possible opportunities for nutrient, water, and energy recovery within the context of plant and livestock-based agriculture.

Nutrient recovery

Leachates and runoff may often contain high levels of nutrients such as nitrogen and phosphorous that could be recovered for reuse. Large-scale (river basin) treatment of runoff streams is a costly proposition and previous experience with treatment at this scale (e.g., the Yuma desalination facility) suggests that this option is currently cost prohibitive, despite any value off-set from recovered nutrients. Leachate collection from tile-drained fields is a common practice in agriculture in the U.S. Treatment of leachates from individual fields may be possible for high-value crops where field size is smaller. A key limitation of many current technologies for concentrating and reusing nutrients is the relative non-selectivity of processes such as adsorption, precipitation and membrane separation. Ion exchange, which can achieve by comparison more selective removal of ionic species, should be the benchmark for comparing any new nano-enabled adsorbents.

Adsorbents might also be developed for soil amendment that would improve retention of nutrients in the field, avoiding the need for field-scale treatment of runoff. These materials must exhibit selectivity, limited persistence, and some degree of reversibility so that nutrients captured from soil water can be subsequently released.

Magnetic separations, even in the case of superparamagnetic particles, are notoriously inefficient. However, where complete removal of particles is not required, as may be the case in a nutrient recovery scheme, it is conceivable that adsorbent materials might be formulated to also be superparamagnetic to facilitate separation. However, the performance (recovery and energy consumed) of this option must be compared with density or membrane-based options for separation.

Water recovery

In addition to recovering nutrients, leachate recovered from field could be treated to allow for water re-use. In this case, it may be desirable to leave nutrients in the water while selectively managing salinity and removing pesticides. Most current separation processes for ionic materials favor removal of multivalent species first, followed by monovalent removal. In contrast, the desired outcome would be to remove some monovalent species (e.g., Na, Cl) while leaving behind other monovalent (e.g., $NH_4$) and multivalent species (Fe, Ca, $PO_4$). Nanofiltration (NF) and reverse osmosis (RO) remain the benchmark technologies for ion removal, although electrodialysis reversal may also be cost-effective for low-salinity waters.

Pesticide removal or degradation might be accomplished using adsorbent, membranes processes, chemical reduction/ oxidation or biodegradation. Background organic matter competes with pesticides for adsorption sites, increasing costs associated with adsorbent usage. The development of adsorbents selective for pesticides or other organic compounds has been a goal for several decades and there are no foreseeable prospects for nano-enabled adsorbents that address this problem. The potential for nanomaterial applications in pesticide treatment may be best in the area of materials for redox transformations that may include electron donors, catalysts and photocatalytic materials.

Energy recovery

Plant residuals on fields are a potential feedstock for biofuel production. In contrast with direct cultivation of biofuel feedstocks, which may be net energy consumers and require large quantities of water, plant residuals may have a much lower lifecycle footprint. Homogeneous thermolysis of biomass-derived macromolecules within woody biomass and/or grasses involves thousands of reactions producing a mixture of hundreds of compounds referred to as bio-oil. The heteroatom content of woody biomass and bio-oils (biomass with O-levels ~50 wt%) implies there is a pressing need for new catalysts for removal of oxygen from biomass. Pretreatment for anaerobic digestion using nanomaterials may have potential for increasing the degradability of residual plant materials and subsequent methane production. Waste streams from energy recovery processes will present second tier needs for wastewater treatment and potentially nutrient recovery.

Due to solids handling issues, nutrient recovery from animal waste is likely to be preceded by treatment for carbon management and energy recovery. Implementation of facilities for biogas generation from porcine and poultry waste has accelerated over the last 15 years. Additional innovations in anaerobic treatment include the advancement of anaerobic membrane bioreactors that further reduce the footprint of these facilities. Zerovalent iron nanoparticles

have been shown to increase biogas production and increase the ratio of methane to $CO_2$. However, the sustainability of such approaches must be assessed as the energy input for zerovalent iron (or any nanomaterial) production is typically not trivial. Additional innovation may come in the development of more resilient membranes and new membrane geometries. As these are often materials-based issues, nanomaterials may play a role in improving membrane properties. The potential and limitations noted for recovery of nutrients from leachates noted above apply to treatment of animal wastes.

*Scientific and Engineering Challenges*

A number of critical (yet, not insurmountable) scientific and engineering challenges were identified as it relates to utilization of nanomaterials to enhance resource recovery of agricultural waste streams across the supply chain. First, the performance of nanomaterials in complex waste systems hinges on the understanding of their behavior not in pristine environments, but rather in systems that are heterogeneous in composition and with high variability. We currently have insufficient understanding of how potential catalysts or sorbents, for example, perform in the presence of high organic and biological content that may not have consistent day-to-day composition. Second, the extreme organic loading makes it near impossible to apply advanced membrane separation techniques due to anticipated rapid biofouling. As such, novel and innovative separation techniques focusing on elegant manipulations of chemistry, for example, in a rather crude system will be challenging. Finally, the concept of multifunctional platforms was discussed as a way to efficiently achieve multiple objectives (e.g., rapid composition analysis, release of appropriate treatment, and selective adsorption). Realization of such capabilities requires an innovative leap in nanomaterial design. While synthetic pathways to obtain nanomaterials with certain structures and physical\chemical properties have been elucidated, we have not yet established relationships between specific material features and the elicitation of a given desired response. Establishment of these relationships is critical to realizing next generation nanotechnologies, including the proposed multifunctional platforms, for the aforementioned applications.

*Conclusions*

Overall, nanotechnology offers a number of potential paths to improve our ability to recover energy, water, and nutrients from agricultural waste streams. These opportunities come primarily from the ability to provide more controllable membrane geometries for separations, greater selectivity and reactivity of the nanomaterials for target analytes, and the ability to produce multifunctional materials. Realization of these benefits in highly variable and complex

waste streams will require design of innovative treatment platforms that can operate under extreme conditions that typically lead to fouling of membranes and poisoning of catalysts. Fundamental research is still needed to determine the relationships between specific material properties and the elicitation of a desired functionality.

## Critical Opportunity 3.

## NANOMATERIALS FOR IMPROVED EFFICIENCY AND PERFORMANCE OF WATER SYSTEM AT THE FEW NEXUS

Nanotechnology offers significant opportunities for improving resource utilization efficiency, cost-effectiveness, and versatility of water treatment technologies to enable access to water of suitable quality for the intended use almost anywhere in the world. However, realization of these opportunities requires them to be correctly positioned within water treatment systems serving the food energy water nexus. Key opportunities for nanotechnology to make water more available, as well as less costly and energy intensive to provide include the following:

- Ability to tailor water treatment systems at the nanoscale for greater efficiency in solar-driven processes, heat transfer, mass transfer, physical-chemical specificity, and material resiliency
- Enhanced use of alternative (impaired) water sources for agriculture, emergency response, or humanitarian aid.
- Opportunities for distributed low-energy desalination of sea water, briny groundwater and hypersaline wastewaters
- Better ability to match treated water quality to intended use
- Use of sunlight for water decontamination
- Better biofouling and inorganic fouling or scaling control of membranes
- Selective and reactive separation processes (e.g., multifunctional sorbents and membranes) for contaminant removal

Realizing these benefits will require materials development, enabling recycling and reuse of materials, integration into treatment reactors and systems without loss of efficacy upon immobilization, and commercialization and dissemination of these products.

The workshop attendees considered two perspectives on the potential for nanotechnology to increase sustainability at the FEW nexus. The first is an analysis of where nanotechnology could contribute to sustainability in water treatment systems serving the FEW nexus. The second

describes the need to identify high value opportunities for nanotechnology using a comprehensive systems or "gap analysis" for process-level and materials-level interventions.

*Key opportunities, technology, and impact on sustainability*

Agricultural Space

Key opportunities in the agricultural space determined by participants include: 1) improving the energy efficiency of water treatment by enabling distributed (point of use and point of entry) systems; 2) decreasing water inputs by improving the recovery rate of water treatment processes, as well as by tapping unconventional water sources such as municipal wastewater; 3) improving opportunities to match treated water quality to intended use because of the enhanced ability to selectively remove only the contaminants that matter for the intended use, e.g. increasing crop yields by selectively removing ionic species that reduce crop yield. This increases treatment capacity per system volume or energy input; 4) enhancing multifunctionality of materials and reactors and modular approaches that contribute more flexibility to respond to changes in source water quality variability or treatment objectives (e.g., endocrine disruptors or antibiotic resistance genes standard's adopted), 5) recovering nutrients (see opportunity 2 of this report for additional details).

Energy Space

Key opportunities in the energy space include: 1) decreasing the fresh water consumption in energy conversion processes by enabling more efficient heat transfer processes in dry cooling; 2) decreasing fresh water withdrawals by enabling reuse of impaired water sources; and 3) improving the energy efficiency of wastewater treatment associated with energy extraction and energy conversion processes, particularly when those wastewaters have high salinity.

Municipal water treatment

Key opportunities in the municipal or human consumption water systems space include: 1) decreasing fresh water withdrawals through strategic reuse of wastewater; and 2) development of small distributed water systems that co-locate supply and use, especially for the "bottom billion". Distributed systems dramatically lower the energy cost of distribution. Nanotechnology can improve performance of these systems, e.g. improved disinfection processes.

Engineering water treatment systems at the nanoscale enables greater efficiency in solar-driven processes, tailored heat transfer, mass transfer, physical-chemical specificity, and material resiliency. These properties are particularly valued in drinking water treatment systems where

the price of product water is high, and can be equally as valuable in the food and energy space by allowing treatment technologies to match the water quality to its intended use, e.g. selectively removing interfering species for oil & gas production or for agricultural purposes. Nevertheless, workshop participants were optimistic that cost would not be prohibitive if the material and technology resiliency issues were appropriately addressed in design, e.g. providing ability to recycle or reuse nanomaterials, avoiding the need for ultra-high purity nanomaterials in the design, incentivizing economy of scales with well-publicized successes.

Key opportunities for better heat transfer in water treatment systems serving the food energy water nexus include 1) utilizing solar or waste heat (where available) to drive water treatment; 2) capturing a greater range of the solar spectrum; and 3) improving heat dissipation in power generation. While heat driven water treatment technologies are practical for water treatment at electric power generation facilities, where ample heat is available, solar driven technologies are more likely to find application in agricultural systems. Key technical opportunities in nanotechnology include development of nanostructures capable of capturing and transferring heat and solar energy in membrane distillation processes, and nano-structured materials for improved heat dissipation in dry cooling processes at electric power facilities that would improve the energy efficiency of dry cooling processes and limit the dependence upon wet cooling.

Key opportunities for improved mass transfer in FEW water treatment processes include: 1) improved membrane permselectivity for higher water recovery rates and lower energy consumption; 2) tailoring surface hydrophobicity; and 3) design of tracers for monitoring transport of water. Improving membrane permeability will allow for smaller, more economically feasible distributed treatment systems, while tailoring surface properties is critical to moving contaminants of concern to selective deactivation sites. Tracers, be they nanoscale materials/chemicals or sensors capable of detecting unique constituents already present in the water, present a rich opportunity space for nanotechnology contributions.

Improved selectivity in water treatment processes is another critical opportunity for nanotechnology applications at the FEW nexus. These include nanotechnology's potential contributions to improving 1) membrane selectivity for drinking water treatment applications, 2) selective adsorption and rapid desorption for removal of high value trace elements and phosphorus in e.g. agricultural runoff, 3) selective intercalation of ionic species for facile electrochemical separation, e.g. to allow for removal only of monovalent ions of concern for crop yield, and 4) selective targeting of dissolved species or the use of photoactive materials to more efficiently deliver disinfection or degradation capability are also opportunity areas. Leveraging nanotechnology to improve selective removal of constituents from municipal,

agricultural, or industrial wastewater also enables system-level changes in how water is transferred between food, water, and energy applications. Most critically, wastewater reuse can limit the deployment of more energy-intensive desalination processes.

Finally, materials resiliency enabled by nanoscale materials design has the potential to improve the strength and extend the lifespan of materials used in water treatment systems. A particularly critical contribution in this realm would be the design of self-cleaning, self-repairing, multi-functional, and high strength membranes for treating high salinity feed streams from energy extraction and power generation. Similarly, membranes able to withstand higher hydraulic pressures than current reverse osmosis systems would improve water recovery rates in municipal and industrial water treatment systems and improve the energy efficiency by minimizing pretreatment. Extending the lifespan of materials for water treatment, either by reducing fouling of membrane surfaces, enhancing the recycling potential of sorbents, or reducing the corrosion in water conveyance systems would also improve systems-level efficiency.

*Scientific and Engineering Challenges*

Many of the applications cited above face the challenge of 1) slow technology diffusion in the municipal water treatment industry; 2) uncertainty in the cost-to-value ratio of technology innovation in the low-profit margin spaces of water, agriculture, and energy; 3) safety and public perception concerns when utilizing nanomaterials in water treatment systems; and 4) life-cycle issues associated with nanomaterials, including sustainably fabricating nanomaterials at large scales, ensuring nano-activity throughout the product lifecycle, recovering nanomaterials from matrices, and the fate and transport of nanomaterials if they are released into the environment should be addressed in the design phase of any nano-enabled water treatment application.

<u>Gap analysis to identify high value opportunities for nanotechnology to improve sustainability at the FEW nexus.</u>

While there is good reason to believe that nanotechnology has the ability to create “disruptive” or “leapfrog” technologies in water supply and treatment, this assumption demands a quantitative needs assessment.

Water as a limiting resource in food production which is inextricably tied to the energy required to provide this resource. Characteristics of the water challenge in the context of FEW include:

- Large quantities of water to be handled, even in comparison with municipal needs;
- Wastewater that may contain high concentrations of salts and organic matter (e.g., and produced waters) and as well as nutrients, pesticides, and pharmaceuticals (in livestock and aquaculture applications);
- Agricultural applications that are located in low rainfall, surface water-scarce regions with high potential for evaporative losses;
- Large tracts of land that may not be located near traditional water grids, resulting independence on groundwater resources and,
- Growing demands of urban centers for water that may compete with agricultural water demands;
- The larger urban-agricultural system will entail multiple end uses of water and associated treatment needs.

As a result, water needs in the context of the FEW nexus may share some characteristics of both modular "off-the-grid" systems and large scale systems that make up the water infrastructure grid. This suggests that more efficient configurations for water treatment, wastewater treatment, water reuse, and distribution may lie between these two models. There is therefore a need to evaluate the types of water handling configurations that are best adapted to meeting water volume and quantity needs for agriculture while minimizing environmental impact and energy usage. Identification of such configurations must include a consideration of the role of urban areas as water consumers and possible trade-offs that may exist between urban and agricultural needs and capabilities. In a first iteration, consideration of such configurations should also be "technology-agnostic" in the sense that generic processes such as "nutrient recovery" or energy sources need not be provided by known technologies.

An examination of these configurations and comparison with the outlook for the current inventory of technologies that might provide at each step within the configuration will reveal potential gaps where new technologies might be needed or where they might significantly reduce costs. Nano-enabled technologies can, in turn, be considered as potential solutions to filling these gaps. Finally, quantitative estimates of improvement (e.g., % recovery, % reduction in cost) over technologies currently available will indicate if and where nanotechnologies might play a role in meeting FEW objectives.

*Conclusions*

There are significant opportunities for nanotechnology to decrease the energy inputs for water treatment, enable small scale distributed treatment, improve the selectivity of water treatment

processes, and enable treatment to be optimized for its intended use. However, a technoeconomic assessment of potential technologies must be undertaken to identify the highest value opportunities.

## Critical Opportunity 4.

## MINIMIZING FOOD LOSS, WASTE-DETECTION AND INTERVENTION

Food loss can occur pre- and post-harvest all along the value chain; in Europe and North America it is estimated that 30-50% of food supply is wasted[22, 23] at all levels of the value chain: in consumer households, retail establishments, food processing, and on the farm (buyers are only one point of rejection). Food waste, a subset of food loss, occurs post-harvest and also represents substantial losses of embodied energy and water. For example, 31% of the 2010 United States post-harvest food supply was estimated to be wasted at the retail and consumer level, resulting in economic loss on the order of USD$160 billion[24]. The US Environmental Protection Agency estimated that food waste in 2013 accounted for 21.1%(35.2 Mt) of the municipal solid waste stream[25]. Food waste is often a result of spoilage from the activity of bacteria and fungi. Detecting the presence of these organisms, destroying them, and preventing their spread in either food or animal systems will decrease spoilage and waste. A variety of chemical- and thermal-based, radiation, and non-thermal based technologies are currently used to combat spoilage. These are old technologies with drawbacks including a decrease in food quality and sensory effects, the inability for interventions all along the farm to fork continuum, consumers' perception about the condition of foods (i.e. suitability for consumption after intervention), possible health implications, and the reluctance to use chemical treatments for organic products. Thus, there are significant opportunities for improvement over these antiquated technologies, including the following.

- Nano-based systems for detection of pathogens and toxins (toxins can include small molecules left behind by microorganisms or fungi even if those pathogens are no longer present or viable) on or in foods
- Nano-based systems for intervention to prevent the formation or spread of these organisms.
- Nano-based catalysts and sorbents to recover valuable components from wasted food, or to convert food waste into usable products or energy.

*Key opportunities, technology, and impact on sustainability*

There are substantial opportunities for nanotechnology to improve pathogen and toxin detection and for selected intervention mechanisms. These both can reduce food loss and

improve sustainability at the FEW nexus. Preventing food loss and waste improves usable crop yields without a corresponding increase in water or energy inputs, and without the need for more arable land for agriculture. There are also opportunities for nanotechnology to convert food losses and wastes into useable products, or to extract high value materials from waste. The participants identified the following opportunities as having the greatest potential benefits.

- Developing nano-based systems for antimicrobial disinfection across the farm-to-fork continuum. This includes both airborne and waterborne pathogens (and human infectious agents), spoilage microbes on food crops, fresh produce, and animals, and disinfection of contaminated surfaces where food is processed and prepared[26, 27].
- Developing user-friendly, inexpensive, and robust nano-based real-time detection systems for crop foods and animals, including both airborne and food-borne pathogens on food surfaces and food products.
- Preventing adhesion of microbes to food surfaces and food processing surfaces.
- Developing nano-based reactive sorbents and catalysts to control chemical contaminants
- Developing low cost sensors for continuous temperature monitoring.
- Developing nano-enabled antimicrobial packaging technology to extend shelf-life.
- Developing methods to recover high value components from food waste (e.g. zeins from corn) or to transform components of waste foods into value added products (e.g. biofuels)
- Developing technologies to remove non-value added products before food processing.

Nanotechnology can improve our ability to realize many of these opportunities. The following specific opportunities for nanotechnology in this space were elaborated on further during the workshop.

<u>Catalyst and sorbent development for transforming waste foods into value added materials, i.e. recovering energy and chemicals from food losses</u>.

Given the high levels of embodied energy and water in food production, it is imperative to recover some of this energy in the (inevitable) food loss. For example, nanotechnology platforms will provide catalysts for conversion of wastes into useable products. Nanosorbents and catalysts can be developed to help remove contaminants from cooking oils to promote reuse and conversion to biofuels or to recover high value components from food waste.

Next generation time and temperature information (TTI) to minimize food loss from farm to table.

Efficient tracking foods from farm to table will enable better management, improve quality, and reduce spoilage and waste. In particular, time and temperature indicators hold tremendous opportunity to accurately monitor food quality and shelf life. Nanosensors may be used for direct tracking of time and temperature, or through the detection of selected indicator microbes or their metabolites.

Nano-based antimicrobial platforms to protect against spoilage and foodborne diseases from farm to table.

There is significant opportunity for development of nanotechnology-based antimicrobials to replace or reduce water and energy-intensive chemical and thermal treatments for food safety. This includes antimicrobials that can be applied to foods at harvest, packaging, retail outlets, and at the consumer level. Novel nanomaterial applications to foods in order to prevent adhesion and proliferation of pathogenic and spoilage organisms is also a promising approach. Nano-enabled spoilage detection and reporting technologies could add precision to the concept of a "use-by" date.

Advanced food packaging (home, retail, and food services).

Food packaging can provide a unique platform for improving shelf life and reducing spoilage. Nanotechnology offers opportunities to improve the performance of food packaging so as to reduce spoilage during transport, shelving, and after consumer purchase. For example, nanomaterials in food packaging can be used to control gas permeability to keep food fresher longer, or can include antimicrobial agents for preventing proliferation of pathogenic or spoilage microorganisms.

*Scientific and Engineering Challenges*

There are a wide range of nano-based antimicrobial agents and nano-enabled sorbents that have been proposed and investigated. However, there are a number of scientific and engineering implementation challenges that make it difficult to use these materials effectively, especially in complex food matrices. The following challenges identified by workshop participants will need to be overcome to make these nanotechnologies viable for use.

- Increased sensitivity of detection of pathogens and toxicants in complex food matrices. Very low detection limits are likely required.
- Capability to distinguish between positive and false-positive results, such as viable (infectious) and inert/dead pathogens in detection systems.

- Reducing the cost of time temperature indicators and detection and prevention technologies.
- Development of robust sensors and technologies that can operate reliably in the highly variable composition of many foods and food waste streams. For antimicrobials, this includes an ability to be effective at high microbe to nanomaterial ratios. The highly complex and variable nature of the composition of many foods and food waste streams will require that a technology be robust over a wide range of spoilage organisms, chemical conditions, and temperatures for a sustained period of time.

*Conclusions.*
There are significant opportunities for nanotechnology to improve detection and prevention of pathogens and food spoilage organisms and to reduce overall food waste. Reducing food waste will decrease energy and water inputs of food production (on a per unit consumed basis). There are also opportunities for nano-enabled catalysts and sorbents to extract value added products from food waste. These have the potential to reduce the lifecycle energy footprint of food production systems.

## Critical Opportunity 5.

## FOOD SAFETY DETECTION AND INTERVENTION APPROACHES AND NEUTRACEUTICALS

Food safety (post-harvest) has a critical role to play in sustainability at the FEW nexus. Based on data from US Center for Disease Control, every year in the U.S.A., approximately 48 million people get sick, 128 000 are hospitalized, and 3000 die of foodborne diseases at an economic cost of nearly $16 billion. This is expected to increase as the proportion of consumed raw produce rises, and as food is produced farther away from the point of consumption, with associated longer transport times. Ensuring food safety requires the ability to control chemicals/toxins, microbes/pathogens, and allergens from farm to fork. Current food safety approaches, including thermal and chemical processes, UV disinfection, and (non-thermal) radiation and pressure treatment have a number of drawbacks. For example, there are issues with worker safety (UV treatments) and negative impacts on taste and other sensory effects (food quality); most approaches are single-point interventions that do not provide opportunities for intervention across the farm to fork continuum. There are also negative public perceptions about these processes, as well as limits to their application on organic products.

*Key opportunities and impact on sustainability*
In parallel to the areas identified above for minimizing food loss and waste, the workshop participants identified several key opportunities for nanotechnology to improve food safety.

- Nano-based antimicrobial platforms from farm to fork, including nano-enabled food packaging systems that can not only provide long-term protection throughout transport and storage, but also significantly extend the shelf-life of food.
- Nanomaterials for removing or transforming harmful chemical and biological agents from foods
- Nano-based treatments to prevent adhesion of pathogens to food surfaces, wrappings, or the surfaces of food processing equipment
- Nano-based detection platforms to reduce the time and cost associated with testing for pathogens. This will not only broaden the sample size for testing but also improve the accuracy for pathogens and toxicants, i.e. limit false negatives.
- Nanotechnology based nutraceuticals

Each of these opportunities can improve food safety and improve sustainability at the FEW nexus in different ways. A nano-based antimicrobial platform has the potential to prevent proliferation of harmful bacteria or pathogens throughout the transport and storage process prior to consumption. This could offer greater protection against food-borne illness compared to single point interventions used today. There are also potential lifecycle environmental benefits that result from using nano-based antimicrobials as compared to current chemical or UV based systems. The use of nanomaterials to transform or remove residual chemicals/toxins on food during transport or storage has the potential to be less energy intensive and more chemically benign/sustainable than traditional chemical treatments (e.g. chlorine). Nanomaterial coatings on surfaces that prevent the adhesion of pathogens on food or on food processing equipment could lessen the frequency of cleaning with water and chemical sanitizers. Nanotechnology can also play an important role in nutrition, food fortification and modification. There are opportunities to develop nutraceuticals with higher stability and bioavailability.

*Scientific and engineering challenges*
The workshop participants identified multiple scientific, engineering, and social challenges to implementing any nano-enabled solution for food safety; these issues must be addressed prior to widespread adoption of these technologies.

- Commercialization, scalability, and cost effectiveness must be achieved. The shear mass of food that is moved each day requires that solutions be cost effective and scalable.
- The safety of nano-enabled packaging and products used directly on foods and food processing equipment must be verified to avoid any unintended negative consequences

of their use such as leaching into the food or other user exposures. The safety of new materials to workers and consumers must be demonstrated to obtain consumer acceptance of the technologies.

- Methods are needed to target nanomaterials for selected pathogens that may be present in low amounts (selectivity) and that are able to distinguish live from dead pathogens. Efficacy must be achieved at low doses in highly complex food matrices.
- In addition to being safe for human consumption, nanomaterials used in foods and food packaging should be reusable, recyclable, and/or biodegradable.
- Engineering implementations are needed that make sensors easily deployed and able to provide real-time information at low cost.
- A culture change in industry to adopt safe-by-design principles is needed.
- Effective management of risk perception by consumers and manufacturers is needed, including transparency and education.
- Communication tools that empower consumers to produce less food waste must be developed.
- Regulatory challenges surrounding the safety and acceptance of nanotechnologies for food production, handling, transport, and storage must be addressed.

*Conclusions.*

There is significant opportunity for nanomaterials, nano-coatings, and nano-enabled packaging to improve food safety. However, manufacturing these materials cheaply and safely, and designing them as selective, sensitive and durable for use in highly complex food matrices is a significant challenge. Nano-enabled nutraceuticals may provide higher stability and bioavailability of supplements for foods and improve nutritional values of foods. Managing risk perception by consumers and manufacturers, and overcoming the regulatory challenges to implementing these new technologies is also essential to their successful adoption.

## Critical Opportunity 6.

## NANOMATERIALS FOR FERTILIZERS AND PESTICIDES

Pesticides, fertilizers, and micronutrients are essential to global food production. Delivering these agents in part as multifunctional nanomaterials could significantly promote sustainability at the FEW nexus[28] The most promising opportunities for nanomaterials in this space were the following.

- Multifunctional nanomaterials that can contain multiple active ingredients and can be synthesized and formulated for strategic, timed and targeted release.
- Targeted delivery of pesticides to crop plants.

More efficient use of fertilizers and pesticides can significantly lower energy inputs for agriculture, and reduce environmental and human health impacts resulting from their use. However, regulatory and socioeconomic acceptance of nano-enabled pesticides and fertilizers will be needed to realize these potential benefits.

*Key opportunities and impact on sustainability*

Currently, the amount of fertilizers and agrochemicals applied to croplands greatly exceeds the amount needed, causing eutrophication problems as well as increased environmental burden from pesticide drift and overspray, in addition to economic waste. The use of targeted, multifunctional nanomaterials could increase efficiency and minimize waste. It may also help to protect pollinators by enabling more targeted delivery of pesticides. These materials can reduce energy and water consumption both on the field and on the materials production side, in addition to increasing food yield via nutrient addition and pesticide control.

The optimal nutrient, water, and pesticide requirements for a crop are not uniform over a field, but vary spatially and temporally. Optimized delivery of these essentials involving nano-chemicals and nano-enabled sensors has the potential to increase the efficiency of crop production and, on large scales, to significantly reduce waste of these essential inputs. Nano-enabled materials could be formulated for targeted delivery to agro-systems. The nanomaterials may then increase agricultural production and efficiency. These nanomaterials can decrease water inputs in agricultural systems particularly by enabling fewer over-all applications of these agrichemicals. For example, nanomaterials could contain a balanced formulation of nitrogen, phosphorus, and other plant nutrients in the most effective ratios. Release rates could be controlled for best timing of uptake by plant cells or availability from the soil, and nanomaterials could be formulated for specific soil types and characteristics. The application of nanomaterials to improve pesticide efficacy could reduce exposure risk to humans and the environment through improved selective targeting mechanisms or from the decreased amount of pesticides used. Energy inputs will also be decreased as fewer chemical applications to crops and less irrigation will be needed. More efficient use of fertilizers would decrease the nutrient footprint. Truly novel approaches to making plants resistant to pests without continued pesticide applications may also be possible, e.g. delivery of double stranded RNA to plants to provide them the necessary resistance to pests. In general, costs would be lower, increasing crop yield per dollar and per energy unit, gallons of fuel or kilowatts of electricity. Operating costs would be lowered by fewer agrichemical applications. Nanosensors and other sensor systems could be linked to the use of these nanomaterials to provide better management data.

Nanomaterials could potentially be formulated to facilitate plant growth in arid or marginal soil locations, which could be particularly important for developing countries. Nanomaterials can be synthesized to package micro/macro nutrients and pesticides together into one delivery system. Timed release of these multifunctional materials can decrease loss to the waste stream.

*Scientific and engineering challenges*

Several challenges prevent implementation of smart nano-agrochemicals today. It is uncertain what material formulation aspects are needed to optimize plant growth. Methods need to be developed to track and analyze the fate of these nanomaterials in soil/plant systems. Areas for research include design and formulation of materials—properties such as size, shape, surface structures, composition. There are challenges in formulation related to different soil types and the mechanism of uptake in relation to species-specific plant characteristics. Targeted pesticides remain a goal, incorporating genetic information and biologic systemic responses. It remains unclear whether biological modes of targeting or physical/chemical modes of targeting are the best overall approach with respect to greatest efficiency and safety of use.

The fate of these multifunctional nanomaterials with respect to soil type can be linked using information from nanosensors used for soil tests/characterization. Methods are needed for tracking organic nanomaterials (in particular) in soil and plants, as well as for tracking their fate and degradation products.

The cost associated with introducing new agrichemicals to market is high (typically US$100's of millions), and there are challenges associated with the social and regulatory acceptance of nano-enabled fertilizers and pesticides.

*Conclusions*

There are multiple opportunities to use nanomaterials at the FEW nexus, particularly in delivery of pesticides and fertilizers with fewer field applications and more efficient timed uptake by the crops. The unique nature at the nanoscale enables the use of materials in many ways that are different from conventional chemicals. The potential of these materials to improve sustainability at the food water energy nexus is a tremendous opportunity, but will require substantial investments in research and development, as well as serious efforts to gain regulatory and public acceptance of the benefits of the approach.

## Critical Opportunity 7.

## ANIMAL HEALTH PROTECTION AND INTERVENTION APPROACHES

Animal husbandry consumes an enormous share of the water and energy resources devoted to food production; for example, beef is estimated to require 3,000-20,000 L/kg gallons of water for production depending on the production system (industrial systems vs. grazing)[29, 30].. With meat consumption increasing globally in step with rising living standards[31], reducing the resources utilized for animal product consumption has a clear and critical role to play in aiming for more sustainable agriculture. The loss of livestock to disease represents a significant loss in water and energy investment as well as a loss of capital. With this in mind, workshop participants prioritized protection and intervention methods to maintain animal health as a high priority area for nanotechnology at the FEW nexus.

Technologies and applications to improve sustainability at the FEW nexus were envisioned including:

- Improve animal health of herds, flocks, and schools through disease surveillance
- Disease control through more efficient and targeted vaccines and nanomaterial-based antimicrobial alternatives to current drugs (minimize overuse of medications)
- More efficient and precise estrus detection in mammalian livestock.
- Greenhouse gas reduction via waste management, flatulence control in ruminants, and animal waste conversion to resources for energy and materials
- Disinfection of aquaculture and poultry process water to enhance animal health and achieve sustainable farming.
- Develop nutritional platforms to fortify food products (milk and meat) – "personalized" nutrition

*Key opportunities and impact on sustainability and scientific and engineering challenges*
Selected specific opportunities for nanotechnology to provide cost-effective and efficient solutions for these key issues were discussed in detail as outlined below. The scientific and engineering challenges are provided together with each opportunity.

<u>Disease Detection Surveillance</u>

Developing nanotechnology solutions to detect diseases within individual animals will potentially decrease water and energy loss via prevention of loss of animals. If an animal does

not survive until its intended market date, then the resources invested in its care until that point are lost. Better detection of disease can also lead to more responsive rather than prophylactic medication practices, thereby improving water quality by reducing unnecessary drug use, and perhaps limiting the size of outbreaks within herds or the emergence of zoonoses among farm workers or consumers. Such practices can also reduce costs while enhancing yield per dollar, per gallons of water, and per kWh energy consumption. Such detection and surveillance technology can reduce food waste by saving animals, and can protect humans from the risk of disease transmission.

The barriers to realizing this opportunity center around identification of appropriately responsive nanomaterials and nano-enabled sensors that are economically viable and environmentally benign with sufficient specificity to identify bio-targets, sufficient selectivity to overcome interferences, and sufficient sensitivity to detect relevant levels of targeted compounds. Also work is needed in the identification of biochemical targets. The identification of agents present in air in trace amounts is associated with significant detection challenges. The need for multiplexing (systems integration) and pattern recognition represent key engineering challenges to implementing these technologies. For example, artificial olfaction or "bionic noses" are designed with carbon nanotubes, where amperometric enzyme electrodes can selectively detect chemicals (propanol vs. ethanol, vs. carbon monoxide)[32]. Similar nano-scale devices are now utilized to detect cancer[33]. However, cost, durability, and physical implementation challenges of such sensor technologies, including the ability to miniaturize detection devices were also noted as current barriers.

Disease Control (Vaccines and Drugs)]

In a very similar sense to the disease detection technologies discussed above, this opportunity will potentially decrease water and energy loss via prevention of loss of animals. Again here, nano-enabled veterinary medicines and vaccines could improve water quality by reducing unnecessary drug use, reduce food and water waste by saving animals, and thus achieve cost reduction while enhancing yield per dollar, per gallons of water, and per KW energy. The inventiveness exhibited in nanomedicine for humans will most likely have spill-over applications in veterinary medicine, with the creation of nano-enabled vaccines and drugs, delivery systems for small and large therapeutic molecules (anti-infectives for internal and external parasites, anti-inflammatories) with greater efficacy and targeted delivery, and novel diagnostic tools. Other potential applications that do not directly fall under the "disease" category but could take advantage of drug delivery technologies might include delivery of birth control to feral nuisance animals, either predators or competitors for food resources[34].

Several challenges prevent current implementation of nano-enabled vaccines and drugs. Technical challenges include the efficient delivery of proteins and nucleic acids and the need to overcome biological barriers for uptake and mechanisms for intracellular degradation. The difficulty of designing to delay the development of antibiotic resistance was also recognized, as well as designing pharmaceuticals that are potent, safe, selective, non-perishable, and economical. [35].

Estrus Detection

Identifying the time of estrus –fertile windows for female animals – is a labor-intensive and error-prone component of dairy farming. Pheromone or hormone detecting nano-noses could offer significant improvements in this currently difficult process. Should nanotechnology prove efficacious in addressing this problem through detection of biomarkers indicating estrus, this application could indirectly decrease water and energy by increasing the efficiency of artificial insemination, and hence reducing the energy and water overhead of maintaining unproductive cows. This intervention would enhance the economic and operational sustainability of farming, and thus achieve cost reduction while enhancing yield per dollar, per gallons of water, and per kWh energy consumption.

To realize this potential application, sensor-platforms need to be developed to monitor appropriate chemical and physiological signals. Sufficient detection, response, and transduction need to be achieved to interpret and formulate timely responses to the information. Specific scientific and engineering challenges to addressing these barriers will require advancing materials and detection capabilities. It will be important to detect the appropriate molecule(s), at sufficiently low concentrations.

Animal Waste and Green House Gas Management

Animal waste was also discussed in terms of resource recovery elsewhere in this workshop report; in this priority area the discussion focused both on reducing waste generation and on recovering resources specifically from animal waste. Reduction and/or re-use of wastes and associated management of GHG emissions would impact sustainability in a number of ways, including: generating value added products from waste stream, thus offsetting operation costs and moving toward “self-sustaining” and “zero-discharge” farming. Achieving this opportunity would also decrease climate footprint by reducing GHG emission.

Science and engineering challenges include developing feed additives that reduce methane production by ruminant animals, developing targeted soil amendments to reduce $N_2O$ reduction, controlling odors, and purifying biogas. Surmounting these challenges will depend on the design of catalysts for pre- and post-treatment of wastes. High surface area sorbents will be needed for soil amendments that would absorb compounds in animal urine that lead to $N_2O$ generation, or that can manage toxicants present in animal waste, e.g. arsenic in poultry litter[36, 37]. Another recognized barrier includes the design and optimization of distributed energy production from biogas using combined heat and power processes.

Water Quality Needs for Fish and Animal Health

Several applications for nanotechnology were thought potentially influential in protecting water quality for aquaculture. Impacts might include lowering the energy for water treatment, and again realizing all of the sustainability benefits outlined from the protection of animal health. Key challenges in this sector include lack of efficiency in UV disinfection (long-term irradiation), which leads to proliferation of opportunistic pathogens[38] and viruses[39]. It was envisioned that alternative disinfection technologies might be used for indoor fish farming to enable the recirculation of water and that novel nano-particulate biodegradable flocculants could be developed to manage organismal and particulate contamination.

The barriers to developing and implementing novel water treatment and management approaches include techno-economic constraints, such that sufficient marginal benefit would need to be demonstrated to unseat the pervasive use of traditional disinfection techniques. The benefits of nanotechnology can also be harnessed to enhance the performance of the traditional systems (e.g. photo-catalytic nanoparticles to enhance UV disinfection). Challenges include process optimization, the large microbial load and water flow rate of agricultural waters, practical difficulties of deploying immobilized antimicrobial agents, and the preference for designing biodegradable technologies. Multiple, sometimes competing technical constraints that pose challenges to achieving these opportunities include the need to develop high efficiency processes that are effective and safe. The developed technologies must be tolerated by fish and avoid development of antimicrobial resistance. Preserving the colloidal stability of disinfection agents while flocculating particulate contaminants poses a further design challenge to designing alternative chemical (e.g. replacement for chlorine) and physical processes for disinfection.

*Conclusions*

The potential sustainability impacts of protecting animal health while minimizing the required resources are significant given the considerable quantities of water and energy consumed along the food chain to generate animal products. Nanotechnology may have a key role to play in detecting and treating disease, protecting animal health, reducing the resources required to care for them, and increasing agricultural efficiency. Workshop participants anticipate the potential for application of nanotechnologies in a number of arenas in need of development or optimization, including targeted delivery of drugs, detection of biomarkers that will enable more timely and effective decision-making on disease intervention and breeding, and development of technologies to modify animal environments.

## Interesting side bars

In addition to the seven key opportunities presented above, there were several cross-cutting themes present in many of the separate discussions. These important cross-cutting discussions include the following:

- Critical need for research and tools to support social and regulatory acceptance of nano-enabled technologies across the FEW nexus (e.g. water treatment, food treatment, food packaging)
- Potential for longer-term high-risk high-reward opportunities
- The difficulty of valuing the economic and environmental benefits of nanotechnology contributions to agriculture, a sector where key inputs, like energy and water are subsidized, i.e., artificially underpriced.

*Tools and activities to promote regulatory and public acceptance of nano-enabled solutions at the FEW nexus.*

The need for tools to support regulatory and social acceptance of nano-enabled technological solutions for food and water applications was pervasive in discussions throughout the meeting. For example, the opening plenary lecture by BASF stressed the importance of academic research and publications in promoting public acceptance of the technology and the development of pragmatic regulatory frameworks for nano-enabled agrochemicals. In general, the regulatory challenges surrounding the safety and acceptance of nanotechnologies for food production, handling, transport, and storage must be addressed. Technologies for treating water (especially drinking water) and food using nanomaterials will surely be heavily scrutinized by the public to ensure safety. Tools to quantify the benefits of the technology, as well as

evidence that the nanomaterials used in the treatment are not themselves problematic, are needed. Effective management of risk perception by consumers and manufacturers is needed, including transparency and education. Methods to effectively convey the cost/benefit ratio for these technologies in a way that promotes public awareness and acceptance are needed. Communication tools that empower consumers to produce less food waste must be developed alongside technology development to truly promote sustainability. It will also be important to communicate the realistic scope of impacts that nanotechnology, or any technological solution, with respect to achieving sustainability. The scientific and engineering community can promote sustainability best by not overselling the potential of technological advances as a panacea for the critical challenges at the FEW nexus, but rather acknowledge the importance of these contributions alongside behavioral changes in consumption and an increased acceptance of a shared world where benefits and costs accrue to all. Finally, a culture change in industry to adopt safe-by-design principles is needed.

*Potential for longer-term high-risk, high-reward research*

The workshop participants identified a number of opportunities where nanotechnology may significantly benefit the FEW nexus. However, in many cases there was not a clear indication of how the desired materials could be created, and ultimately manufactured at large scale for a reasonable cost. This included e.g., nanomaterials that respond to their environmental conditions (e.g. the need for a particular nutrient, materials with high selectivity for an analyte and with an easily measureable property such as a specific spectral signature based on its interactions with environmental constituents) for use as dispersed sensors. There were also a number of highly desirable engineering applications, e.g. distributed sensing of agricultural lands, or the ability for real-time sensing of animal health using nano-enabled (contact lens) sensors on their eyes. Workshop participants suggested the need for exploratory high risk-high reward research in these cases where a clear path to realization of the technology is highly uncertain.

Other potential high risk/reward opportunities were also discussed including development of artificial media for plant growth (since soil is a limiting resource). In these cases, nanotechnology may be used to create materials with tunable water holding capacity, texture, metal immobilization, and delivery of essential nutrients at the appropriate rate. Incorporating $N_2$-fixing capability could eliminate the need for nitrogen fertilizers. However, questions remained about such an approach: Can the media be recyclable/ reusable? Can the necessary soil microbiome be created? Is this approach sustainable, or is production and application of the technology simply shifting the water and energy inputs to other areas (e.g. material synthesis)? Other ideas included methods to synthetically, increase the photosynthetic

efficiency of plants through nano-enabled manipulation of enzyme production or efficiency, or accelerate plant growth with plant growth hormones delivered using nanomaterials. It was noted that many of these approaches would face significant skepticism from the public and regulatory agencies that would have to be addressed.

*Valuing (Nano) Technology's Benefits for Agriculture*

Agricultural goods and services contribute both public and private benefits, as well as incur public and private costs. Valuing these public and private benefits and costs will be critical to evaluating the sustainability and economic viability of nanotechnology innovation at the FEW nexus.

Unfortunately, agricultural systems are particularly difficult to value. On the public side, there is wide variability in valuation of public goods from stated preference, revealed preference, and participatory approaches. Similarly there is significant uncertainty and wide spatial variability when valuing the public health damages associated with agricultural, water, and energy systems. Valuing public costs using restoration costs is difficult because restoration is rarely undertaken. On the private side, valuing benefits and quantifying costs is similarly difficult. Inputs to agricultural processes are often based on non-market or under-valued (subsidized) market goods like water, energy, and land. There is significant uncertainty in fertilizer-yield relationships for agricultural systems, meaning that adding additional fertilizer may help in some years or locations but be completely ineffectual in others. Finally, highly variable worldwide commodity prices on food make the price paid for agricultural goods and the margin for agricultural products uncertain.

While technology diffusion generally occurs naturally when public and private net benefits increase, there is less comprehensive understanding of how to guide technology development when public and private net benefits are ambiguous. Regulatory intervention to reduce public damages from agricultural systems, for instance, has been slow to be implemented, relying on voluntary measures and incentives. Subsidies to encourage private adoption of practices that benefit public goods can generate secondary market distortions. A more comprehensive understanding of best practices in the regulatory and subsidy space for agriculture will be important in both valuing nanotechnology benefits and driving innovation in technology development.

## Recommendations

There are a great number of opportunities for nanomaterials and nanotechnologies to promote sustainability at the FEW nexus. These range from development of highly sensitive and selective nanosensors for managing crop and livestock health, development of multifunctional nanomaterials for targeted and timed delivery of nutrients and medicines. System-wide optimization opportunities can be realized through nanomaterials applications for precision agriculture, more energy efficient distributed water treatment, and the ability to match treatment needs with the intended uses, better management of livestock health, and more efficient use of pesticides and nutrients (including recovery opportunities). The workshop recommends investments in basic science to support the 1) development of nanosensors for agriculture, animal health and husbandry, and pathogen detection. This includes development of the infrastructure required to distribute and power the sensors, and the analytical tools needed to analyze the data. 2) Development of multifunctional and environmentally responsive nanomaterials to enable targeted delivery and timed releases of important agrochemicals. 3) Development of nano-enabled platforms for pathogen detection and intervention along the farm to fork continuum. 4) Development of nanomaterials for antimicrobial surfaces, antifouling surfaces and disinfectants. 5) Development of nano-enabled pharmaceuticals for veterinary purposes and other agricultural purposes, 6)Development of multifunctional nanomaterials with high selectivity (adsorbents, reactants, or membranes) for use in water treatment, recovery of high value materials in wastewater and food waste. Also, fundamental research is still needed to determine the relationships between specific material properties and the elicitation of a desired response. A technoeconomic gap analysis should be performed for proposed nanotechnology based solutions to identify the highest value opportunities. Tools are needed to better perform these analyses at the integrated systems level. However, we recommend that the NSF ask applicants for INFEWS projects to include some analysis of potential systems-level benefits of any proposed engineering solution for sustainability at the FEW nexus. Finally, there is a pervasive need for qualitative, quantitative and communication based tools to support regulatory and social acceptance of nano-enabled technological solutions for food and water applications.

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## Appendix A: Pseudo-NGT As Applied to eliciting priorities for nanotechnology's role in the Food, Energy, Water Nexus

*Introduction*

The pseudo-Nominal Group Technique (pseudo-NGT) is an organized approach to eliciting opinions from a group of individuals, structured so as to facilitate discussion across a group while ensuring that diverse perspectives are heard. Guided by an appointed facilitator, each individual is given an equal opportunity to offer her or his views about the topic around which the pseudo-NGT session is centered. The approach utilized here differs in one small but important way from traditional NGT, which would ask participants in the group to come prepared to advocate for one of a prescribed set of options that would be prepared and distributed prior to the meeting by organizers. In the pseudo-NGT process utilized for this meeting, participants were instead asked to generate recommendations, in an open-ended sense, in reaction to a charge question and to some preparatory documents that summarized the challenges and opportunities for research *in general* at the Food, Energy, Water nexus. After reflecting on preparatory materials and in consideration of their own individual expertise, participants were each asked to ***come prepared to advocate for the top priority areas of research where nanotechnology may have a role to play in achieving sustainability at the FEW Nexus.*** These facilitated discussions are typically most successful with group sizes ranging between 18-25 at the most, so workshop participants were divided into three groups that each carried out a separate pseudo-NGT process.

The output of NGT and pseudo-NGT processes is typically a ranked list; as indicated by the charge to participants, this workshop was designed to generate a ranked list of areas where nanotechnology can help achieve sustainability at the FEW nexus. This list of opportunities was generated the first day, and the top ranked opportunity areas were then addressed in further detail in dedicated smaller break-out groups on Day 2, who generated descriptive lists of the critical scientific and engineering challenges to realizing those solutions.

*Ground Rules*

For best success in utilizing the tightly scheduled time for maximum output during the pseudo-NGT process, it is helpful to set expectations and agree to process-specific etiquette in advance of breaking into groups.

Ground rules agreed upon for the facilitators of each of the three breakout groups were to:

- Capture participants ideas as close to verbatim as possible so that people are visibly able to see that their input is driving the process
- Gently but strictly enforce the schedule and NGT time limits using an audible timer
- Make any real-time judgment calls about the process with the guiding principles in mind to make sure everyone feels adequately heard yet trusts the leader to stay true to the structured process, and to avoid derailing tangential discussions by staying focused on the charge.

Ground rules requested for the participants of each of the three breakout groups were to:

- Be on time and engaged for all portions of the sessions
- Honor time limits
- Refrain from interrupting, honoring the NGT round robin structure to utilize one's allotted turns to voice any dissenting opinions
- Honor the progressive design of the workshop, so that once ideas have been consolidated, evaluated or voted on, the group focuses on the next steps at hand without referring to any potential previous disagreements. (In exchange, it is promised that dissent will be captured in sidebar and represented in workshop report.)

**Day 1**

***The goal of Day 1 was to generate a ranked list of areas where nanotechnology can help achieve sustainability at the FEW nexus.***

Each of the three break-out groups, with membership pre-assigned by conference organizers, met in a closed room set up in a U-shaped format so that all participants and the facilitator were visible to one another for the entire discussion process. As a starting point, each group was provided a suggested subset of overall FEW nexus sustainability challenges as listed in the NSF report circulated as a pre-read for the event, though participants were not required to limit themselves to only these areas if one that they felt strongly about fell outside those bounds.

*Round-Robin*

Posted on the wall of each room was the charge to participants, to maintain focus on the day's task: "What is the top priority research area where nanotechnology can help achieve sustainability at the FEW nexus?". The process consists of a timed round-robin elicitation of each individual's opinions and reasoning for their nomination of top priority area, with multiple rounds carried out until everyone's ideas were represented (the agenda was designed so that this would be possible within the timeframe; typically a group of ~20 people needs 1.5-2 hours for the round robin brainstorm process). Each workshop participant, going around the U-shaped table in order, was given a timed 2 minutes to present her or his case for why their suggestion should be ranked as a high priority for further attention in a Day 2 breakout group. (See Figure 1, excerpted from the brief training presentation made to all workshop participants prior to the pseudo-NGT process). Though participants were asked to address one topic per turn, in terms of content one could choose to use their allotted time in whatever manner they preferred: to advocate a new idea, to support a previously suggested choice, to critique or de-prioritize a previously suggested choice, or to offer a rebuttal to a previous critique. No visual aids were allowed by participants, but every person's contribution was captured on a separate, numbered sheet of a flip chart, which were then placed in order around the perimeter of the room. Throughout this process, the wording on the flip charts is verified as adequately representing the intended meaning of the contributor; it is explicitly forbidden to

focus on consolidating points, rather, all of the ideas are listed separately to maintain the purity of the brainstorm. During this time, a rapporteur documents the points on the flip charts as well as pertinent discussion detail.

At the end of this round-robin brainstorm process, the room is filled with numbered ideas representing the thoughts of all group members.

**What to do with your 2 minutes**

1) Briefly introduce yourself.
2) State the most promising area where nanotechnology can help to achieve sustainability at the FEW nexus, and why.
   - When you are making your 3 minute "case", you are advocating for why people should prioritize your suggestion as important.
   - You want to encourage the highest # of people possible to ultimately vote for this nano-enabled FEW Nexus opportunity as a high priority to ensure it receives detailed attention in later sessions.
3) If you agree/disagree with a previous participants' priority, you can use your time to state this along with your rationale.
4) Be mindful of the 2 minute time limit.

**Figure 1: NGT Guidelines for Participants**

*Consolidation*

The facilitator then leads the group through a loosely structured process of seeking consensus for which of the brainstormed areas are redundant, or similar enough that they should be grouped into a single priority area. A prompt appeared on the wall of the room with a guiding criterion for whether or not two numbered sheets should be lumped together in one: if the priority was elevated to the top for further consideration on Day 2, would further evaluations in terms of scientific and engineering challenges differ greatly between the two areas? Or would discussion of one area really cover both? Groups could handle this according to their collective preference for whether to have people offer suggestions of areas that jump out as belonging together, or whether the facilitator would systematically start with #1 and ask for any areas that should be consolidated, then move forward around the room. Throughout the discussion, the rapporteur for the group types on a screen that is projected for the room to see, capturing a title for each consolidated area that encompasses all aspects included in the grouped area. For this workshop, these titles were entered into an evaluation table for further consideration against benefit criteria in a next step. This process typically takes ~30 to ~45 minutes, and at the end of this exercise the group has produced a streamlined list of priority areas, consolidated into a smaller number and ready for evaluation.

*Evaluation*

The consolidated list of ideas for each break-out group were then evaluated against a table where the rows were the consolidated areas where nanotechnology has potential to help achieve sustainability at the FEW Nexus, and the columns included descriptive aspects of their potential realization and benefits. Groups were permitted to add columns if desired as well. See Figure 2 for table template.

**Figure 2: Day 1 Consolidated List Evaluation Table**

| Number | Nanotechnology Enabled Opportunities | Potential for Sustainability Impact | Criticality of Nanoscale Engineering to Enabling Approach | Magnitude and Severity of Potential Risks | Potential for Global Implementation | Cost Feasibility |
|---|---|---|---|---|---|---|
| # | e.g. Sensors for water moisture | High/Med/Low | High/Med/Low | High/Med/Low | High/Med/Low | High/Med/Low |

The purpose of generating these tables was to provide a methodical, semi-consistent thought process for groups to walk through consideration of the relative strengths of the various ideas. Though there was not a formal analysis of these tables, the exercise serves as a process to bring individuals through a final review of their collectively generated ideas prior to the voting process.

*Voting*

Finally, participants voted for their top priority ideas in a secret ballot process. Each person had ten votes to distribute however they desired across the consolidated list; multiple votes could be cast for one priority. Facilitators tallied the votes at the end of the day, and the top four priorities from each group were elevated for consideration on the second day. These top 12 priority areas were then consolidated overnight according to facilitator judgment. Some were directly redundant across groups and were therefore consolidated. Two other priority areas were more general, but the detailed notes supporting the group discussion showed that they included aspects that were directly aligned with multiple high priority areas. For those two, the general areas were distributed across the relevant aligned areas, and detailed aspects were included as notes underneath those priority areas such that everyone on Day 2 would be able to recognize the language of their top priority nano opportunities within the 7 final prioritized areas.

**Day 2**

***For each of the priority areas identified on Day 1, the goal of Day 2 was to develop detailed, descriptive lists of the scientific and engineering challenges to realizing the opportunities for nanotechnology to help achieve sustainability at the FEW nexus.***

In the morning of Day 2, the facilitator presented the consolidated results of the Day 1 process, along with the charge for Day 2. For each of the prioritized areas, a smaller dedicated break-out group was asked to carry out a self-facilitated NGT process. For the prioritized promising area where nanotechnology can help to achieve sustainability at the FEW nexus, groups were asked to state the most critical scientific and engineering challenge to realizing that solution.

Each of the top 7 priority areas were listed out on a flip chart page; these pages were then placed around the perimeter of the plenary room, visible to all participants. After plenary, participants were asked to select the topic that they felt most interested in and qualified to address, with the constraints that each group should ideally have no more than five and no fewer than three members. Groups were asked to utilize a flip chart and easel for visible brainstorming, and were provided with an MS PowerPoint template to prepare their report-outs and guide the development of their detailed recommendations.

Each group was only tasked with a single topic area, but due to individual variations in the timing for groups to address a topic fully, we also provided some secondary topics that groups could choose to work on if they should finish the first. Two of these topics gathered the un-prioritized areas pertaining to energy and to water. It was noted that though this was a workshop focused around the Food–Energy–Water Nexus, most of the discussion and prioritization centered around Food-related aspects of this nexus. However, multiple priority areas appeared across all three groups that pertained to energy and water, so a flip chart page was prepared and hung for Energy issues, and Water issues. Another set of topics common to all groups but not elevated in any of them centered around nano-bio materials development and synthetic systems and food development, so this was also offered as a topic to address. As it turned out, each of these were indeed addressed by groups as well.

At the end of Day 2, each group presented their results, detailing for each topic:

1. In what ways would this nano-opportunity impact sustainability at the FEW nexus? (e.g. decrease water inputs, increase crop yield per kW, etc.)
2. How would you describe the role this technology might play in achieving sustainability at the FEW nexus?
3. What prevents us from realizing this nano-enabled opportunity today?
   (Barriers; large scale challenges, e.g. we cannot control the pore size in a membrane well enough to pull out phosphorous)
4. What are specific scientific and engineering challenges to being able to address the barrier(s) listed in #2?
   (More specific limitations, e.g. we don’t understand phase inversion casting well enough)

## Appendix B: Detailed outputs of the discussions in the three Day 1 Breakout Groups

### Day 1 Breakout Group Activities and Detailed Notes

Groups were color-coded for logistical direction, and divided into three sets of pre-assigned participants. As a starting point, each group was provided a suggested subset of overall FEW nexus sustainability challenges as listed in the NSF report circulated as a pre-read for the event, though participants were not required to limit themselves to only these areas if one that they felt strongly about fell outside those bounds. Detailed results of all discussions on Day 1 are included per group below.

#### *Green Group*

16 Participants

Facilitator: Joshua Viers

Rapporteur: Eleanor Spielman-Sun

Charged with the topics of: Crop protection and agrochemicals (pesticides and fertilizers), Soil quality maintenance, and Closing the loop on N&P cycling.

*Results of NGT Round Robin:*

This section includes notes as captured by the rapporteur. For this group, the notes represent the brainstormed ideas seen throughout the room as well as additional points of discussion in chronological order.

1. Enhanced efficiency of fertilizers (particularly phosphorus)
2. Targeted pesticide delivery to reduce runoff and overspray; Increase specificity for pests
3. Recovery of nutrients from run off; reuse for energy
4. Field deployable low cost, easily deployable rapid detection strategies for pathogens or toxins present in foods
5. Phosphorus / nitrogen recovery
6. Carbon recovery for energy
7. Veterinary medicine
8. Minimizing food waste with antimicrobials
9. Sensors for detections of pathogens
10. Livestock→ safety of livestock and water for livestock; prevention of pathogens
11. Multifunctional nanomaterials that can release nutrients/ pesticides; time release

12. Sensors are incredibly important to focus on the nanoscale and then move up to the global scale to share the data (scale up by big data analytics); globally and locally;
13. Nitrogen and phosphorus; soil moisture content→ nano should be bio based
14. Non energy-intensive materials for fabrication
15. Nanoelectronics must be degradable
16. Nanoporous materials have potential if they can be engineered for multifunctionality
17. Low cost nano-vaccines for livestock and poultry (note, MUST be low cost in order to be competitive with current vaccines) such as salmonella and other pathogens
18. Use of nanoremediation for toxins in foods
19. Using nanosensors to help developing a more agro-ecology model; can tailor field to environmental conditions
20. Micronutrients; how do we package micronutrients so they can be delivered to plants rather than just ending up in the environment;
21. Synchronize crops and nutrients; nano-bio sensors; tailor crop to nutrient needs
22. Produce nutritious food
23. NNCO were looking for nanotechnology inspired challenges; processes for pre-disease detector, treatment, and therapeutic interventions; tracking of animals from field to plat; decreasing greenhouse gas emissions;
24. Development of smart field systems; using drones with sensors to detect in the canopy the early onset of plant diseases and the implementation
25. Developing of new plant varieties that are more drought resistant
26. Processing that occur in soil water properties in relation to other soil properties; soil water interface for more targeted ; minimizing leaching and minimizing application rates
27. Applied irrigation: ways of integrating or sorbing contaminants from waste streams for agriculture;
28. Crop soils; crop protectants; reducing of salinity; either NP added to soils
29. Multifunctional smart biodegradable nutrient systems for nutrient and pesticides
30. Targeted delivery→ less impact on environment
31. Echoing 32, delivering cocktails for herbicides to deal with resistance; coupled to the idea of triggered release
32. Similar to 17 and 24; diagnosing livestock health; cost effective vaccines; triggered release of antibiotics only when needed (to deal with antibiotic resistance)
33. Similar to 13: if we are going to use sensors, they need to be degradable electronics
34. Improving efficacy; improving EH&S, reducing residue on food and commodities
35. Soil quality; nanotechnology to limit soil erosion and compaction, and nutrient reduction
36. To deal with nitrogen in soils to reduce nitrogen leaching
37. Spray drift to reduce aquatic exposure; by standard exposures
38. Crop residues, target plant injury (crop protection)
39. Groundwater and surface water contamination; human exposure and environmental exposure
40. Bring pollinators; direct exposure and indirect exposure; pesticide spray, dust from seed coating, eliminating fugitive dust; pollen and nectar (less exposure, less active ingredients to crops) targeted delivery
41. Turn data into decisions
42. Targeted delivery to reduce waste and run off
43. We’re leaving out energy and forgetting our part of the FEW nexus; these are good sustainability things, but not necessarily for FEW nexus
44. Decreasing the energy cost of nitrogen for fertilizer
45. Agriculture for biofuels; can we use nano to get more energy from cellulosic conversion of corn
46. In situ remediation of groundwater
47. Bioproducts are becoming more of an issue than biofuels in terms of potential value
48. Can we make nano-bees as a substitute for bees being destroyed, to substitute as pollinators

49. Soil quality from a compaction, chemistry, physics, organic matter, nutrient depletion
50. Development of new plants with drought tolerance and resistance to flood
51. Market for more plant based fabric instead of polyester
52. Increase efficiency of separation of biomaterial and plants (use NP to extract flavonoid)
53. Growing food molecule by molecule
54. Can plants be grown without soil at all? Artificial soil (not just hydroponics)
55. Is there a way to increase photosynthesis of plants (if we can do it with photovoltaics)
56. Can there be a spray that could disperse the dust particles so the plant can get more sunlight (cleaner leaves= less scattering) or something to broaden the energy spectrum of the leaf
57. Cosmetics are moving away from microplastic beads toward nanocellulose
58. Bio-based nanomaterials
59. Industrial ecology approach

*Results of Consolidation and Evaluation:*

| Nanotechnology Enabled Opportunities | Potential for Sustainability Impact | Criticality of Nanoscale Engineering to Enabling Approach | Magnitude and Severity of Potential Risks | Potential for Global Implementation | Cost | Barriers to Adoption | FEW Nexus System |
|---|---|---|---|---|---|---|---|
| 1. Smart Nanomaterials | High | High | Med | Med/ High | med | High (regulatory and trade) | High |
| 2. Recovery, Remediation, Recycling | high | High | Med | High | Med | Low/ med (trade) | High |
| 3. Nanosensors and Analytics | Med | High | Med | Med | Med | Low (privacy concerns) | High |
| 4. Animal Health | High/ med | High | Med | high | Med | Med (regulatory) | Med/ high |
| 5. Carbon Cycling | High | Med | Low | High | Med | Low | High |
| 6. Sustainable Nano-Bio materials | High | High | Low | high | Med | Low | Med/low |
| 7. Artificial Systems | Low | High | High | Low | high | High | high |

*Results of Voting:*

| # | Area | Votes | | | | | | | | | | | | | | Count | Rank | Percentage |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | **Smart Nanomaterials** | 3 | 1 | 6 | 7 | 3 | 3 | 3 | 5 | 0 | 4 | 0 | 2 | 2 | 4 | 43 | **1** | 31% |
| **2** | **Recovery, Remediation, Recycling** | 3 | 1 | 2 | 3 | 0 | 0 | 3 | 1 | 0 | 0 | 4 | 1 | 2 | 1 | 21 | **4** | 15% |
| **3** | **Nanosensors and Analytics** | 2 | 4 | 2 | 0 | 5 | 1 | 4 | 4 | 0 | 0 | 3 | 2 | 2 | 2 | 31 | **2** | 22% |
| **4** | **Animal Health** | 2 | 2 | 0 | 0 | 0 | 4 | 0 | 0 | 10 | 4 | 0 | 1 | 2 | 1 | 26 | **3** | 19% |
| 5 | Carbon Cycling | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 5 | 6 | 4% |
| 6 | Sustainable Nano-Bio materials | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 2 | 2 | 3 | 0 | 1 | 10 | 5 | 7% |
| 7 | Artificial Systems | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 4 | 7 | 3% |

***Pink Group***

15 Participants

Facilitator: Christine Ogilvie Hendren

Rapporteur: Katherine McMahon

Charged with the topics of: Ensuring food security and safety, Minimizing food waste, Reducing energy inputs in food production, processing, and distribution

*Results of NGT Round-Robin:*

This section includes notes as captured by the rapporteur. For this group, the notes represent the brainstormed ideas seen throughout the room as well as additional points of discussion as grouped underneath the relevant ideas; not always chronological.

1) Water
    a) Using nano to improve treatment and desalination to increase water supply /maintain or increase production of food
    b) Techniques that quantify the costs of desalination
2) Sustainably ensure the agricultural production (plant and animal based) system to meet pop growth and health needs
    a) Use nano to improve plant and animal resistance to stress / diseases via technologies for:
        i) Early detection
        ii) Better treatment
3) Sensors to minimize food waste by detecting properties / status and communicating that info to people
    a) Conversation Note: important to consider in what system we're considering the "best idea" – developing world vs. developed world
    b) Support for resource intensive products (milk or meat)
4) Crop protection: 10-25% of crop grown is lost to pests and pathogens : i.e. targeted nanoscale micronutrients
    a) Ex. Work to date (Jason White) has shown that by spending $ on copper significantly increased yield ($100 spent turned in 128K increase)
5) Capturing energy from waste (food waste and animal waste products)
    a) 141 Trillion calories wasted /year
6) Take stuff off fields (waste reduction for energy) may reduce soil carbon and micronutrients
7) Logistical issues of food waste: reducing via refrigeration (energy connected
8) Sensor applications in nanotech to detect and monitor in high resolution of environmental conditions (spatial and temporal detail) for agriculture, water treatment
    a) Conversation note: several participants noted their own lack of nano background; could imagine applications, but didn't know precisely the technological barriers, challenges, details

9) Sensors to minimize resource waste on unacceptable plants (e.g. already infected) – remove from production immediately
    a) Belongs in 5: Create value added bio products from the waste – utilization component – transform waste products into a higher value product
10) Antimicrobial uses of nanotech to enhance food safety - reducing risks from microorganisms and food borne illnesses – and minimizing food spoilage.
11) Intelligent food packaging: nano for preservation and to indicate spoilage (e.g. RFID to detect oxidation)
    a) Intelligent Materials design of packaging, e.g. Polymeric matrix to control gas transfer
    b) Belongs in 5: capture wasted energy / use nanotech to capture wasted water and organic compounds
12) Use of nano is indirect when used in sensing. Nanosensors: state changes, plasmon resonance enables single molecule detection; oxidation detector (e.g. ag nano wire).
13) Reduction of electricity transmission with smart distribution materials (smart grid technology, e.g. armchair quantum wire)
14) Edible nano coatings… (was suggested that this belongs in 10/11 – group required a few redirections to not consolidate during brainstorm, only freely brainstorm)
15) Convo Note: Should we start with properties of nano we want to use? OR applications of nano to specific food areas: there are many ways to seemingly attack the problems. Look at challenges that are issue cutting: e.g. sensors can be used for enviro detection/ food waste minimization / water issues.
16) Could be consolidated with #7. Use nano to improve heat transfer efficiency: minimize energy.
17) Targeted deposition of pesticides (environmental justice aspect)
18) Energy and water lifecycle analysis of manufacturing nano? Compare with the positive sustainability impacts to ensure a net benefit to sustainability.
19) Surface properties control the rates of absorption / release of water, fertilizer ex. naturally-occurring sorbents, to immobilize soil or proactively determine soil content
20) Nano-bio materials for diverse applications: extracted proteins from spinach to exploit photosynthesis for light energy conversation.
21) Energy input in food chain – 30% of it occurs within home/food service industry. Opportunity for nano in smarter appliance industry. Tech need is quite different.
22) Note: Shifting expectations of food: education? Communication?
23) Important note: we would like to include in the final report an aspect of non-technical development, but which is critical to sustainability at the nexus: communication involving the expectations for technological development and impact as far as ensuring sustainability. The group articulated that it would be irresponsible to roll out technologies in a way that furthers a message that technological advancements will increase efficiency to the point that behaviors do not need to change. We believe that people will have to consume less, waste less, and participate in the notion of a shared world in addition to realizing benefits conferred by nanotechnology or any other advancement. It is the opinion of this group that this message should be included as part of a communication plan that would be developed in tandem with new technologies.

*Results of Consolidation and Evaluation:*

| Number | Nanotechnology Enabled Opportunities | Potential for Sustainability Impact | Criticality of Nanoscale Engineering to Enabling Approach | Magnitude and Severity of Potential Risks | Potential for Global Implementation | Cost Feasibility |
|---|---|---|---|---|---|---|
| | e.g. Sensors for water moisture | High/Med/Low | High/Med/Low | High/Med/Low | High/Med/Low | High/Med/Low |
| 1 | Increase agricultural efficiency<br>-crop protection<br>-high resolution sensors for conditions of crops and enviro<br>-animal production | H | H | L | H | M (range) |
| 2 | Nano-enabled targeted delivery to agro-systems | H | H | unknown | H | M |
| 3 | Food Safety (Detection and Intervention Approaches) | H | H | L | H | M |
| 4 | Food Waste and Loss (Detection and Intervention and Recovery Approaches) | H | H | L | H | M |
| 5 | Increased Energy Efficiency (Heat Transfer, refridge, etc) | H | H | L | H | L (required) |
| 6 | Protect water quality for food safety and security (preventing transmission of pathogens, detection technology, treatment) | H | H | L | H | L |
| 7 | Food Quality (eg Nutriceuticals) | H | H | L/M | H | Unknown |
| 8 | Nano-Bio Materials | H | H | M | L | It depends |

*Results of Voting:*

| | Area | Votes | | | | | | | | | | Count | Rank | Percentage |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Increase agricultural production and efficiency | 2 | 1 | 2 | 2 | 2 | 3 | 4 | 1 | 4 | 3 | 24 | 1 | 24% |
| 2 | Nano-enabled targeted delivery to agro-systems | 2 | 3 | 2 | 1 | 2 | 2 | 2 | 0 | 0 | 3 | 17 | 4 | 17% |
| 3 | Food Safety | 1 | 2 | 4 | 2 | 2 | 0 | 3 | 4 | 2 | 2 | 22 | 2 | 22% |
| 4 | Food Waste and Loss | 2 | 3 | 0 | 2 | 1 | 3 | 0 | 2 | 3 | 2 | 18 | 3 | 18% |
| 5 | Increased Energy Efficiency | 1 | 1 | 0 | 0.5 | 1 | 1 | 0 | 0 | 0 | 0 | 4.5 | 6 | 5% |
| 6 | Nano-enabled water quality protection for food safety and security | 2 | 0 | 0 | 0.5 | 1 | 1 | 1 | 0 | 1 | 0 | 6.5 | 5 | 7% |
| 7 | Food Quality | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 2 | 0 | 0 | 4 | 7 | 4% |
| 8 | Nano-Bio Materials | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 4 | 7 | 4% |

***Yellow Group***

14 Participants

Facilitator: Meagan Mauter

Rapporteur: Megan Leitch

Charged with the topics of: Water supply and treatment; applications of smart sensor grids for precision agriculture

*Results of NGT Round Robin:*

This section includes notes as captured by the rapporteur. For this group, the notes represent the brainstormed ideas seen throughout the room as well as additional points of discussion in chronological order. In some of the cases within this section, the ideas are attributed to the contributing participant for ease of following the discussion as well.

1) Navid – WS&T – disinfection of water in the area of fisheries:
   a) Why? Fishes are grown in water. Disinfection in indoor fisheries /raceways an issue. High-density. 10-20% water recycled – if it contains bacteria and parasites disinfection important. High hardness
   b) Challenges? UV disinfection used High hardness
   c) How and why nan? Increase efficiency of UV, new materials
2) Omowunmi – SNO, Chemist perspective
   a) Don't study in isolation, study in situ (how we live), vs autopsies of systems, things are interconnected
   b) Oxidative/chlorine resistance membranes (for RO)
      i) Think beyond polyamides polysulfones)
      ii) Resistance, nano sensors, low cost
3) Mark – water treatment side much less promising for nano- we've been working on it for 25-30 years, still haven't been integrated
   a) water system – look at water distribution and provision system, interface agriculture land and city. Optimize design of entire system, then look for holes.
4) Brandi - NSF: Sensor side- hyperspectrally responsive materials - nano as delivery systems for pesticides (things that sense thing you can see from outer space/remotely)
5) Mario
   a) Mandate by congress to DOE – "waste" no longer exists as a word. (nanotechnology to extract resources/nutrients on wastewater) at point of collection – sense what is coming to the treatment plant, redirecting waste, , – especially if everything is decentralized
6) Mario –
   a) His bias opportunities lie in "miniaturization of sensing" improve operational efficiency
   b) Design a nervous-system – detect water-main breaks, etc. – new materials
7) Mario –
   a) Sensor in water/fluid (laced/dosed to tell you something about the infrastructure)

b) Automatic repair mechanisms (nano) (self-healing mechanisms)

8) Jie hu – Sensors Monitor water quality in situ (doesn't necessarily have to be nano). Apply nano to treat water – for nutrient recovery and removal.
9) Pedro –solar based systems, photo disinfection for off-grid water treatment and reuse. Combine density function theory with CFD. Important for emergency response. Minimize fresh water withdrawal. Niche for distributed water system
10) Greg Theis – Policy perspective –
    a) A way to reduce agricultural water footprint – better controlling chemical inputs (runoff, etc.) (water protection)
    b) Use of water for non-food, feed or fiber applications.
    c) Optimize to better balance needs of cities/private businesses. Use of water for producing fuels, recreational purposes (golf courses) economics tradeoffs.
11) Paul – regulating cheaply – expensive point source of information not useful for CA. Where water is, who owns it, how it moves. What constituents are in the water in the soil. Endorse sensors for orbital detection, other distributed sensor. (we can choose how to
12) Nick – Distributed sensors – many can industries can apply
    a) Opportunities to measure/monitor/manage ag networks using nanotech. Lack of reliable high density, reliable ground trothing.

Round 2

13) Navid – we're thinking about tech transfer – unprecedented capacity for increasing efficiency via nano
    a) Water treatment continues to be a problem
    b) Minimizing energy to treat water using nano
    c) Specificity of sensors is where nano can help.
14) Suomisa – sensor needs to be in-situ, distributed, multiparametric. Nano can help.
15) Mark – expanding #4 – groups with 5, 6, 7, 2
    a) Take particles with hyperspectral responsive characteristics (responsive to a chemical, a delivery agent (and qty thereof), and be
    b) Response to water treatment solar tech - membrane cost scales with packing density – if photocataylic/sunlight dependent
16) Brandi – on board with sensors. NSF – need to look for things that are completely disruptive, look 50 years in the future, don't fall into the trap of using existing infrastructure.
17) Brandi – addition – resources waste water – close the nitrogen/phosphorus cycle denitrification is very energy-intensive. Can we leave it in the WW, somehow extract using nano.
18) Mario – likes that sensing idea. Like hyperspectrally responsive materials. – can be used in distribution systems.
19) Jie –
    a) sensor development – developing sensor for e-coli in water, and phosphorus level.
    b) Lots of challenges for e-coli monitoring –, real time, current methods detect viable and nonviable. Recycling nitrogen.
20) Pedro –whether we want to or not, we might need to rely on distributed water systems.
    a) Water industry is much more used to centralized treatment.
    b) Need to begin coupling models of with modularized systems. Need to work on model.
    c) Life cycle techno-economic assessment will inform network topology
21) Greg –
    a) Public acceptance of sensors in drinking water – difficult

b) New EPA rule – waters of the US – permitting locations. Monitoring where permits are required through sensors. Every producer may need to buy permit. Sensors must be inexpensive, long life (like fire alarms with 10 year life, disposable).

22) Paul – heart is in sensors.
    a) Distributed networks. Applying water desalination to inland brackish, particularly for selective removal of contaminants. Difficult to operate distributed networks.
    b) Waters of the US – comment interesting 0 now regulating non-navigable waters , but don't know what's in those waters.
23) Nick – need to monitor nitrogen for grapes, very variable – nitrogen sensor needed for those tracking an input and for those tracking contaminants – like synergy around sensor networks

One more round of edits:

24) Brandi – If you build it, they will come. Need a platform for multiple purposes universal systems for data management.

Round3:

25) Navid – We talked about infrastructure. Need to consider off-grid people – need to target nanotech to impact people who don't have distribution system. Nano an equalizer. Modular: Off-grid techs can be combined with on-grid. Nano can help
26) Suomi – Sensors are resonating. Nano can help with –
    a) Enhancing sensitivity without increasing noise (in many matrices).
    b) Sensor selectivity.
    c) Need to go beyond sensors in the workshop – what type, what do they do?.
        i) Robustness
        ii) Bias,
        iii) Response time
        iv) Cost
        v) Matrix effect
27) Mark –
    a) Wouldn't differentiate between local and remote sensing (hyperspectral – local characteristic sensed remotely)
    b) Haven't explored the intermediate space between on-grid and off-grid. What does the system look like? What are the gaps? That's where nano-enabled technologies fit in. True for any system. Developing world issue – they want to be on the grid, not another high-tech solution for a bottle of water.
28) Pedro – in mega-cities, definitely; in Bangladesh – with arsenic, don't give us another well, give a water treatment plant
29) Brandi – we're funding research across the world
30) Mario – Mention we haven't discussed nano's impacts on batteries for energy storage. Necessary for water supply treatment applications, powering sensors, etc.
31) Jie - Promising area – water treatment. If we can use NP, large surface area, tailored adsorption to make water treatment more sustainable – reduce use of chemicals large-scale chemicals.
32) Pedro – Revolutionary vs. evolutionary conundrum; ½ the hospital beds in the world are filled with people with water-borne illnesses. Add to Navid's comment - use nano to help "the bottom billion"
33) Greg –
    a) All new data collected from sensors should be open platforms. Inability to filter out what's in public drinking water, including pharmaceuticals – of

b) If nano/membranes can help this, then we should do it.
c) Consider life cycle of sensors. – What is their disposal/recycling plan (don't create an environmental problem)

34) Paul – Data sharing resonates with me. Anyone with access to land-sat can have the data. Data-sharing to prevent redundancy? Standardization/centralization of data processing
35) Meagan – there's a material life-cycle, and there's a data life-cycle
36) From Liz Casman – nano-enabled "artificial" noses to detect aromatics released by plants (response to plant tissue damage, ripening or rot, dark fruit, insect pheromones.
37) From Pedro – do we have a sufficient, well-trained workforce? Teach our students to know, rather than to "do". They don't know how to do a business plan, they are not trained to be entrepreneurs. We need to develop our workforce in US.
38) Nick – need bioinformatics, modeling people in addition to a traditional workforce (horticulturalists, etc.). If you gave him nanosensors today – who would run them?
39) Greg – where's the money coming from to support all this? IF the sensor technology is launched, departments and agencies need focus to figure out how to obtain and spend limited money. (Need a high-level look at where agencies are spending their money)
40) Brandi – need students who can talk about and advocate for science in DC
41) Navid – reinvigorate NSF education program for students work with industry. Broader impacts (working with industry).

*Discussion During Consolidation Process*

- Nick – 12, 4 => "A"– "Nano to protect water sources" Sensor technology development – platforms applied to agriculture
- Paul => Add "21a" to "11" – Modification to agriculture markets, cost of doing business. Downstream effects of nano-implementation for agriculture.
- Greg => agree 21a+11 "B"– Managing downstream effects. Add 10 (nano to protect water resources) to 12 and 4.
- 37+33a – Sustainability of nanotechnology
- 12+4+10 "A"=> We're using this nanotech to protect water resource
- 5a+8 => "C" "Nanomaterials for resource recovery" (nutrient recovery)
- Jie – Add 17 and 31 to the 5a+8 group.
- Brandi – add 10b to "B"
- 37+33a "D" Framework for workforce development impact nano-enabled businesses
- 27a,b+9+3 +25= "E"–"Gap analysis for system configurations and nano-applications." Once you do the evaluation, then you see where nano fits in. "25" – see where nano can help. Should evaluate where nano should NOT fit in, "Strategic deployment of nanotechnology for…." Cost and benefit analysis of water provision systems. Limited to water/wastewater.
- Add 2B to 28a,b – "F" – Nano-enabled membranes
- Add 2A Study of systems in situ to "E"
- Add 29 to "B" (Materials lifecycle
- 1, 13 "G" "Nano for disinfection needs relevant to aquaculture" –
- 19b +26– "H" Sensors for food safety – both upstream and downstream "nano to distinguish b/w viable and non-viable pathogens." Downstream and upstream, sensitivity + selectivity
- 30 – "I" – Nano for Batteries, energy storage, to power sensors
- 24+ 7a – Nano for nutrient sensing
- "C" Nano for resource recovery
- "K" (from 36) Nano-enabled artificial noses to detect aromatics.

*Results of Consolidation and Evaluation:*

1-“A” Enhanced spectral signal with ground-level nanosensors

2- “B” Distributed nano-sensors for regulatory compliance

3-“C” Nano for nutrient recovery

4- “D” Framework for inter-agency workforce-development impacting nano-enabled businesses

5- “E” Technology-gap analysis for system configurations and nano-applications

6- “F” Nano-enabled membranes

7- “G” Nano for disinfection needs relevant to aquaculture

8- “H” Nano sensors for food safety

9- “I” Nano for batteries/power sources for sensors

10- “J” Nano for nutrient sensing and management in aqueous systems

11- “K” Nano-enabled artificial noses to detect aromatics (in air)

12- “L” Use of nanotechnology to track and direct water resources

13- “M” Nano-sensor enabled automated systems for decision-making

*Results of Voting:*

| | Area | Votes | | | | | | | Count | Rank | Percent |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Enhanced spectral signal with ground- level nanosensors | 3 | 3 | | | | 2 | 2 | 10 | 1 | 13% |
| 2 | Distributed nano-sensors for regulatory compliance | | 1 | 8 | | | | | 9 | 2 | 11% |
| 3 | Nano for nutrient recovery | | | 2 | 4 | | 2 | 2 | 10 | 1 | 13% |
| 4 | Framework for inter-agency workforce development impacting nano-enabled business | | 1 | | 1 | 2 | | 1 | 5 | 3 | 6% |
| 5 | Technology gap analysis for system configurations of nano applications | 4 | | | 1 | 2 | 2 | 1 | 10 | 1 | 13% |
| 6 | Nano-enabled membranes | | 2 | | | | | | 2 | 4 | 3% |
| 7 | Nano for disinfection needs relevant to agriculture | | | | 8 | 1 | | 1 | 10 | 1 | 13% |
| 8 | Nano sensors for food safety | | | | | 2 | | | 2 | 4 | 3% |
| 9 | Nano for batteries/ power sources for sensors | | | | | | 2 | | 2 | 4 | 3% |
| 10 | Nano for nutrient sensing and management in aqueous systems | | 2 | | | 4 | 1 | | 1 | 8 | 3 | 10% |
| 11 | Nano- enabled artificial noses to detect aromatics (in air) | | | | | | 1 | | 1 | 2 | 4 | 3% |
| 12 | Use of nanotechnology to track and direct water resources | 3 | 1 | | | | 2 | 2 | | 8 | 3 | 10% |
| 13 | Nano-sensor enabled automated systems for decision- making | | | | | | 1 | | 1 | 2 | 4 | 3% |

**Day 2 Breakout Group Activities and Detailed Notes**

The discussions of the first day resulted in a total of 28 areas, a combined 12 of which rose to the top of the voting process by taking the top 4 from each of the three breakout groups. These top 12 priority areas were then consolidated overnight according to facilitator judgment. Some were directly redundant across groups and were therefore consolidated. Two other priority areas were more general, but the detailed notes supporting the group discussion showed that they included aspects that were directly aligned with multiple high priority areas. For those two, the general areas were distributed across the relevant aligned areas, and detailed aspects were included as notes underneath those priority areas such that everyone on Day 2 would be able to recognize the language of their top priority nano opportunities within the 7 final prioritized areas.

Table 1 below shows the top 7 ideas as prioritized from Day 1 for further consideration on Day 2. They are listed here in two groups, but not in ranked order, because there was not a method for normalizing the votes across the three groups. In addition, reporting a quantified ranking falls outside of the justifiable interpretation of this method, which is intended to elevate important ideas to the top but not necessarily to generate quantitative data.

**Table 1: Top 7 areas of opportunity for nanotechnology to support sustainability at the FEW Nexus**

| Group | Consolidated Topics from Day 1 – Top Priority |
|---|---|
| 1 | Nanosensors and Analytics<br>Enhanced spectral signal with ground-level nanosensors<br>Distributed nano-sensors for regulatory compliance<br>Increase agricultural production and efficiency: high resolution sensors; minimize resource waste |
| 2 | Nano for nutrient recovery<br>Recovery, Remediation, Recycling<br>Food Waste and Loss: recovery approaches |
| 3 | Technology gap analysis for system configurations of nano applications |
| 4 | Food Waste and Loss: detection and intervention approaches<br>Nano for disinfection needs relevant to agriculture: anti spoilage |
| 5 | Food Safety: detection and intervention approaches<br>Nano for disinfection needs relevant to agriculture: anti food borne illness |
| 6 | Smart Nanomaterials for fertilizers/pesticides<br>Nano-enabled targeted delivery to agro-systems<br>Increase agricultural production and efficiency: targeted nanoscale micronutrients |
| 7 | Animal Health: protection, detection and intervention approaches<br>Increase agricultural production and efficiency: improve animal resistance to stress<br>Nano for disinfection needs relevant to agriculture: protecting animal health |

Table 2 shows the remaining ideas that did not receive sufficient votes from across all breakout groups.

Table 2: Brainstormed ideas from Day 1 breakout groups that were not prioritized highly for further consideration on Day 2

| Unconsolidated Topics from Day 1 - Not Top Priority |
|---|
| Carbon Cycling |
| Sustainable Nano-Bio materials |
| Nano-Bio Materials |
| Artificial Systems |
| Increased Energy Efficiency |
| Nano-enabled water quality protection for food safety and security |
| Food Quality |
| Framework for inter-agency workforce development impacting nano-enabled businesses |
| Nano-enabled membranes |
| Nano sensors for food safety |
| Nano for batteries / power sources for sensors |
| Nano for nutrient sensing and management in aqueous systems |
| Nano-enabled artificial noses to detect aromatics (in air) |
| Use of nanotechnology to track and direct water resources |
| Nano-sensor enabled automated systems for decision-making |

From these topics, three additional options for break-out groups were prepared in the event that they finished their primary tasks and had bandwidth to undertake another. These are shown in Table 3 below; of these, Topics 8 and 10 were ultimately addressed by break-out groups.

Table 3: Consolidated "Bonus Topics" for groups to address in the event they had additional time

| Group | "Bonus Topics" – Combined from non-prioritized areas commonly identified across all groups |
|---|---|
| 8 | Water:<br>Nano-enabled membranes<br>Nano-enabled water quality protection for food safety and security<br>Nano to track and direct water resources |
| 9 | Energy:<br>Increased energy efficiency<br>Nano for batteries / power sources for sensors |
| 10 | Sustainable nano-bio materials<br>Artificial systems |

*Breakout group activities: Detailed notes by Topic Area*

1. Nanosensors and Analytics
   Enhanced spectral signal with ground-level nanosensors

   Distributed nano-sensors for regulatory compliance

   Increase agricultural production and efficiency: high resolution sensors; minimize resource waste

Group members:

Nick Dokoozlian

Gregory Theis

Peter Vikesland

Paul Welle

Title: Nano-enabled systems & distributed sensing systems

a. In what ways would this nano-opportunity impact sustainability at the FEW Nexus?
   - Decrease water inputs
   - Decrease energy inputs
   - Decrease cost to operate
   - Decrease food waste
b. How do you describe the role this technology might play in achieving sustainability at the FEW nexus?
   - Nanosensors have potential broad applicability to detect parameters of interest in a diverse array of environments.
   - Parameters of interest: pathogens, nutrients, moisture, pH, etc…
   - Potential environments: air, water, soil, porewater, plant/animal tissue, etc…
   - We considered a 'sensing system' to be composed of three parts:
   - The sensor – the device that does the sensing and reports.
   - The transmission system – relays the output from the sensor to the user and/or network.
   - Data analysis network – big data analytics
   - Why Nano? A disruptive technology that will enable highly distributed, real-time sensing of key performance metrics or other parameters of interest
   - Depending on desired application may be low cost (e.g., paper-based devices) or higher cost (e.g., multiplex detection in real-time)
   - Recoverability leads to sustainability
   - Potentially a game changer that is comparable to GPS, smart phones, and cloud based computing.
c. What prevents us from realizing this nano-enabled opportunity today?

- Much of research in the nanosensor field has been done within the medical community. This valuable research has provided support for the general utility of nanosensors to the FEW nexus, but the applicability and use of these existing sensors in highly variable water, soil, plant, and animal environments needs to be critically assessed.
- Safety issues
- Longevity concerns (biofilms, degradation)
- Recoverability/reuse issues
- These concerns vary depending on use
- Transition of laboratory-based research to real world field applications remains minimal due to lack (perceived or real?) of funding to support this transition.

d. What are specific scientific and engineering challenges to being able to address the barrier(s) listed in section c above?
   i. Knowledge transfer between developers and users – need to inform developers (who might not know what needs to be sensed), users (who might not know what can be sensed), and research funders (who might not be aware of the differences between biomedical applications and FEW applications).
   ii. Key questions to consider in sensor design and use:
      - How to maintain sensor over time?
      - Should sensor be recoverable and/or reusable?
      - Should sensor be degradable or permanent?
      - Should it be highly distributed (lower-cost) or centralized (multiplex)?
      - Toxicity of nanosensors?
      - Redundancy of design?
      - Power supply for sensor and/or transmission system?
      - Variability in sensor response from point to point as well as temporally?
      - How will the collected data be used? Who will have access?
   iii. Appropriate scale of 'sensor system development' – should we start at small scale (i.e., point of use) or at larger scale (i.e., distributed sensor networks)

e. Value added – additional section created by this group to describe who would accrue the benefits of developing these technologies
   - Value for regulators:
     Larger database for more accurate and scientifically based regulation
   - Value for those being regulated:
     - Better functioning systems
     - Able to offer a defense for regulations that are perhaps too stringent
   - Cooperation between these actors (data-sharing, careful regulation) is critical

2. Nano for nutrient recovery
   Recovery, Remediation, Recycling

   Food Waste and Loss: recovery approaches

Group members:

Brandi Schottel

Jie Xu

Jerome Rose

Leanne Gilbertson

Lorenzo Booth

Title (Report out notes divided into two portions):

1: Multi-functional Platforms Category

a. In what way(s) would this nano-opportunity impact sustainability at the FEW nexus?
    - Decreases water inputs (medium potential)
    - Decreases energy inputs (medium potential)
    - Decreases nutrient footprint (high potential)
    - Decreases cost to operate (medium potential)
    - Increases crop yield per dollar (medium potential)
    - Increases crop yield per gallon (low potential)
    - Increases crop yield per kilowatt (high potential)
    - Decreases food waste (high potential)

b. How do you describe the role might this technology play in achieving sustainability at the FEW nexus?
    - Multifunctional platforms can be used as a unit process across different systems, to recover nutrients or energy, depending on the specific need.
        - For example: A reactive membrane that can produce different carbon by-products (methane or ethanol) from crop waste.
    - Nanotechnology in biological reactors can be very selective/target specific organics.
    - Multifunctional platforms can be used as a unit process across different systems, depending on need.
        - For example: A reactive substrate or batch reactor that can produce different carbon by-products (methane or ethanol)
    - Can improve efficiency by recovering energy from crop waste, reducing the energy footprint of a food production operation.
    - Can potentially aid in the removal of antibiotic resistant organisms or other novel pathogens from waste streams.

c. What prevents us from realizing this nano-enabled opportunity today?
    - Regulations which prevent the adoption of novel techniques
    - Training of scientists familiar with specific food/agriculture applications of nanotechnology.
    - Uncertainty regarding benefits of nanotechnology for unit processes

        - E.g. heat exchanger increase efficiency from reactions of organic waste streams

d. What are specific scientific and engineering challenges to being able to address the barrier(s) listed in section c above?
    - We don't fully understand the fate/toxicity of nanomaterials in the environment and the impact on the food chain/system in question (waste water stream, etc.).
    - Challenges in separating nanomaterials from the recovery product
    - Challenges in unit process efficiency
    - Dealing with the complexity of the matrix (e.g. wastewater or waste solids)
    - Specifically, interfaces between several chemical components, and dependence on pH, salinity, etc.

2: Separation/Recovery, Reversible Collection, and Remediation/Treatment

a. In what way(s) would this nano-opportunity impact sustainability at the FEW nexus?
    - Decreases water inputs (medium potential)
    - Decreases energy inputs (medium potential)
    - Decreases nutrient footprint (high potential)
    - Decreases cost to operate (medium potential)
    - Increases crop yield per dollar (medium potential)
    - Increases crop yield per gallon (low potential)
    - Increases crop yield per kilowatt (high potential)
    - Decreases food waste (high potential)

b. How do you describe the role might this technology play in achieving sustainability at the FEW nexus?
    - Recovery opportunities for desired resources
        - The meat / fat / protein that currently goes to solid waste
        - The meat / fat / protein that goes to wastewater
        - Water from agricultural waste
    - Associated with these recoveries – separation processes might be developed
        - Non-membrane (biofouling)
        - Liquid-liquid
        - Replace chemical techniques currently used
        - Removal of pathogens and high organics from water
    - Nanocatalysis in anaerobic digestion
    - Enhanced transformation processes
    - N, P, Metals (Cu, Zn),organic carbon
    - Removal of undesirable contamination from waste streams
        - Pharmaceuticals
        - Metals (potentially As, Se depending on stream type)
    - Nano can preclude the incineration of waste products (since incineration efficiency are poor in general)
    - Could target waste along the supply chain including
        - In the field – farmers

        a. Overproduction
        b. Not fit for consumption, but still usable
    - Distribution and processing
    - Consumer
    - End of life

c. What prevents us from realizing this nano-enabled opportunity today?
    - Certain desired resources are so cheap as to make recovery not economically practical.
    - Realizing this opportunity does not have to rely on a nano-solution

d. What are specific scientific and engineering challenges to being able to address the barrier(s) listed in section c above?
    - Chemistry challenge regarding the potential interactions between different components in the waste stream.
    - Identifying platforms (materials or unit processes) appropriate for accomplishing the desired outcome.
    - Choosing nanomaterials that are selective for desired contaminants.
    - Remediation would not be necessary given sufficient advances in recovery and separation.
    - Designing reversible collection technology
        - Separate/remove, then release
        - Recover nanomaterial and the resource (e.g. nutrient) or contaminant (e.g. organics in wastewater)
        - Non-exchanger (e.g. heat/energy released from processing)

Group members:

3. Technology gap analysis for system configurations of nano applications

Group members: Mark R. Wiesner

Because this group was comprised of a single member, he elected to directly generate the text for inclusion in the workshop report.

4. Food Waste and Loss: detection and intervention approaches
   Nano for disinfection needs relevant to agriculture: anti spoilage

5. Food Safety: detection and intervention approaches
   Nano for disinfection needs relevant to agriculture: anti food borne illness

The same group chose to address both topics 4 & 5 at once, because they were closely related and the same people had interest in addressing both.

Group members:

Michael Appell

Hongda Chen

Phil Demoktritou

Jennifer Gaddis

Helen Nguyen

a. In what ways would this nano-opportunity impact sustainability at the FEW nexus?
   - Decreases water inputs
   - Decreases energy inputs
   - Decreases nutrient footprint
   - Decreases cost to operate
   - Increases crop yield per dollar
   - Increases crop yield per gallon
   - Increases crop yield per kilowatt
   - Decreases food waste

b. Challenges
   - 20% of illness is due to foodborne and consume more raw produce
   - Chemical-based, thermo-based, radiation, non-thermal
   - Drawback of current technique: decrease food quality, challenges to keep track of food (farm to fork), consumers' perception, cannot use chemicals for organic produce
   - Spoilage of food at consumers' house, retail, food processing, and farms.
   - Food packaging waste.
   - Chemical, thermal, non-thermal treatment to prevent spoilage.
   - Zoonotic diseases for food safety.
   - Overuse of antibiotics
   - Reduced fertility and reproduction of animals

c. Opportunities for Technology Development (detection and intervention)
   - Develop nano-based antimicrobial disinfection across farm-to-fork including food packaging. Microbes: pathogens and spoilage microbes. Both crops and animals. Airborne and waterborne infectious agents.
   - Develop nano-based detection systems. Reduce cost. Real-time detection. Both crops and animals. Airborne and waterborne.
   - Develop nano-based vaccine to animals to prevent contamination.
   - Prevent adhesion of microbes to food surfaces and food processing surfaces.
   - Develop nano-based sorbents to control chemical contaminants
   - Develop detection system that individuals can use. User-friendly and robust.

- Low cost monitor temperature in real-time and space.
- Take out the high-valued components (zeins from corn)
- Develop packaging technology to keep food longer from farm to fork.
- Develop technology to remove no-value added products before food processing.
- Target delivery of drugs to animals. Increase efficacy of delivery.
- Improve fertility of animals using nanotechnology
- Preserve drugs using nanotechnology

d. Scientific challenges
- Environmental and human (consumer and worker) safety of nano-based technologies.
- Sensitivities in complex food matrixes. Low detection limit. Viable (infectious) and dead pathogen detection.
- Complex food chemistry and interactions with nanomaterials
- Cost of time temperature indicator and other technology.
- Variability in food waste (from commodity to commodity)

e. Implementation challenges
- Industry adoption
- Risk perception for consumers and manufactures
- Scalable and cost-effective technology
- Life cycle of products
- Tools and communication to empower individuals to detect food spoilage
- Lack of regulation framework
- Culture change for both consumers and providers

6. Smart Nanomaterials for fertilizers/pesticides
   Nano-enabled targeted delivery to agro-systems

   Increase agricultural production and efficiency: targeted nanoscale micronutrients

Group members:

Jason White

Chris Dimkpa

Cristina Sabliov

Eleanor Spielman-Sun

Sonia Rodrigues

a. In what way(s) would this nano-opportunity impact sustainability at the FEW nexus?
- Decreases water inputs (medium potential)
- Decreases energy inputs (medium potential)
- Decreases nutrient footprint (high potential)

- Decreases cost to operate (medium potential)
- Increases crop yield per dollar (medium potential)
- Increases crop yield per gallon (low potential)
- Increases crop yield per kilowatt (high potential)
- Decreases food waste (high potential)

b. How do you describe the role might this technology play in achieving sustainability at the FEW nexus?
   - The amount of agrochemicals greatly applied exceeds the amount needed→ Major efficiency issue
   - Nano-based solutions to increase agrochemical efficiency, which will reduce energy and water upfront (mostly indirectly, in the production side, not field), but will also increase food yield
   - Could potentially use these formulations to grow plants in arid soil locations; allows you to grow plants in more marginalized land (more for developing countries rather than US); can package it all together (micro/macro nutrients and pesticides= multifunctional)
   - Decrease loss in waste stream

c. What prevents us from realizing this nano-enabled opportunity today?
   - Material formulation aspects to optimize plant growth
   - Tracking and analyzing fate of the NM in the soil/plant systems (method development)
   - Regulatory aspects
   - Social acceptance

d. What are specific scientific and engineering challenges to being able to address the barrier(s) listed in section c above?
   - Design and formulation of materials; properties(size, shape, surface properties)
   - Fate of nano-formulations in relation to soil type, linked to sensor based soil testing.
     - Design challenges given the different types of soils
   - Mechanism of uptake in relation to plant characteristics
   - Targeted→ pesticides
     - Systemic responses from a biological standpoint
     - Can we have genetically targeted pesticide delivery
   - Tracking organic NMs in soil and plants (need method to do this, much easier for inorganics)
   - Tracking fate/ degradation products of NMs

e. Extra Category – Topic #10: Artificial Systems
   - General point: Is [the concept of artificial systems] really sustainable from an energy/ water efficiency point of view (or are we just trading one for the other)
   - Artificial media for plant growth (since soil is a diminishing resource):
   - Can we come up with an alternative sand?
   - Can the media be recyclable/ reusable?
   - Challenge= getting the microbiology correct
   - Synthetically fortify foods
   - Synthetically grown meat
   - Nano-scaffolds

- How can we better control the texture and taste?
- Increasing photosynthetic efficiency of plants
- NP catalyst to increase enzyme efficiency?
- TiO2
- Can we create nano-pollen? (if we kill off too many bees)
- Can we accelerate plant growth with plant growth hormones
- Can we deliver these hormones with NP?

7. Assigned topic:
   Animal Health: protection, detection and intervention approaches

   Increase agricultural production and efficiency: improve animal resistance to stress

   Nano for disinfection needs relevant to agriculture: protecting animal health

Title: Animal Health Monitoring, Management, and Commerce

Group members:

Norman Scott

Robert Tilton

Elizabeth Casman

Jason Unrine

Navid Saleh

This group summarized the topic overall, but then spent most of their efforts working on detailed descriptions of the challenges across five specific technology areas addressing this nano-enabled opportunity area. After this summary section, they are detailed each as a separate opportunity in this section.

a. In what way(s) would this nano-opportunity impact sustainability at the FEW nexus?
   - Decreases water inputs
   - Decreases energy inputs
   - Decreases nutrient footprint
   - Decreases cost to operate
   - Increases crop yield per dollar
   - Increases crop yield per gallon
   - Increases crop yield per kilowatt
   - Decreases food waste

b. How do you describe the role might this technology play in achieving sustainability at the FEW nexus?
   - Achieving sustainability by improving animal the health of herds, flocks, and schools
   - Minimize overuse of medications
   - Prevent disease transmission to humans
   - Animal waste conversion to resources for energy and materials
   - Greenhouse gas reduction via waste management and intervention of enteric GHG production
   - Disinfection of aquaculture and poultry process water to enhance animal health and achieve sustainable farming

c. What prevents us from realizing this nano-enabled opportunity today?
   - Developing appropriate materials and diagnostic systems

d. What are specific scientific and engineering challenges to being able to address the barrier(s) listed in section c above?
   - Design and engineering materials, systems, and devices to detect, prevent, and treat diseases while enhancing productivity and adequately managing waste

Disease Detection Surveillance

a. In what way(s) would this nano-opportunity impact sustainability at the FEW nexus?
   - Decreases water inputs
   - Decreases energy inputs
   - Decreases cost to operate
   - Increases crop yield per dollar
   - Increases crop yield per gallon
   - Increases crop yield per kilowatt
   - Decreases food waste

b. How do you describe the role might this technology play in achieving sustainability at the FEW nexus?
   - This opportunity will potentially decrease water and energy loss via prevention of loss of animals
   - Improves water quality by reducing unnecessary drug use
   - It can achieve cost reduction while enhancing yield per dollar, per gallons of water, and per KW energy
   - Such detection and surveillance technology can reduce food waste by saving animals

c. What prevents us from realizing this nano-enabled opportunity today?
   - Specificity to identify bio-targets
   - Selectivity and overcoming interferences
   - Sensitivity
   - Cost
   - Durability
   - Need for multiplexing (system integration) and pattern recognition

- Miniaturization of detection devices
- Identifying agents in air has significant challenges for detection

d. What are specific scientific and engineering challenges to being able to address the barrier(s) listed in section c above?
   - Identifying appropriately responsive nanomaterials that are cheap and environmentally benign

Disease Control (Vaccines and Drugs)

a. In what way(s) would this nano-opportunity impact sustainability at the FEW nexus?
   - Decreases water inputs
   - Decreases energy inputs
   - Decreases cost to operate
   - Increases crop yield per dollar
   - Increases crop yield per gallon
   - Increases crop yield per kilowatt
   - Decreases food waste

b. How do you describe the role might this technology play in achieving sustainability at the FEW nexus?
   - This opportunity will potentially decrease water and energy loss via prevention of loss of animals
   - Improves water quality by reducing unnecessary drug use
   - It can achieve cost reduction while enhancing yield per dollar, per gallons of water, and per KW energy
   - Such disease control technologies can reduce food waste by saving animals

c. What prevents us from realizing this nano-enabled opportunity today?
   - Administering them in a mass-scale cheaply
   - Efficient delivery of proteins and nucleic acids
   - Overcoming biological barriers for uptake
   - Alternative antimicrobial agents that are less susceptible to antibiotic resistance; e.g., biophysics-based antibiotics

d. What are specific scientific and engineering challenges to being able to address the barrier(s) listed in section c above?
   - Developing agents that are potent, selective, and safe
   - Bio-compatibility
   - Non-perishable agents

Estrus Detection

a. In what way(s) would this nano-opportunity impact sustainability at the FEW nexus?
   - Decreases water inputs
   - Decreases energy inputs
   - Decreases cost to operate

- Increases crop yield per dollar
- Increases crop yield per gallon
- Increases crop yield per kilowatt
- Decreases food waste

b. How do you describe the role might this technology play in achieving sustainability at the FEW nexus?
   - This opportunity will indirectly decrease water and energy loss via prevention of loss of animals
   - It can achieve cost reduction while enhancing yield per dollar, per gallons of water, and per KW energy
   - Will enhance economic and operational sustainability of farming

c. What prevents us from realizing this nano-enabled opportunity today?
   - Sensor-platforms need to be developed to monitor appropriate chemical signal
   - Detection, response, and transduction need to be achieved

d. What are specific scientific and engineering challenges to being able to address the barrier(s) listed in section c above?
   - Appropriate molecule detectability required
   - Detectability at low concentration necessary
   - Development of devices needed
   - In situ and ex situ detection need to be achieved

Animal Waste and Greenhouse Gas Management

a. In what way(s) would this nano-opportunity impact sustainability at the FEW nexus?
   a. Decreases water inputs
   b. Decreases energy inputs
   c. Decreases nutrient footprint
   d. Decreases cost to operate
   e. Increases crop yield per dollar
   f. Increases crop yield per gallon
   g. Increases crop yield per kilowatt
   h. Decreases food waste
   i. Minimize GHG emissions

b. How do you describe the role might this technology play in achieving sustainability at the FEW nexus?
   - Offsetting cost
   - Toward “self-sustaining” farms in terms of energy
   - “Zero-discharge” farms
   - Generating value added products from waste stream
   - Decrease climate footprint by reducing GHG emission

c. What prevents us from realizing this nano-enabled opportunity today?
   - Develop feed additives that reduce methane production in the gut
   - Soil amendments to reduce $N_2O$ reduction

- Odor control
- Biogas purification

d. What are specific scientific and engineering challenges to being able to address the barrier(s) listed in section c above?
   - Catalysts for pre- and post-treatment
   - High surface area sorbents
   - Distributed energy via combined heat and power process

Water Quality Needs for Fish and Animal Health

a. In what way(s) would this nano-opportunity impact sustainability at the FEW nexus?
   a. Decreases water inputs
   b. Decreases energy inputs
   c. Decreases nutrient footprint
   d. Decreases cost to operate
   e. Increases crop yield per dollar
   f. Increases crop yield per gallon
   g. Increases crop yield per kilowatt
   h. Decreases food waste
   i. Reducing pressure on natural fisheries

b. How do you describe the role might this technology play in achieving sustainability at the FEW nexus?
   - Low energy water treatment
   - Alternative disinfection technologies for indoor fish farming (recirculating water)
   - Alternative chemical and other disinfection techniques for poultry processing
   - Novel nano-particulate biodegradable flocculants for organismal and particulate contamination

c. What prevents us from realizing this nano-enabled opportunity today?
   - Using traditional disinfection techniques
   - Process optimization
   - Large microbial load and water flow rate need to be addressed
   - Immobilized antimicrobial agents
   - Biodegradability is preferred

d. What are specific scientific and engineering challenges to being able to address the barrier(s) listed in section c above?
   - High efficiency processes
   - Efficacy, safety need to be achieved
   - Fish tolerance to materials used
   - Colloidal stability
   - Avoid antimicrobial resistance
   - Alternative chemicals (instead of chlorine)
   - Alternative physical processes for disinfection

8. Assigned topic:
   Nano-enabled membranes

   Nano-enabled water quality protection for food safety and security

   Nano to track and direct water resources

Title: Nano for water applications

Group members:

Omowunmi Sadik

Megan Leitch

a. In what way(s) would this nano-opportunity impact sustainability at the FEW nexus?
   - Decreases water inputs
   - Decreases energy inputs
   - Decreases cost to operate
   - Increases crop yield per dollar (definitely)
   - Increases crop yield per gallon
   - Increases crop yield per kilowatt (maybe)

b. How do you describe the role might this technology play in achieving sustainability at the FEW nexus?
   - Nano incorporated into water applications should reduce energy inputs, reduce waste (of water or nutrients in run-off, wastewater, etc.)
   - Implementation of nano should be considered not only for its economic and energy benefits, but for its potential as an equalizer for the "bottom billion"

c. What prevents us from realizing this nano-enabled opportunity today?
   - Economics:
     - Energy and materials costs associated with nano-innovations are high
     - Clear economic benefit to implement nanotech enhancements (vs. existing or alternate new technologies) have rarely been demonstrated
   - Scientific advancement is still needed:
     - Next-generation ENMs (bio-based, multifunctional nanostructures) required for targeted separation/sensing in complex media
   - Social/regulatory acceptance
     - Particularly for use of nanotechnology in drinking water applications
     - Low-Risk/Sustainability must be proven

d. What are specific **scientific** challenges to being able to address the barrier(s) listed in section c above?

- Design and control of multi-functional nano-scale chemistry and geometry of surfaces for specific water treatment applications. e.g.:
    - Lowering hydrophobicity of membranes
    - 3D structures for fouling control and disruption of concentration polarization
    - Prevention of organic/inorganic/bio fouling of surfaces/membranes
    - To improve transport/sorption properties and approach thermodynamic minimum in separation (membrane- or sorption-based)
- Design of alternative technologies for disinfection (use of renewable/waste energy sources and/or reusable ENMs vs. electricity (UV) and/or bulk chemical treatment)
- Design using earth-abundant, inexpensive materials
- Design of ENMs in water distribution networks
    - Sensing quantity (Flow monitoring, water break detection)
    - Sensing quality (Contamination/pathogen detection)
    - Improving/maintaining water quality
- Design of bio-enabled or bio-based ENMs for specific, effective targeting in complex water matrices
- Design of self-healing materials

e. What are specific **engineering** challenges to being able to address the barrier(s) listed in section c above?
- Process-level-challenges:
    - Process design for incorporation of nanotechnology in large systems
    - Economic scale-up
    - Predictive modeling to determine where nano is
        - More effective
        - Cheaper
        - Safer…. Than standard/alternate technologies
    - Effective design for use of photoactive materials without increasing capital cost
- Application-level-challenges
    - Irreversible incorporation of ENMs in membranes or on surfaces without loss of functionality
    - Sustainable/green fabrication methods (low-energy, non-toxic byproduct, etc.)
    - Design to maintain nano-related benefits despite operational conditions (fouling, cleaning processes, etc.) *over entire life cycle*
    - Design for acceptable ENM fate (re-use, vs release into environment)

## Workshop Participants list-Appendix C

| | Name | Affiliation | Expertise |
|---|---|---|---|
| 1 | Lowry, Greg | CMU | Nano and water/food |
| 2 | Hendren, Christine O. | Duke University | Nano/NGT |
| 3 | Karn, Barbara | SNO | Nano/Sustainability |
| 4 | Sadik, Omowunmi | Binghamton University | Membranes/water and energy |
| 5 | Safarpour, Maximillian | BASF | Industry perspective on targeted pesticide and fertilizer delivery |
| 6 | Viers, Joshua | UC Merced | Agricultural hydrologist, sustainability |
| 7 | White, Jason | Connecticut Agricultural Experiment Station | Nano/agriculture |
| 8 | Wiesner, Mark R. | Duke University | Membranes, water treatment, nano |
| 9 | Appell, Michael | USDA | Keynote : Food Security |
| 10 | Dokoozlian, Nick | EJ Gallo | Keynote : Sensors |
| 11 | Mauter, Meagan | CMU | Keynote : value of innovation |
| 12 | Alvarez, Pedro | Rice/NEWT | Keynote : Energy -water |
| 13 | Casman, Liz | CMU | Public policy, nanomaterial fate, systems |
| 14 | Chen, Hongda | USDA | Nanotechnology and food production |
| 15 | Cheung, Chin | University of Nebraska-Lincoln | Nanochemistry |
| 16 | Cohon, Jerry | CMU | Water Resources/Optimization |
| 17 | Tilton, Robert | CMU | Surface Science/Polymers |
| 18 | Demoktritou, Phil | Harvard | Nano for food preservation |
| 19 | Dimkpa, Christian | VFRC | fertilizers, nano-agriculture |
| 20 | Hanson, Jaydee | ICTA | NGO |
| 21 | Matthews, Scott | CMU | LCA/Energy/Food |
| 22 | Morgan, Granger | CMU | Public policy, systems, sustainability |
| 23 | Murray, Jeff | BASF | Nanopesticides |
| 24 | Rose, Jerome | CEREGE | Nanomateirals/LCA |
| 25 | Rubin, Ed | CMU | Energy Systems/Climate |
| 26 | Sabliov, Christina | LSU | Nanopesticides |
| 27 | Saleh, Navid | UT Austin | Water/Nano |
| 28 | Savage, Nora | NSF | Env. Eng. Program officer |
| 29 | Scott, Norman | Cornell University | Sustainability/Energy |
| 30 | Thies, Greg | Skyand Policy Group | Ag/Nano/Policy interface |
| 31 | Vikesland, Peter | Virginia Tech | Sensors/Water |
| 32 | Xu, Jie | Ga Tech | Sensors |
| 33 | Berges, Mario | CMU | Sensor networks |
| 34 | Gaddis, Jennifer | University of Wisconsin-Madison | Interdisciplinary ecology / food / nutrition |
| 35 | Gilbertson, Leanne | Univ. of Pittsburgh | LCA/Nano |
| 36 | Jaramillo, Paullina | CMU | Energy Efficiency |
| 37 | Nguyen, Thanh Huong (Helen) | University of Illinois, Urbana Champaign | Viruses and agriculture |

| | | | |
|---|---|---|---|
| 38 | Unrine, Jason | University of Kentucky | Nanomaterials and soils/agricultural products |
| 39 | Rodrigues, Sonia | Aveiro University | Soil Chemistry |
| | **Students** | | |
| 40 | Booth, Lorenzo | UC Merced | Hydrology |
| 41 | Bohra, Moiz | CMU | Water Treatment |
| 42 | Welle, Paul | CMU | Water Treatment |
| 43 | McMahon, Kate | CMU | Multivariate Analysis |
| 44 | Spielman-Sun, Eleanor | CMU | Nanoparticle plant interactions |
| 45 | Leitch, Megan | CMU | Membrane Tech |

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