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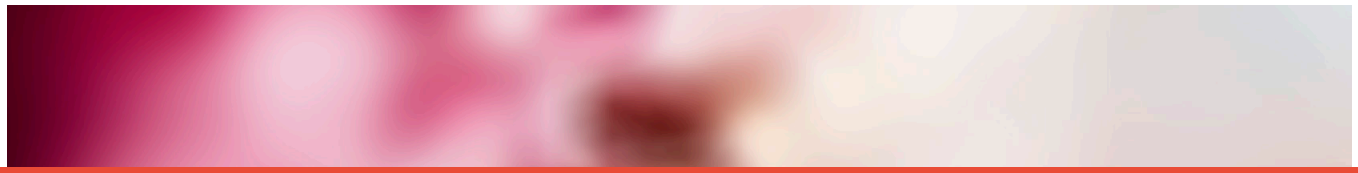
National Science Foundation Workshop on Food Safety Global Supply Chain Needs Final Report

National Science Foundation



NATIONAL SCIENCE FOUNDATION
WORKSHOP ON

FOOD SAFETY GLOBAL SUPPLY CHAIN NEEDS

FINAL REPORT

October 29–30, 2014
Alexandria, VA

Workshop Objectives

The objective of the NSF Food Safety Global Supply Chain Needs workshop was to provide a forum for disseminating information and sharing ideas about the frontiers of food safety research, education, and technology transfer. The workshop discussed the current state-of-the-art and future potential of food safety technology, analyzed the gaps between the future potential and the present reality, and identified what needs to be done in the areas of research, education, and technology transfer in order to close the gaps. The workshop was a two-day event (October 29-30, 2014) in Alexandria, Virginia. The workshop covered four themes: 1) Processes, 2) Global Trends, 3) Packaging, and 4) Supply Network Risk Management. Fourty-one speakers, representing thought leaders from government, academia, and industry, presented brief six-minute white papers to summarize their research goals, and to discuss specific needs that could be addressed though NSF participation in funding in food safety. This workshop had 71 participants, including the white paper presenters, keynote speakers, and representatives of government agencies. The ideas presented by the speakers and generated from the discussion sessions are summarized in this final project report. This report will be delivered to all workshop participants and relevant funding agencies as well as disseminated widely to industry, government, and academic stakeholders.

Background

Food safety combines a number of scientific disciplines fundamental to the handling, preparation, transportation, and storage of food ingredients and final products in ways that prevent foodborne illness. This includes understanding the risks about the sources and origins of food products, processing and packaging of food products, and the practices relating to import and export inspection and certification systems for foods.

Food safety is a multifaceted issue and made even more complex in today's global economy. By several estimates, imports of food account for a sizable portion of the food consumed each year in the United States. According to recent U.S. Food and Drug Administration figures, imports account for 80 percent of the seafood, 50 percent of fresh fruit, and 20 percent of fresh vegetables that we eat each year. While the benefit to the consumer is being able to enjoy a wide variety of foods all year round, there are challenges to consistently maintain a high degree of food safety.

Behind the scenes, hundreds of thousands of growers and processors worldwide are producing food for the United States and other markets. They use increasingly diverse and complicated processes. They manage complex and extended supply chain networks, and make millions of decisions every day that affect food safety. Many of these decisions are being made within countries that historically have had no effective health and regulatory systems in place for food safety and public health.

The private sector has stepped in to fill some of the gaps especially in training and educating the work force in emerging countries. That has helped to partially reduce risks to food safety and preventable foodborne illnesses. However, more work is needed to develop competencies and capacity building in food safety before there is uniformity in health protection practices and harmonized standards worldwide. The private sector is also challenged by the risk posed from a diversity of suppliers within supply chain networks especially beyond the first tier suppliers.

The global scale, exponential growth and complexity of the food system makes it impossible for the U.S. Food and Drug Administration, U.S. Department of Agriculture, and other regulatory bodies to employ historic approaches to food safety and still provide the assurances needed to maintain a high level of consumer confidence in the safety of food coming from global supply sources. Regulatory agencies and the private sector worldwide are transforming and adjusting to a paradigm where food is produced in a global market with a diversity of risks. That has led regulatory counterparts becoming stakeholders with the private sector to jointly focus on achieving a common goal of safe food for consumers everywhere.

Need for the Food Safety Workshop

Food safety is not a stand-alone issue. As the population on earth increases, it will require more food. The United Nations estimates that by 2050 the world will have nine billion people and we will need to increase food production by 60 percent. Food production is also tied to water and energy. Together this presents a rich set of research problems for NSF and other federal agencies to address in the near future.

As the supply chains used within the food industry have become increasingly globalized, there has been an increasing realization that process analytical technologies, food processing infrastructure, and best practices must evolve to enable more pervasive quality control against “natural” and intentional events that compromise food safety. As the supply chains used by the largest food manufacturers extend into countries with less stringent regulatory environments than the United States, and as a single packaged food product is likely to incorporate components that originate from many parts of the world, it is more necessary than ever to develop approaches that enable rapid traceability of these components, should a food safety crisis arise.

An area of opportunity of advancement is the integration of novel and innovative approaches from other technological areas into agricultural and food science for the screening of pathogens and chemical contaminants in real-time during growth, harvest, transportation, and processing. These technologies must be inexpensive, accurate, mobile, integrated by communication with data systems, and reliable. The food industry, recognizing the negative impact upon their business of adverse food safety events, including loss of public trust and the cost of recalls, is seeking new technologies that can efficiently and accurately assure the safety of their products to assuage the concerns of the public and build public confidence. For instances in which pathogen contamination, adulteration, chemical degradation, and unapproved ingredient substitution have the potential to lead to valuable time and effort being invested into the production of food products that must later be scrapped, the food industry is seeking technical approaches that can increase the speed and cost of characterizing the properties of ingredients and precursors before they are incorporated into downstream products. There is also tremendous interest in the development of technology that might prevent pathogenic or chemical contamination through innovation incorporated into food processing equipment, packaging, and safe antimicrobial ingredients. Having identified these needs, the food industry would benefit from a research program specifically targeted towards development of technology that can have a significant and broad impact upon food safety.

The workshop was intended to bring leading industry, government, and academic experts in the field of global food safety challenges to identify the most pressing gaps in the food safety infrastructure, and to

identify research areas in which investment by NSF can have the most impact in terms of fundamental new approaches in sensing, taking advantages of the emerging capabilities of "big data" networks for managing traceability within global supply chains, and approaches for incorporating new capabilities into food processing equipment and packaging. The workshop also explored topics in which development of the food safety workforce, regulations, food formulation, and education may have a substantial impact.

Keynote speakers

The following four keynote speakers shared their unique perspective:

Dr. Todd Abraham
Senior Vice President of Research and Nutrition
Mondelēz International, Inc.

Dr. Julie Callahan
Deputy Director, Strategy, Partnerships and Analytics
Office of International Programs
U.S. Food and Drug Administration

Prof. Michael Doyle
Regents Professor of Food Microbiology
Director, Center for Food Safety
University of Georgia

Dr. Robert Holland
Deputy Director for NIFA Operations
U.S. Department of Agriculture

Dr. Todd Abraham (Mondelēz International)

In his keynote presentation, Dr. Abraham described the industry perspective from the viewpoint of a global company that can compare the regulatory environment, research infrastructure, and government research support for food safety in the US, with those in other countries. Dr. Abraham noted that precompetitive research in the UK and Europe are getting ahead of the US in the areas of:

- Waste minimization
- Manufacturing of the future
- Health & wellbeing through diet
- Smarter packaging
- Food safety
- Authenticity & traceability
- Energy & water

Using "industry councils" to leverage corporate research investments with government agency funding; more than $500M for basic bioscience research related to food was cited in:

- Food Security, Bioenergy, and Industrial Biotechnology
- Basic Bioscience
- Underpinning Health

via:

- Knowledge Engineering, Innovation and Skills
- Exploiting New Ways of Working
- Partnerships

Companies such as Mondelēz International view food safety efforts as a pre-competitive core value of the company, for which they are willing to share technology and best practices with others. Mondelēz is reluctant to join academic-industry consortia that don't have a relevant business related end point or are general "liaison" programs, but instead seeks to engage directly with any faculty or startup company, regardless of their membership in a research center, if that individual or company can address a specific need. Mondelēz implements an "open innovation" process in which their current research challenges are posted on a special web site, thereby inviting interested parties to contact them with potential solutions.

Dr. Abraham specifically identified several areas for which he felt that NSF investments would have a substantial impact:

- Smarter packaging
- Waste minimization
- Building sensors into food systems throughout the supply chain
- Authenticity and traceability – developing systems for positive verification of ingredients
- "Self-protecting" non-harmful bacterial to adjust pH
- Fundamental biology research that addresses open issues in food metabolism and neurological sensations involving food (e.g., fat receptors, glucose modulation, gut microbiota, satiety mechanisms, sweet taste adaptation)

Dr. Julie Callahan (U.S. Food and Drug Administration)

Dr. Callahan's talk, entitled "Globalization and Food Safety," described statistics surrounding how much food and how many types of food are currently imported, and how many food shipments cross the US border every year. She emphasized that the US border can no longer be the first line of defense against the entry of unsafe products into the US. The situation presented makes it clear that it will be extraordinarily challenging, if not impossible, for a government agency with limited resources to test every shipment with any degree of thoroughness. Using specific food examples, Dr. Callahan described the complexity of the global supply chain, and the number of companies and countries that a food product passes through on its journey from its agricultural origin to the consumer. There approximately 240,000 registered export facilities in 200 countries that export products to the US. Dr. Callahan described the complexities that arise when each country has its own set of regulations and the difficulties posed by the lack of harmonized standards and allowable safe limits. FDA is embarking on building a coalition of regulatory agencies in countries with similar standards to accept and share the audit results of food production facilities. While New Zealand is the only country so far that FDA accepts inspection results from, the process will ease the regulatory inspection burden for all as more countries enter the coalition.

Dr. Callahan described the goals and impact of the recently adopted Food Safety Modernization Act (FSMA) that has the objective of preventing food contamination by regulating farmers, importers, manufacturers, and processors that may not have been subject to regulation in the past. New testing requirements and preventative control mechanisms are being put into place as a result of FSMA, although the law itself does not fund the development of new technical approaches or research. Performance indicators must be implemented to quantify whether FSMA is reaching its goals.

Dr. Callahan also listed several specific areas in which NSF funding may have an important impact:

- Detection devices
- Handheld devices
- Ways to detect pathogens without sending product to a lab
- Detect bootlegged drugs and inauthentic food products.
- Growing interest in big data and data mining
- Translating research capabilities into operational practice

Prof. Michael Doyle (University of Georgia)

Prof. Doyle used his keynote dinner presentation to describe how some of the practices used in raising food animals, crop irrigation, food processing, and harvesting methods are compromising food safety with examples drawn from documented pathogen outbreaks. For example, the practice of fertilizing with human sewage in parts of the world that supply the US with a variety of fruits and vegetables, but that are not regulated by US laws, is leading to situations in which pathogens are incorporated within plant tissues, and are thus impossible to remove by rinsing. Similarly, seafood and shellfish raised in aquaculture facilities are likely to be fed using waste products and feces from other animals, and are also treated with huge doses of antibiotics to reduce the incidence of infections among large, dense populations of tightly constrained animals. Prof. Doyle explained how the practice of partially processing leafy green vegetables in the field is leading to incorporation of pathogens in the soil, and is contributing to several documented pathogen outbreak incidents. Yet another example of compromised food safety is the desire of food companies to appear responsive to a vocal (but misinformed) segment of the public who is demanding reduction or elimination of the use of safe, effective antibacterial ingredients(such as benzoic acid) in processed meats, fruits, and vegetables.

Prof. Doyle's talk expanded upon three key areas in which NSF investments in food-safety related research would enable progress to be made in areas that are not currently addressed effectively by the research programs of other government agencies. These areas are:

- Real-time pathogen detection/advanced sampling methods
- Effective, cost-effective prevention pathogen controls
- Innovative pathogen inactivation treatments

Dr. Robert Holland (U.S. Department of Agriculture)

Dr. Robert Holland's talk, entitled "USDA NIFA Food Safety Program" summarized the NIFA grand challenge to improve food safety, and the research efforts that have been funded around that goal by USDA. Dr. Holland lists USDA NIFA's current research priorities as the following:

- Detection technologies
- Interventions and control strategies
- Understanding pathogens
- Emerging pathogens (and climate change impact upon emerging pathogens)
- Advanced processing

Several existing funding mechanisms have been implemented to address the priorities. These include:

- AFRI – food safety and food science. Awards $150K and up.
- SCRI – specialty crop research initiative. Plant breeding and food safety methods. Taste, quality, appearance.
- SBIR – small business innovative research.

Dr. Holland gave examples of specific research projects that have received funding from these programs. They include receptor-based detection methods, nanotechnology-based sensing approaches, portable biosensors, alternatives to thermal processing for antimicrobial treatment (pressure assisted, enzyme-based approaches, irradiation, predictive modeling and technology validation), nanomaterials for food processing equipment, and materials (membranes, lipids, etc.). USDA supports an area called "Capacity-Funded Research" that is geared towards bridging science gaps with multi-disciplinary, multi-state efforts that have included information technology, computer modeling, and predictive hazard detection. Funds are available

to support pre-doctoral and post-doctoral research to help build the community of scientists engaged in food safety.

Moving forward, Dr. Holland cited several of the highest research priorities for USDA:

- Anti-microbial resistance and mitigation
- New/improved food processing technologies
- Forces, dissemination, and ecology of foodborne hazards
- Water
- Climate variability impacts on food safety
- Animal-plant-human microbiome

Presentation of White Papers and Breakout Discussions

The bulk of the workshop agenda was devoted to presentation of six-minute white papers from the attendees. The submitted abstracts were roughly divided into four segments based upon the topics that were received:

Section A: Processes (10 papers)
Section B: Global Trends, Food Fraud, and Traceability (10 papers)
Section C: Packaging (4 papers)
Section D: Sensor Technologies (17 papers)

Following a group of 10 white paper presentations, the workshop attendees were sorted into three working groups of ~20 people, which separately discussed the just-presented white papers. The groups were instructed to consider the fundamental science and engineering topics among the white papers that might be components of an NSF-funded emphasis in food safety. Each group was assigned a discussion leader/scribe who was instructed to record the important discussion points to assist in preparation of this report.

Group A: Processes

The white paper topics presented in Section A are listed in Table A. Topics were mainly focused around approaches under development for treating food for reduction/elimination of pathogen (viral and bacterial) contamination, while still maintaining the positive attributes of the product (taste, texture, odor, color, nutrient bioavailability, etc.). Process technology focused upon treating the food itself, decontamination of food process equipment, storage containers, and shipping containers.

First Author	Paper Title
Dudley, Edward	Nonthermal Processes for Improving the Microbial Safety of Foods
Dulikravich, George	Modeling of Electrical Resistance Heating of Multi-Particulate Foods
Jeong, Sanghyup	Advanced Technologies for Cleaning and Sanitation in Food Manufacturing Systems
Jones, David	Systems Processes Modeling and Simulation for Improving Food Safety
Locke, Bruce	Green Plasma Technology for Food Production
Marks, Bradley	Developing and Validating Processing Technologies and Systems to Ensure Pathogen Reduction in Challenging Food Matrices
Sastry, Sudhir	Technologies for Mitigation of Foodborne Hazards in the Supply Chain
Shur, Michael	Deep UV LEDs to Extend Storage Time of Agriculture Products and Reduce Waste
Wan, Jason	Next Generation Processing Technologies for Ensuring Food Safety
Yousef, Ahmed	Biotechnology Approach to Fight Food-transmitted Pathogens

Table A: Whitepapers presented in Group A (Processes).

Basic research needs cited during the ensuing discussion include the following:

- Microbiology-focused research into the mechanisms for effective antimicrobial treatment, mechanisms for antibiotic resistance, and genomic/proteomic study of pathways for development of new antibiotic treatments. This topic can include development of surrogate organisms used for testing/validation, establishing critical process limits, and modeling the spatial/temporal variations of treatment approaches. This topic can be distinct from the study of antibiotic treatments for humans and animals based upon the highly challenging constraints of cost, time, and potential toxicity of treatments applied to extremely large volumes of food products that will be consumed by people. For example, it was suggested that perhaps transgenic plants could provide built-in pathogen resistance, which might be activated on demand.
- Microbiology-based research into the mechanisms for biofilm formation and development of new tools for studying biofilm formation mechanisms and evaluating the effectiveness of anti-biofilm treatments. Discussions cited the broad applicability of biofilm research, as it impacts not only food safety, but also semiconductor processing, medical implants, and sterilization of medical devices. Research in this area may also include development of new engineering approaches to anti-biofilm nanostructured surfaces, and other programs in the material science-related components of NSF that seek to understand and manipulate the material-biological interface.
- Fundamental research into the mechanisms for development of antibiotic resistance, as the problem applies to strains of microorganisms that are able to rapidly evolve to counter the chemical and physical treatments being applied to them in food safety (which are quite different than approaches used to combat antibiotic resistant bacteria that regularly infect hospital patients). Development of a more fundamental understanding for why certain bacterial strains can develop resistance to anti-microbial processes. Development of "multi-mode" approaches to containing bacterial populations that perhaps rotate over time to prevent or reduce acquisition of antimicrobial resistance. Focus upon control methods for strains of bacteria that have proven to be especially resistant to countermeasures.
- Materials-related research into surfaces that would be capable of resisting incorporation of residual microbial and chemical allergens that might be incorporated into food processing equipment and packaging.
- Support for a more rigorous approach to process modeling, which can help predict the effectiveness of various forms of food treatment, and aid in process scale-up. Topics with a fundamental science focus can include development of approaches that model the interface between physics and biology to develop a more thorough understanding of interacting materials, and heterogeneous, multiphase food materials that are currently not well characterized. Models should ideally incorporate food-specific outcomes as they relate to enhancing the performance of multiple parameters of importance such as taste, temperature, and nutrition.
- Identify information gaps from enabling models to be used as assessment tools to determine and assess pathogen mechanisms in food processes. Process modeling can include system level analyses for incorporation and sustainability of new technologies into existing infrastructure.
- Innovative processes that will result in low water consumption and high energy efficiency to reduce the negative impact on the environment.
- Understanding of the transfer of micro-organisms throughout processing procedures from ground to product.

Group B: Global Trends, Food Fraud, and Traceability

The white papers presented in Group B are listed in Table B. Group B continued some of the discussion surrounding treatment of food processing equipment for more effective sterilization, particularly for approaches that do not consume water. This session considered how next-generation sequencing is shedding new light on the pathogenesis and evolution of foodborne pathogens, and how global companies (Mondelēz as an example) establish the organization infrastructure, operating protocols, and reporting structure for an effective food safety program. Several talks addressed the challenges involved in detection and remediation of intentionally adulterated food (and food ingredients) that are motivated by economic gain or terrorist intent. This session also featured a talk that described why *Salmonella* has proven to be a very difficult microorganism to combat, with very little documented progress against it despite enormous efforts.

Fundamental science/engineering topics that may fit NSF's criteria for high intellectual merit and broad impact that were discussed in the breakout sessions include:

- Development of food safety cyber-infrastructure that can be used to perform predictive modeling of economic conditions (such as prices of certain commodities, weather…) that favor food fraud. Such an approach can be quite complex and incorporate a surprising number of interrelated variables, even compared to weather forecasting or financial market analysis. Such an infrastructure may be made available to participating companies that can field networks of process analytical technologies to feed data into the system from sites distributed throughout the world.
- Genomic investigation of foodborne pathogens as an approach that may suggest specific countermeasures.
- Development of point-of-use detection technologies for detection of food fraud by genomic, chemical, or proteomic means. Research in this area should include research into lab-on-a-chip devices that can address the unique sampling and processing challenges that are specific to food matrices, and in fact are more challenging than sensing similar analytes in more uniform and "clean" bodily fluids.
- Novel multidisciplinary approach for the unbiased detection of food supply network anomalies using Big Data to characterize risk in supply chains. Such an effort could include development of a strategic information system to allow food supply data to become widely available for research into supply network safety and risk assessment purposes.
- Understanding how the effects of climate change will affect the geo-distribution of foodborne pathogens, mycotoxins, and parasitic pathogens in the regions where food is produced.
- Novel/natural antimicrobials added as food ingredients.
- Sanitation chemicals and technologies that target allergens and pathogens
- New processing technologies, generic, that are applicable to many food types and can eliminate bacterial, viral, and parasitic pathogens.

First Author	Paper Title
Baier, Robert	Food Facilities Require Safe Sterilization Science
Baumler, David	Analysis of Global Trends of Foodborne Outbreak Strains Using Genome-Scale Metabolic Models
Bontempo, Nancy	Global Trends for Harmonizing Standards Category
Bourquin, Leslie	Private Food Safety Standards and Third-Party Certification: Impact On Supplier Food Safety Practices, Hazard Incidence and Public Health
Everstine, Karen	Food Fraud and Economically Motivated Adulteration: Future Research Directions
Gragg, Sara	*Salmonella*: Why Won't it Go Away?

First Author	Paper Title
Kennedy, Shaun	Economically Motivated Food Adulteration
Moore, Jeffrey	Food Fraud and Economically Motivated Adulteration (EMA) Increasing Food Safety through Novel, Predictive and Risk-Based Approaches to Mitigate EMA Risks
Spink, John	Research Needs to Address the Public Health Threat of Food Fraud and Economically Motivated Adulteration
Zhang, Jianrong	Food Traceability in China: Increasing Understanding and Expanding Implementation

Table B: Whitepapers presented in Group B (Global Trends, Food Fraud, and Traceability).

Group C: Packaging

The Group C talks are summarized in Table C. This session contained further information on the biology of biofilms, and the similarity between food-related biofilms and those encountered in medically-related surfaces such as catheters. In addition, several packaging-related issues were discussed, including concepts for integrating slow release of antimicrobials into plastic-based food packaging via nanoparticles, concerns stemming from un-intentional releases of volatile chemical compounds from packages into food, and the development of inexpensive sensors into food packaging that can indicate exposure to temperature, humidity, pH, or other environmental variables that are of interest in tracking the likelihood of food spoilage.

Fundamental research topics that are related to this topic, discussed in the breakout sessions, include:

- Development of more complete biological understanding of the formation, maintenance, and treatment/elimination of biofilms, as noted also in the Group A discussion.
- In a similar vein to fundamental research on slow, sustained drug release for treatment of human disease, food science can also benefit from development of polymer matrices, functionalized nanoparticles, nano-clay materials, and new nanomaterials (such as carbon nanotubes or grapheme) that may be adapted to the unique challenges of food packaging. Drug-release technology for spoilage reduction must not only be inexpensive to manufacture, but be comprised of consumption-safe materials, have no impact upon taste/smell/appearance of food, be compatible with wide-scale adoption in food processing plants, be recyclable, and be capable of obtaining approval from the FDA.
- Nanostructures, chemical strips, or other devices that can serve as process “witnesses” to food. One can imagine sophisticated devices with integrated RFID technology, multiple sensors (pH, T, RH, color) – provided that the cost can be extremely low. Development of methods to integrate novel packaging for in situ detection of food conditions during transport.
- Study, testing, and selection of materials suitable for food packaging that also have pathogen inactivation properties.
- Development of active packaging that shapes the electromagnetic field of cooking devices to achieve safe cooking temperatures for a pathogen deactivation evenly throughout food products.
- Innovation of “smart” packaging that (a) provides information to the consumer on food safety parameters of consumer interest and (b) reduces or eliminates the adverse impact of the environmental conditions (e.g. temperature) on product quality.
- Novel handheld biosensor systems for sampling selectivity and analysis of pathogens in complex food matrices and non-homogenous food mixtures.
- Understanding if volatile compounds that are produced by pathogens in different food matrices can be used by sensing systems as sensitive markers for presence of bacterial contamination with sufficient sensitivity to circumvent foodborne illness.
- Foods are complex mixtures that contain essential bacteria that are important to food preparation processes, but that mask the presence of bacteria that are potentially harmful making them harder to

detect. Research into microbial sample separation and preparation to quickly target selected pathogens in the presence of masking bacteria would allow quicker analyses by food companies to be completed at production level speeds. This topic was also part of the discussion in Group D.

First Author	Paper Title
Berger, Bryan	Engineering Acid-Tolerant Enzymes with Broad Substrate Specificity to Eliminate Bacterial Exo and Cell Surface Polysaccharides
Rubino, Maria	Research Needs to Address the Public Health Threat of Food Fraud and Economically Motivated Adulteration
Vorst, Keith	Detecting, Characterizing, and Screening of Substrates for Quality and Safety when used for Direct Food Contact Surfaces: Proposal to Automate Manufacturing Quality Control and Product Certification of Direct-Food Contact Thermoplastic Packaging
Yagoobi, Jamal	Packaging with Phase Change Material for Maintaining Product Quality

Table C: Whitepapers presented in Group C (Packaging).

Group D: Sensor Technologies

A listing of the white papers presented from Group D are shown in Table D. This group was the largest of the four, reflecting the importance placed upon development of new sensor technologies that can perform extremely challenging tasks that are unique to food safety. A variety of biosensing platform technologies were summarized, with emphasis upon portability, separation of pathogens from complex food matrices, achieving single-pathogen sensitivity, discrimination of live/dead pathogens, and detection of chemical contaminants.

During discussion, several fundamental research needs emerged:

- Fundamentally new approaches are needed to solve the "sampling problem" in which it is necessary to find a single microorganism hidden within a large volume of food. Approaches that involve sparse sampling from several distinct locations within a large shipment of material, homogenization (i.e. blending or otherwise physically disrupting) a test sample, or mixing with nanoparticles are not providing the desired information. While DNA-amplification approaches can be highly sensitive, they are subject to false readings, while they are not able to determine if a sensed pathogen had been alive. Efficient methods for target extraction from complex food matrices is needed, representing a challenge that is typically not addressed in DARPA or NSF programs in biosensor pathogen detection for bio-warfare or medical applications. Desired characteristics include: inexpensive, real time, sensitive, specific, accurate and simple to operate in field.
- Sensors and portable sensor networks are desired for performing laboratory-based tests in locations that include loading docks, supplier locations, storage facilities, and others. The development of lab-on-a-chip cartridges that can largely automate sample preparation from a raw sample all the way through a test result with minimal user intervention or reagent addition is desired, along with inexpensive handheld detection instruments with internet connectivity. Unique nanoparticle engineering, isothermal PCR, SERS surfaces, and biosensor transduction methods are in excellent alignment with current NSF programs, but the unique challenges of food-related sensing could be incorporated into these programs.
- New technologies for sensing the presence of heavy metals within irrigation water and within food matrices was cited by several Industry participants at the workshop, as an area that would welcome new research approaches.
- New approaches for hyperspectral imaging that might be used in ultra-high rates for detecting chemical or biological contamination of processed meats, fish, fruits, or vegetables would be of enormous value. Fundamental technologies that include THz imaging, or adaptation of biomedical imaging modalities are potential research topics.

- Exploring the role of "Big Data" in the context of food safety monitoring includes applying non-traditional information and developing predictive approaches that identify and assess risks posed by global food supply networks. This includes information about supply sources of ingredients, actions by foreign suppliers, regulatory situations in other countries, weather, transportation, and other activities encompassing the safety of a product. These are important factors affecting safety and risk that need to be understand and utilized as more foods will be produced in foreign locations and exported globally.
- Many needs for the development of novel biological and chemical sensor technologies were discussed with specific criteria that are not addressed by sensor development in medical applications. Examples include the need for low cost portable biosensor systems for selective detection of pathogens in non-homogenous mixtures, the ability to differentiate between live/dead pathogens, and detection of pathogens residing upon food preparation and equipment surfaces. Viable approaches can include methods for detection of the toxins and allergens produced by pathogens, non-contact (i.e. standoff imaging or vapor) detection methods, and approaches that can be performed at high throughput in real time on large volume food process streams.
- Understanding competing treatments and additives in foods that would produce undesirable outcomes in food systems.
- Novel food ingredient handling and preparation processes to reduce allergens.

First Author	Paper Title
Alocilja, Evangelyn	Nano-Biosensors for Rapid Screening and Pathogen Detection in Foods
Batt, Carl	Surface Enhanced Raman Spectroscopy as a Food Contaminant Diagnostic
Bau, Haim	Smart Connected System for On-Site Molecular Detection of Food-borne Pathogens
Buser, Michael	Advancement of Whole-Chain, Stakeholder Driven Traceability and Food Safety System
Chen, Junhong	Rapid Detection of *Escherichia Coli* Bacteria in Food
Cunningham, Brian	Mobile Sensors for Food Safety
Fairow, Clint	Identifying Toxic Agents that Could Realistically be Used in an Intentional Mass Food Contamination
Hanasoge, Srinivas	Development of CD Based Fluidic System for High Throughput *Salmonella* Capture and Sampling
Kealey, Kirk	Food Safety Needs for Fresh Fruits and Vegetables - Real Time Detection Methods for Hazards
Koley, Goutam	Rapid Detection of Food Contamination Using Smartphone Based Photoacoustic Spectroscopy
Labuza, Theodore	Advancing Development and Use of Time-Temperature Integrators to Enhance Food Safety Management in the Global Cold Chain
Lin, Shan	Assuring Food Safety with Supply Chain Co-Location Control
Pierson, John	Pre-Concentration and Enrichment Implications for Sensor Designs
Silver, Robert	Using Big Data in Risk Management for Food Safety
Subbiah, Jayem	Spectral Imaging for Detecting Microbiological and Chemical Hazards in Foods

First Author	Paper Title
Wang, Hua	Low-Cost CMOS Sensor Platforms for Rapid Large-Volume Food Quality Inspection - Fast THz Imaging and "Wide Spectrum" Multi-Modality Cell-Based Assays
Xu, Jie	Viable Pathogen Separation for Improved Rapid Detection

Table D: Whitepapers presented in Group D (Sensor Technologies).

Conclusions

The goal of the workshop was to assemble thought leaders in industry and food safety academic research community to suggest topics that, if addressed by NSF, would have a fundamental impact upon the development of the science/engineering infrastructure of the US for improving food safety in an increasingly global environment. The workshop participants were instructed to especially focus their suggestions to NSF to include research topics that are not currently being well-addressed by other funding agencies, so that a new NSF emphasis on food safety would not overlap with topics funded by USDA or FDA. In additional to the topics outlined previously in the report, participants expressed a desire for scientists with backgrounds in food safety to become more engaged in NSF review panels to help make the panel aware of the fundamental research challenges and societal impact of food safety-related science/technology. Especially if future NSF RFPs include topics that are related to food safety, the workshop participants felt that proposals will receive a more fair review if review panels include expertise in food safety or if food safety had its own programmatic track within NSF.

Workshop participants also expressed the need to address the social dimensions of food safety technologies that can include global education and outreach for broad adoption of new technologies, development of more global public policies, harmonizing standards across national borders, and development of the engineering/science food safety workforce.

Workshop Organizers

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Transport Systems (CBET)

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and Cellular Sciences (MCB)

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