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NANOTECHNOLOGY IN AGRICULTURE AND FOOD PRODUCTION

ANTICIPATED APPLICATIONS

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NANOTECHNOLOGY IN AGRICULTURE AND FOOD PRODUCTION: ANTICIPATED APPLICATIONS

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About the Authors

Jennifer Kuzma, Ph.D., joined the Hubert H. Humphrey Institute of Public Affairs and the Center for Science, Technology, and Public Policy (CSTPP) at the University of Minnesota in 2003. Prior to this, she served for four years as Program Director and Senior Program Officer at the National Academy of Sciences National Research Council (NRC). At the NRC, she directed programs and studies related to biotechnology and bioterrorism policy, including Genetically Modified Pest Protected Plants: Science and Regulation (2000) and Countering Agricultural Bioterrorism (2002).

She earned her Ph.D. degree in biochemistry from the University of Colorado at Boulder in 1995 and was subsequently a Research Fellow at the Rockefeller University in the Laboratory for Plant Molecular Biology. Her postdoctoral work in plant signal transduction led to a publication in the journal *Science*. She holds a patent on the production of isoprene from bacteria.

Her career in science and technology policy began when she was awarded an American Association for the Advancement of Science (AAAS) Fellowship sponsored by the United States Department of Agriculture (USDA). At USDA, she worked on risk assessment and policy issues associated with foodborne hazards. In addition to her NRC reports, she has authored several papers in basic research, risk assessment, and science policy.

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Peter VerHage, M.S., graduated from North Park University with degrees in biology and in politics and government in 1999. In 2006, he completed an M.S. degree in science, technology, and environmental policy at the Hubert H. Humphrey Institute at the University of Minnesota where he was a Research Assistant for the Center for Science, Technology, and Public Policy at the Humphrey Institute. For five years before attending the University of Minnesota, he worked as an information technology manager and consultant.

Foreword

In early 2006, the Project on Emerging Nanotechnologies (the Project) released the first online, searchable inventory of nanotechnology-based consumer products (available at www.nanotechproject.org/consumerproducts). The inventory contains information on nearly 300 products from 15 countries. It includes nanotechnology merchandise that can be purchased in department stores, pharmacies, and sporting goods shops as well as over the Internet-everything from cosmetics to athletic equipment and from clothing to electronics.

While the Project's nanotechnology consumer products inventory contains manufacturer-identified foodstuffs such as a canola oil and a chocolate "slim" shake, the current number of nanotechnology food products being sold appears to be relatively small. Nevertheless, millions of dollars are being spent globally by both governments and industry to apply nanotechnologies in areas such as food processing, food safety and packaging, and agricultural production. When will this research result in large numbers of nanotechnology food products appearing on the market? Who will be affected? What are the potential benefits and risks? How can consumers be engaged early on?

These are key questions that need to be addressed as soon as possible, not after products appear on the shelves of the local grocery store and elsewhere. The stakes, in terms of consumer perceptions and oversight of nanotechnology in the food sector, are high. Given the recent history of public concerns and policy missteps involving genetically engineered food, the introduction of any new technology into food and agricultural products offers challenges for both industry and governments.

At this point, before too many nanotechnology agrifood products have entered into commerce, there is a unique opportunity to better understand what is coming, to think through the potential impacts, both positive and negative, and to begin to engage the public and other stakeholders in a dialogue about the use of nanotechnology in food and agriculture.

Along these lines, one challenge we face as consumers and policymakers is how to get a "heads up" concerning future applications that are still in the development stage. A research effort initiated and conducted by the University of Minnesota's Dr. Jennifer Kuzma and Peter VerHage has put together a method to anticipate what food-related applications and products are likely to appear over the coming years. The method looks at what areas are likely to see early commercialization; it begins to explore potential benefits and risks; and it aims to help focus the attention of policymakers, educators, and others in the right places at the right times.

Their work, which has resulted in a database of nanotechnology food- and agriculture-related research, looks at the landscape of research investments being made primarily by the U.S. government. It uses that information to map the potential trajectories of products and applications in both the food and agriculture sectors. The researchers and the Project are jointly making this database of nanotechnology food- and agriculture-related government research available online so that it can be downloaded into Microsoft Access software for use and analysis by others. The Project and the researchers welcome comments and collaborations with others in this very important area. The database can be found online at www.nanotechproject.org.

This is not an exact science, nor is it complete. Because the results of corporate research are difficult to acquire, industry research and development in the food sector—which surely will have large impacts—is not included in this database. But even with the data's current limitations, it is better than flying blind into the future and suddenly seeing numbers of products appearing on store shelves or in farmers' fields.

In order to be of use to a wide audience, the following report is divided into three sections and organized so that a reader can approach the material from a variety of perspectives. For readers who are new to the subject of agrifood nanotechnology, the first section provides an overview of ongoing research into the applications of agrifood nanotechnology and situates these research endeavors within the historical context of agriculture biotechnology. For those readers with a greater familiarity with the subject, the second section provides an in-depth discussion of the main findings and conclusions that have emerged from the database research project. The third and final section provides a more technical, detailed description of the methodology used to populate the database, along with guidance on how to use the database most effectively.

This work is the first step in a larger effort to explore the governance challenges around nanotechnology-based food and agricultural applications. The Project on Emerging Nanotechnologies hopes it will be useful to others who are working to understand and communicate the impact of nanotechnologies on our economy and everyday lives.

—David Rejeski
Director, Project on Emerging Nanotechnologies

Overview and Context of Agrifood Nanotechnology

Nanotechnology: Coming to a Supermarket or Farm Near You

A new variety of canola oil contains tiny materials that can block cholesterol from entering the bloodstream.

A chocolate milkshake now on the market is supposedly tastier and more nutritious than conventional products—thanks to the unusual properties of a new ingredient that is 100,000 times smaller than a grain of sand.

Minute droplets of a new substance have been added to pesticides so that formulations that once had to be shaken every two hours to prevent ingredients from separating now hold together for up to one year.

What do these three products have in common? They are all examples of food and agricultural innovations made possible by the rapidly growing field of nanotechnology. They all employ scientific breakthroughs in the ability to manipulate matter at the molecular and atomic levels to teach old products new tricks.

They are also just a preview of what appears to be a flood of food and farm applications of nanotechnology moving to market.

In the food industry alone, experts estimate that nanotechnology will be incorporated into $20 billion worth of consumer products by 2010.[1] Five out of ten of the world's largest food companies are aggressively exploring the potential of the really small to make really big improvements in packaging, food safety, and nutrition. Similarly, in agriculture, some of the world's largest makers of pesticides, fertilizers, and other farm inputs and technologies are betting on nanotechnology to bring unprecedented precision to crop and livestock production.

These applications are commonly known as "agrifood nanotechnology." However, while it is clear that agrifood nanotechnology is expected to become a driving economic force in the long-term, less certain is precisely what to expect in the near-term. Some of the key questions include:

- What individual products are moving rapidly through the pipeline?
- What impact will these products have on the farming and food production chain?
- When these products arrive in the grocery store and on the farm, is there any reason to be concerned—or excited—about putting them in our bodies or using them in our environment?

Today, there are only vague and general answers to these questions. However, if we are to manage the potential health or environmental concerns these products raise and, ultimately, realize their promised benefits, it is critical that we better understand and anticipate food and agriculture applications of nanotechnology.

If industry observers are right, there are hundreds of new food and agriculture products under development, many of which could be on the market in as little as two years. But it does not appear that govern-

1. "Study: Nanotechnology in Food and Food Processing Worldwide 2003-2006-2010-2015." Tübingen, Germany: Helmut Kaiser Consultancy, 2006. Available at http://www.hkc22.com/nanofood.html, accessed July 5, 2006.

ments, industry, producers, and trade groups are ready for their arrival. A research strategy for addressing possible human health or environmental risks is not in place. The public is at best vaguely aware of what the word *nanotechnology* even means, much less how it might be involved with growing and producing food or other agricultural products. And there is no evidence that government oversight bodies are ready to conduct the kind of thorough reviews that these exciting but untested innovations demand. Finally, the U.S. government is investing little in "green," more environmentally friendly uses of nanotechnology in agriculture.

Food and agribusiness concerns are at the vanguard of commercializing nanotechnology innovations, and their successes or failures could affect future commercialization of nanotechnology products in all industries.

There are many reasons why we need to be better prepared for the arrival of food and agriculture applications of nanotechnology:

- Experience has shown that any risks or benefits involved with integrating new technologies into food and agriculture processes are greatly magnified given their potentially far-reaching effects on humans, animals, rural communities, and the environment.

- Public perceptions and acceptance of agrifood nanotechnology will greatly influence how widely these applications enter society.

- Food and agribusiness concerns are at the vanguard of commercializing nanotechnology innovations, and their successes or failures could affect future commercialization of nanotechnology products in all industries.

The Project on Emerging Nanotechnologies, launched in 2005 by the Wilson Center and the Pew Charitable Trusts, was created to help business, governments and the public anticipate and manage possible health and environmental implications of nanotechnology. The Project supported the authors' work in taking a first step toward addressing our insufficient knowledge of pending food and agriculture applications of nanotechnology by developing a database of relevant government-sponsored agrifood nanotechnology research.

The goal of this research is to look upstream in order to develop sound predictions about what is on the horizon. In its current form, the database scratches the surface of potential applications. Nonetheless, it is sufficiently informative to serve as a starting point for a more in-depth dialogue among consumers, business, and government about the near- and long-term uses of nanotechnology in food and agriculture.

To understand why these issues should command more attention, it is helpful to step back and explain just what nanotechnology is and the benefits it could provide in food and agriculture. It is also important to consider why nanotechnology might raise a new set of concerns, particularly when used in food and farm processes, and to examine the challenges the technology may present to government agencies charged with safeguarding the public and environment from unnecessary risks.

With this knowledge in hand, one can then explore in more depth this first database of food and agriculture projects and consider its strengths and weaknesses. What does it tell us about the field and about what is needed to create a more solid foundation for a safe and orderly rollout of nanotech innovations?

Big Things in Small Packages: What Is Nanotechnology?

Though *nanotechnology* is a term used more and more often today, many people—including veteran industry observers—struggle to define what it really means. Consumers can be particularly baffled by the term. The difficulty is that nanotechnologies involve structures and substances so small that they challenge our ability to conceptualize their size.

A nanometer is one-billionth of a meter. The typical nanotechnology utilizes structures under 100 nanometers in size. By comparison, a human hair is 100,000 nanometers wide. Most people have a hard time visualizing something that is tens of thousands of times smaller than a hair. Suffice it to say that things at the nanoscale not only are too small to be viewed by the human eye but also require powerful, cutting- edge technology, such as transmission-electron or scanning-tunneling microscopes, to be seen at all.

Nanotechnologies exist today because scientists have developed sophisticated instruments and processes that allow them to take microscopically small structures—down to individual atoms and molecules—and use them as individual building blocks with which to construct a new generation of substances and materials. While scientists were previously able to see, and even accomplish some crude rearranging of, nanomaterials, it is only recently that they have developed the ability to put or coax them into precise, predetermined configurations.

Ralph Merkle, a professor at the Georgia Institute of Technology, talks about pre-nanotechnology manufacturing as akin to "trying to make things out of LEGO blocks with boxing gloves on your hands. Yes, you can push the LEGO blocks into great heaps and pile them up, but you can't really snap them together."[2] Now that these first-generation applications are beginning to enter the marketplace, an incredible number of useful things—carbon nanotubes far lighter and far stronger than steel, nanomaterials that render surfaces and fabrics "self-cleaning," food packages with nanomaterials that detect spoilage—offer the potential to transform everything from health care and automobile manufacturing to energy production and food processing. Some enthusiasts speak of nanotechnology as ushering in a new industrial age.

According to Lux Research, sales of products incorporating nanotechnology generated over $30 billion in 2005.[3] The National Science Foundation (NSF) estimates that in less than 10 years, products made from nanotechnology will have a $1 trillion impact on the global economy and that the nanotechnology industry will employ two million workers.[4]

A Tiny Revolution in Food and Agriculture

In the food industry, nanotechnology is being used to create better packaging and healthier foods. For example, researchers are working on creating food packages embedded with tiny materials specifically designed to alert consumers that a product is no longer safe to eat. Food scientists also are

2. Merkle, Ralph. "Nanotechnology." Richardson, TX: Zyvex Corporation. Available at http://www.zyvex.com/nano/, accessed July 5, 2006.
3. *The Nanotech Report*™ *4th Edition*. New York, NY: LuxResearch, Inc., 2006.
4. Roco, M.C., R.S. Williams, and P. Alivisatos. *Nanotechnology Research Directions: IWGN Workshop Report*. Berlin, Germany: Springer, 2000, p. iii–iv.

creating nanomaterials whose small size gives the ability to deliver powerful nutrients to human cells where they previously could not reach. In addition, scientists believe nanomaterials can be designed to block certain substances in food, such as harmful cholesterol or food allergens, from reaching certain parts of the body.

Today, many of the world's leading food companies—including H.J. Heinz, Nestlé, Hershey, Unilever, and Kraft—are investing heavily in nanotechnology applications.[5]

Farm applications of nanotechnology are also commanding attention. Nanomaterials are being developed that offer the opportunity to more efficiently and safely administer pesticides, herbicides, and fertilizers by controlling precisely when and where they are released. For example, an environmentally friendly pesticide is in development that uses nanomaterials to release its pest-killing properties only when it is inside the targeted insect. For livestock, the ability of certain nanomaterials to control dosage could reduce the amount of growth hormones needed to boost livestock production. There also are nanomaterials in the late stages of development that can detect and neutralize animal pathogens in livestock before they reach consumers.

"Clearly, there is a growing segment of the public that does not want its food 'engineered'-bio, nano or otherwise," state Evan Michelson and David Rejeski of the Project on Emerging Nanotechnologies, and these segments of the population are willing to pay premium prices for an organic approach.

Examples Are Poor Substitute for Complete Picture

These examples offer a glimpse into the world of food and agriculture nanotechnology, but little more. Almost weekly there is an article in a business or scientific publication rhapsodizing about a new food or an agriculture innovation made possible by nanotechnology. Yet nowhere is there an independent and authoritative accounting of individual agriculture and food products that includes a prediction of their time to market and thoughts on potential risks and benefits. Therefore, no one really knows what to expect in the next few years: 10 products? 100? 1,000? And are these products risky, safe, or beneficial?

Why is it so hard to estimate how many food and agriculture innovations are driven by nanotechnology or what their effect will be? One reason is that there are reasons to both exaggerate and minimize nanotech applications. Analysts from the investment firm AG Edwards warn that "nanotechnology has become so much of a buzzword that we fear its real meaning is: 'We are doing something small, please pay more for our stock.'"[6] In other words, many people justifiably wonder whether everything that a company labels "nanotechnology" is really nanotechnology.

Conversely, some food and agriculture companies, very much aware of the problems caused by consumer fears of genetically modified organisms (GMOs) in food crops, may be wary of attaching the nanotechnology label to new products. For example, few would have predicted 10 years ago that

5. Wolfe, Josh. "Safer and Guilt-Free Nano Foods." *Forbes.com,* August 10, 2005. Available at http://www.forbes.com/investmentnewsletters/2005/08/09/nanotechnology-kraft-hershey-cz_jw_0810soapbox_inl.html?partner=rss, accessed on July 5, 2006.
6. Hittle, Alexander A., Kevin J. McDevitt, and Paul D. Watson. "Nanotechnology." St. Louis, MO: AG Edwards & Sons, Inc., December 14, 2005.

"GMO-free" would become a major marketing slogan in Europe.

"Clearly, there is a growing segment of the public that does not want its food 'engineered'—bio, nano or otherwise," state Evan Michelson and David Rejeski of the Project on Emerging Nanotechnologies, and these segments of the population are willing to pay premium prices for an organic approach.[7] However, the value of the organic food sector—which most people associate with being GMO-free—has increased around 15 percent per year since the mid-1990s, and it remains one of the fastest-growing areas of the food industry.[8] Organic food sales worldwide have exceeded $15 billion annually, and Wal-Mart's decision to stock and sell increased amounts of organic produce is expected to increase the worth of this sector in the future.[9]

Ten years from now, companies do not want a situation in which consumers are attracted to products because they claim to be "nano-free." Additionally, the growth of the organic food sector indicates that firms may gain a real economic advantage with affirmative labeling ("no-nano") that goes beyond just taking a position against bioengineered foods.

Moreover, even if companies believe a food or an agriculture product that utilizes nanotechnology will be welcomed into the marketplace, they are generally reluctant to be forthcoming about what is in their own product pipelines. This tendency to be secretive about new products is not confined to nanotechnology. Whatever the pending product, companies routinely classify any meaningful details, including data submitted as part of a petition for regulatory approval, as confidential business information. Declaring product information as confidential prevents a competitor from stealing a company's ideas or taking unfair market advantage, but it also stops anyone, including government officials, from discussing it with the public.

So, we have a situation in food and agriculture where industries seem to be moving as fast as, or possibly faster than, any other industrial sector to realize the benefits of nanotechnology. Yet predicting precisely what will soon come to market is a speculative exercise. And unless one knows what is coming, it is difficult to undertake a systematic, independent effort to understand whether particular products pose risks to humans, animals or the environment.

Should We Be Worried About Food and Agriculture Nanotechnology?

It is fair to ask: why is this dearth of information and assessment of food and agriculture nanotechnology a problem?

First, it is a problem because consumers and anyone else—workers in the agriculture and food industries, for example—who might come into contact with the minute materials and substances created with nanotechnology have a right to know what they are being exposed to and whether there are

7. Michelson, Evan, and David Rejeski. "Falling Through the Cracks? Public Perception, Risk and the Oversight of Emerging Nanotechnologies," *IEEE ISTAS Conference Proceedings*, June 2006.
8. Greene, Catherine, and Carolyn Dimitri. "Organic Agriculture: Gaining Ground," *Amber Waves.* Washington, DC: United States Department of Agriculture, February 2003. Available at http://www.ers.usda.gov/amberwaves/feb03/findings/ organicagriculture.htm, accessed July 5, 2006. Hansen, Nanette. "Organic Food Sales See Healthy Growth," *MSNBC.com*, December 3, 2004. Available at http://msnbc.msn.com/id/6638417, accessed July 5, 2006.
9. "Wal-Mart Goes Organic." *MSNBC.com*, March 26, 2006. Available at http://www.msnbc.msn.com/id/11977666/, accessed July 20, 2006.

any risks when they inhale or ingest these materials. The risks could be practically zero or they could be significant, depending on the properties of a particular product and exposure levels. For the most part, no one knows. Few risk assessments have been done that allow one to predict what happens when these very small materials, some designed to be biologically active, enter the human body or are dispersed in the environment. A recent analysis of nanotechnology-related environmental, health, and safety research, done by the Project on Emerging Nanotechnologies, could find no research on the impact of nanomaterials on the gastrointestinal tract, though this will be of primary concern for food applications.[10]

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One issue that has come under consideration is whether there is something about human-made creations at the nanoscale in general that raises new safety issues. In other words, when it comes to risk, does size matter?

On one hand, there are scientists who observe that humans, animals and the environment are constantly encountering naturally occurring nanomaterials. In the environment, nanomaterials have been with us for millions of years; for example, every day humans inhale nanosize salt particles carried on the ocean breeze with no ill effects. Biologically active proteins and molecules at the nanoscale in our bodies keep us healthy and functioning. In that sense, one could say there is no reason to be wary of eating or dispersing something just because its size can be measured only in terms of atoms.

On the other hand, there are concerns that nanomaterials now in development are different from anything that exists in nature. As many observers point out, the reason nanotechnology is causing so much excitement is precisely because it allows people to create products that do things that natural particles cannot.

For example, consider the use of nanomaterials to improve the body's ability to absorb nutrients by making them so small that they can slip through cell walls that ordinarily would prohibit their passage. While there can be benefits to breaking down that barrier, such as quicker and more efficient uptake of nutrients into the bloodstream, could there also be unintended consequences? We need to understand the potential side effects before these products come into mass use. Achieving this understanding will require research that focuses specifically on the nanotechnology aspect of the product. Current information—if it even exists—can be of limited value in understanding potential risks.

One method of developing nanomaterials is by creating smaller versions of known substances. For this type of nanotechnology, risk management might seem to be a relatively simple exercise, as anyone concerned about the safety of the nanosize version could simply consult the safety profile of the original. However, this risk management approach may not be sufficient, for some researchers believe that when materials are shrunk to

10. *Nanotechnology Health and Environmental Implications: An Inventory of Current Research.* Washington, DC: Project on Emerging Nanotechnologies, Woodrow Wilson International Center for Scholars, November 2005. Available at http://www.nanotechproject.org/inventories, accessed July 5, 2006.

the nanoscale, they change properties and are no longer simply miniature versions of the original material. For instance, in its original size, a substance might be considered toxic to human beings only when consumed in a certain quantity, say above 100 milligrams. But when that same substance is manufactured at the nanoscale, its properties might change, and it might require a different point of reference to determine toxicity. For example, it may no longer be just the weight of the substance that determines the material's risk. In its new configuration, the material might have a new molecular structure or be capable of affecting the human body or the environment in a manner that its precursor never could.[11,12]

Overall, the point is that new research is needed to fully understand the individual risks posed by products that use nanotechnology. If this research is not done, consumer and environmental health could suffer in two ways: by being exposed to potentially harmful products or, if unfounded fears slow the approval process or lead to over-regulation, by being deprived of what could be very beneficial innovations. In that sense, the need to thoroughly identify any risks related to food and agriculture nanotechnology is not about feeding irrational or alarmist fears. Rather, its purpose is to anticipate the pressure points that, if ignored, will prevent the industry from reaching its potential—whether that involves something vital to humanity, such as safer and more nutritious food, or something merely convenient and commercially lucrative, such as a plastic bottle that uses nanomaterials to keep beverages fresher tasting.

Agriculture Biotechnology: A Bountiful Harvest of Cautionary Tales

If supporters of food and agriculture nanotechnology need to be convinced about the importance of moving aggressively to identify and address health and environmental concerns of nanotechnology before products reach the market, they should consider the many lessons to be learned from the history of genetically modified foods. The tendency to commercialize first and respond to consumer questions later has proven a major problem for an industry that was supposed to transform food and agriculture by offering safer production methods, more nutritious foods, and new opportunities for farmers—the same benefits that we are now hearing will come from nanotechnology.

This dynamic is nothing new for anyone who has witnessed the controversy that has surrounded the use of genetic engineering in food and agriculture. But the tensions that surround the presence of GMOs in food and on the farm go beyond the fact that these applications present so many avenues for encounters with humans and the environment. The clashes over GMOs also teach us that there are strong cultural and personal relationships to food and agriculture that one does not find in other industries and sectors.

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11. Oberdörster, Günter, Eva Oberdörster, and Jan Oberdörster. "Nanotoxicology: An Emerging Discipline Evolving for Studies of Ultrafine Particles," *Environmental Health Perspectives*, July 2005, 113(7): 823-839.
12. Maynard, Andrew, and Eileen Kuempel. "Airborne Nanostructured Particles and Occupational Health," *Journal of Nanoparticle Research*, 2005, 7: 587-614.

Those relationships can heighten public concern about potential negative effects of new technologies.

In addition, as has been the case with GMOs, there is the possibility that consumers could perceive that they will bear the potential risks posed by nanotechnology applications, while the benefits will accrue mainly to others, such as food processors or farmers. And even where there are benefits for consumers, the risk/benefit trade-off in nanotechnology will not be as clear for food and agriculture as it is for other sectors, such as pharmaceuticals. Consumers may have a high tolerance for risks when it comes to drugs and life-saving medical treatments but a much lower tolerance for risk when it comes to food, particularly when they see no direct benefits.

Another lesson from the experience with GMOs is that given the complexity of the technology, a failure to thoroughly explore potential risks and to openly and candidly discuss them with the public can do great harm, even if the actual problems involved end up posing little, if any, real threat. For example, in 1999, there was a spate of news stories in the scientific press that moved into the mainstream media about a study that suggested pollen from crops genetically modified to produce a naturally occurring pesticide (*Bacillus thuringiensis,* or Bt) might be harmful to Monarch butterfly larvae. Numerous follow-up studies questioned whether genetically modified crops posed a serious threat to the Monarch.[13] But the public perception was that industry and government scientists had failed to thoroughly explore and disclose the potential risks to the butterfly, however minimal, before putting the crop on the market. The Monarch itself may not have become a casualty of GMO crops, but there is little doubt that the incident had an impact on public trust and that it raised questions among some consumer and environmental organizations about the capability of the oversight system and of the agricultural biotechnology industry that is supposed to consider the safety of its products.

A second example worth studying is the so-called Starlink controversy.[14] The food industry is still feeling the effects of an incident in 2000 in which a brand of genetically modified corn known as Starlink, which had been approved only for animal consumption, was found in food meant for human consumption. While there was concern that the Starlink variety might provoke allergic reactions in some humans, there were no verifiable reports of health problems linked to the exposure. Nonetheless, the damage to industry was considerable. The unintended co-mingling showed that government regulators, along with food and agriculture companies, were not able to keep GMO animal feed isolated from human foods. This opened the door to the possibility of other, as yet unfound, co-mingling of approved and non-approved GMO foods. In fact, the food that contained Starlink corn was often described as "contaminated with GMOs," a phrase that clearly hindered industry efforts to convince the public that GMOs pose no health threats.

13. Pew Initiative on Food and Biotechnology. *Three Years Later: Genetically Engineered Corn and the Monarch Butterfly Controversy.* Washington, DC: Pew Initiative on Food and Biotechnology, May 30, 2002. Available at http://pewagbiotech.org/resources/issuebriefs/monarch.pdf, accessed August 3, 2006.
14. Taylor, Michael R., and Jody S. Tick. *The StarLink Case: Issues for the Future.* Washington, DC: Pew Initiative on Food and Biotechnology, October 2001. Available at http://pewagbiotech.org/resources/issuebriefs/starlink/starlink.pdf, accessed July 5, 2006.

The effects of the Starlink case have rippled throughout the industry. The incident has been a particularly potent weapon for those opposed to using genetically modified plants to produce pharmaceutical proteins and antibodies in plants because of fears that they could get mixed with food crops. There had been high hopes that "pharma plants" would help drug companies speed production of breakthrough biotech drugs, which are routinely in short supply because conventional manufacturing methods can't stay abreast of demand. The Starlink case has also made it more difficult for U.S. farmers to export their crops, since certain foreign buyers will purchase U.S. grains and food products only if they receive assurances that they contain no, or only certain, genetically modified ingredients.

Meanwhile, in the area of animal biotechnology, the failure to anticipate and manage the consumer issues raised by genetic engineering has left efforts to improve livestock production through genetic engineering essentially dead in the water. Companies have been waiting for years to get guidance from the Food and Drug Administration (FDA) on what will be required to obtain regulatory approval for genetically modified farm animals and to move products to market. Although FDA is aware of the need for such guidelines, it has been reluctant to move forward in a proactive manner. Similarly, many small firms complain that this regulatory indecision is driving away investors, which, in turn, affects the pace of research and development.

In an article on the agricultural biotechnology sector, researchers Joyce Tait and Les Levidow argue that "the industry concerned, and its products, are controlled by a system set up in response to scientifically proven adverse impacts that have arisen in earlier generations of products."[15] As noted earlier, this reactive approach to governance also has the effect of lowering public trust in government and industry's ability to manage the risks posed by biotechnology in particular and by new technologies in general.

This low level of trust in the regulatory system is arising once again with respect to nanotechnology. For instance, in her study *Informed Public Perceptions of Nanotechnology and Trust in Government*, Jane Macoubrie found that both FDA and USDA fared particularly poorly, with citizens lowering their level of trust after learning more about the functions of these particular agencies. Her examination of these issues indicated that "evidence points to FDA, and to a lesser extent, USDA, as significant nanotechnology regulatory concerns for citizens."[16] The actions of these agencies will be critical to the introduction of nanotechnology in food and agriculture products, and Macoubrie's findings demonstrate that government is going to have to take steps in the future to win back the trust of consumers.

Back to the Future: Will Nanotechnology Repeat the Mistakes of Biotechnology?

Unfortunately, it appears there is a danger that the nanotechnology sector could repeat many of the mistakes that caused problems

15. Tait, Joyce, and Les Levidow. "Proactive and Reactive Approaches to Risk Regulation: The Case of Biotechnology" *Futures*, April 1992: 219–231.
16. Macoubrie, Jane. *Informed Public Perception of Nanotechnology and Trust in Government.* Washington, DC: Project on Emerging Nanotechnologies, Woodrow Wilson International Center for Scholars, September 2006. Available at http://www.nanotechproject.org/reports, accessed July 5, 2006.

for food and agricultural biotechnology. In particular, one hears government officials and many in industry voicing the same opinions about nanotechnology as they did with the debut of genetic engineering; namely, that adequate regulatory authority and capacity to manage any risks posed by nanotechnology already exists. Given the paucity of nanotechnology risk research, it is difficult to see how adopting a position affirming adequate authority at such an early stage is helpful. Additionally, it is important to note that even if the current review system is adequate, there are still questions about whether government agencies have sufficient resources—money, expertise, and strategic plans—to enforce, test, and otherwise deal with the expected flood of new nanotechnology products into the marketplace.

There is also the issue of how one can make such a categorical statement about the oversight system's ability to manage risks posed by food and agriculture nanotechnology when there is not a clear view of the particular products now under development. On the basis of analyses conducted by J. Clarence Davies, there is little evidence that federal agencies know enough about products under development to assure the public and industry that they have the proper legal authorities and technical expertise to conduct thorough and timely reviews of safety concerns, even if they thought such steps were necessary.[17]

Foresight is also needed to determine how the main agencies involved—the FDA, the USDA, and the Environmental Protection Agency (EPA)—will coordinate what can be conflicting and overlapping authorities. In the 1980s, it took a considerable amount of work to create a framework for coordinating reviews of new biotechnology products such as genetically modified plants, and problems still persist. A similar federal undertaking is not yet under way for nanotechnology applications or specifically for food and agriculture applications of nanotechnology, even though new nanotechnology applications and products are beginning to reach the market.

However, there are signs that a more proactive approach from the government is emerging. In June 2005, EPA held its first public meeting on a pilot program for industry to voluntarily provide the agency with information on nanoscale materials.[18] Additionally, in the fall of 2006, FDA will hold a public meeting to "gather information about current developments in uses of nanotechnology materials in FDA-regulated products."[19] The FDA meeting is expected to focus on, among other things, nanotechnology that would be used in foods, including dietary supplements and in animal feeds.

Clearly there is still time, before nanotechnology is incorporated into hundreds of food and agriculture products, to focus on what is coming and to lay the groundwork for its orderly entry into the market. But to put it

17. Davies, J. Clarence. *Managing the Effects of Nanotechnology.* Washington, DC: Project on Emerging Nanotechnologies, Woodrow Wilson International Center for Scholars, January 2006. Available at http://www.nanotechproject.org/reports, accessed July 5, 2006.
18. "June 23, 2005–Meeting On Possible Voluntary Pilot Program for Nanoscale Materials." Washington, DC: Environmental Protection Agency, July 27, 2006. Available at http://es.epa.gov/ncer/nano/relevant_meetings/archive/2005/ index.html, accessed July 28, 2006.
19. "FDA Announces Plans for Nanotechnology Public Meeting." Rockville, MD: Food and Drug Administration, April 13, 2006. Available at http://www.fda.gov/bbs/topics/NEWS/ 2006/NEW01356.html, accessed July 5, 2006.

simply, neither industry nor government appears to be doing its homework. Therefore, products could end up in the market without a proper assessment of their risks or end up indefinitely halted at the threshold of commercialization.

Anticipating Rather than Reacting: Building a Database of Future Applications

In an effort to help fill a knowledge gap and start building a framework for a more thorough consideration of how nanotechnology will be used in food and agriculture, we developed a database to identify technologies that may soon be on the market, explore potential risks and benefits associated with these technologies, and help focus the attention of the nanotechnology policy community on this emerging area of nanotechnology's application.

The entries catalogued in the database are largely United States government–funded, application-oriented, research and development projects culled from information provided by USDA, EPA, NSF and websites of a variety of agencies that have funded work in this area: the National Institutes of Health (NIH), Department of Defense (DOD), Department of Energy (DOE), Department of Homeland Security (DHS), and FDA. Total spending from all agencies between 2000 and fall 2005 was $15.2 million. Of that amount, a majority of the research projects in the database (about $11 million from 2000 to 2005) are funded by USDA. During that same period, NSF-funded projects amounted to $3.5 million and EPA projects totaled about $780,000.

The $15.2 million total likely underestimates the government's investment in food and agriculture nanotechnology applications research, since some projects may have been missed. Nevertheless, it is clear that government expenditures on food and agricultural applications of nanotechnology are only a small percentage of the more than $1 billion that the federal government spends annually on nanotechnology, the bulk of which has historically focused on basic research and on industrial and medical applications.

In an effort to help fill a knowledge gap and start building a framework for a more thorough consideration of how nanotechnology will be used in food and agriculture, we developed a database to identify technologies that may soon be on the market, explore potential risks and benefits associated with these technologies, and help focus the attention of the nanotechnology policy community on this emerging area of nanotechnology's application.

One obvious limitation of the database in its current form is that it does not capture industry-funded research and development projects, although it does include a small number of projects gleaned from searching patent applications registered at the United States Patent and Trademark Office (USPTO), which may include industry-related work. Overall, the USPTO database offers little insight into industry agrifood nanotechnology research and development applications, which, particularly among major food companies, are believed to be significant.

Industry projects are largely absent because, unlike government-funded work, there is no requirement or regular effort to disclose information on private sector food and agriculture nanotechnology research. Companies working in this area should consider how they can offer a better preview of technologies under development in a way that informs the public while protecting commercial interests. But as noted above, the tendency in the commercial sector is to keep product development under wraps.

Even with its current limitations, this assemblage of food- and agriculture-related nanotechnology research projects is the only database of its kind currently available. It is far better than flying blind and waiting for products to appear in our supermarkets and on our farms before considering their risks and benefits. This database, which can be searched and manipulated with Microsoft Access software, is being made publicly available online by the Project on Emerging Nanotechnologies in a downloadable form to encourage additions and collaborations. It should be considered one important component of a broader effort to explore the challenges—to government, industry and society—posed by the growing number of efforts to develop practical and profitable uses of nanotechnology.

What We Learned About Food and Agriculture Nanotechnology

As of April 2006, the database contained 160 projects, 146 of which were clearly connected to food and agriculture applications of nanotechnology and 14 that had enough connections to warrant their inclusion. In an indication of how rapidly the field is moving, it is estimated that more than 30 of these projects could produce a commercially viable application in five years or less, and most of the others have the potential to generate a commercial product in the next 15 years.

The majority of projects are focused on the food industry. For example, much of the research looks at using nanomaterials to improve food packaging or to detect and, in some cases, neutralize substances that are the frequent cause of potentially fatal bouts of food poisoning. There is also research that seeks to use nanomaterials to enhance the biological activity of dietary supplements or "nutraceuticals." In fact, a recent inventory of nanotechnology-based products already on the market contains a dozen dietary supplements.[20]

For agriculture applications, the database indicates that using nanotechnology to develop more-efficient and environmentally friendly farming techniques is now a popular area of research. For example, one project seeks to use nanotechnology to develop extremely sensitive devices that can monitor how water flows through farmlands. Potential longer- term applications of this research could help indicate how to stop runoff from crops or how to prevent livestock from polluting nearby streams, rivers and lakes. Other projects explore how to harvest nanomaterials from agricultural waste—or how to use nanomaterials to neutralize farm pollutants—and whether nanomaterials can be made that will help convert leftover crop materials, such as leaves, cornstalks and corncobs, into ethanol, which can be used for fuel.

For each project, the database provides:

- a summary of the project;
- a prediction about when the research might lead to a commercial product;
- types of methods and topic areas for each project.
- the names and institutions of the principal investigators; and
- the funding source and the grant amount.

20. Maynard, Andrew, and Evan Michelson. *The Nanotechnology Consumer Products Inventory*. Washington, DC: Project on Emerging Nanotechnologies, Woodrow Wilson International Center for Scholars, March 2006. Available at http://www.nanotechproject.org/reports, accessed July 5, 2006.

We have also made an attempt to offer a glimpse of each project's potential environmental and health risks and benefits. This aspect of the database, which ranks any risks or benefits that can be identified as "high," "medium," or "low," is considered to be a work in progress. It is an initial effort to move beyond broad generalizations about the promises and pitfalls of food and agricultural nanotechnology and to focus on risks and benefits that may emerge from specific applications. While these risk/benefit rankings may be imperfect, they are nonetheless informative, in part because they highlight the need for a more comprehensive approach to defining risks and benefits of nanotechnology in food and agriculture.

One reason the rankings should be used with caution is that not all potential risks were identified. For example, in examining projects related to food packaging, the analysis did not fully consider whether the food might absorb any nanomaterials from the package. Also, because there was no evidence that any projects would release potentially toxic materials on a wide scale, nothing in the database is rated "high risk." It is conceivable that there are projects in the database where laboratory or farm workers would be exposed to potentially harmful nanomaterials, which might warrant reconsidering the risk ranking.

Overall, the information should be viewed as a first pass in developing risk/benefit rankings. A rigorous analysis is under way to develop an approach to more accurately evaluate individual projects. With a solid set of risk rankings, the database can eventually be mined to identify priorities for safety evaluations.

Putting the Database to Work: Forecasting Food and Agriculture Innovations

To understand how the database can be used to identify and explore applications of food and agricultural nanotechnology that may soon be on the market, consider the following examples it contains.

Intelligent Chicken Feed

If one were to enter the search term "pathogen detection," the database would show, among other projects, an effort to use nanotechnology to improve food safety in the poultry industry.

Under a grant from USDA, bioengineering researchers at Clemson University are working to develop a nanomaterial they hope can be given to chickens and turkeys to remove a common poultry bacterium called campylobacter (pronounced kamp-e-lo-back-ter). The bacteria do not harm the birds, but when ingested by humans, they can cause cramps and bloody diarrhea. The Clemson investigators are trying to create a nanoparticle specifically designed to latch on to molecules that exist on the surface of the campylobacter and then remove the bacteria from chicken or poultry before they reach humans. According to the Centers for Disease Control and Prevention (CDC), campylobacter affects about 1 million Americans each year, with the majority of cases stemming from contact with raw or undercooked poultry.

The database offers insight into the Clemson project by providing a summary that describes the technical details of the research as well as its objective. The database also rates the risks and benefits of the proposed nanomaterial. Among the potential risks that deserve attention is whether the nanomaterial, if it entered the environment, might affect bacteria that are beneficial to an ecosystem. There is also a question of whether there are risks to humans who may ingest the nanomaterial when they eat the treated poultry.

The database rates the potential human and environmental risks as "medium." (The

Assembling this kind of database is a first step of a critically needed systematic preview of coming attractions and applications in food and agricultural nanotechnology. Offering this preliminary database for public consumption could have several benefits that will advance the effort to properly consider what happens when various types of nanotechnology are used either in, or in close proximity to, the things that humans grow and eat.

summary of the project notes that it includes a "safety evaluation" of human exposures.) The benefits are rated as "high," given that the technology targets a "serious food-borne pathogen." According to our estimates, the bacteria-fighting nanomaterials could be ready for commercial use in 5 to 10 years.

Nanotechnology as Rumpelstiltskin: Spinning Gold—Ethanol Actually—From Cornstalks

U.S. dependence on foreign oil can potentially be decreased through nanoscience. A research program at Purdue University focuses on applying nanotechnology and principles of polymer science to improve processing of cornstalks to ethanol, an important biofuel. The researchers are using nanoscience to break apart cornstalks into nanomaterials for easier and cheaper transport of biomass for ethanol production. Transportation of biomass to fuel production plants is currently costly and inefficient. This "nano-processing" step may ultimately make it possible to reduce ethanol production costs significantly as well as to decrease fossil fuel use during transport.

In the database, this project was categorized as "medium" benefit to the environment, given its ability to replace fossil fuel. However, the life cycle issues (that is, energy, carbon dioxide emissions, and chemical use) associated with these processing steps need to be considered in full, considering any potential benefits or harms to the environment. In light of this, the project was also categorized as "medium" risk to the environment.

The Beginning of a Conversation, Not a Last Word

As noted above, assembling this kind of database is a first step of a critically needed systematic preview of coming attractions and applications in food and agricultural nanotechnology. Offering this preliminary database for public consumption could have several benefits that will advance the effort to properly consider what happens when various types of nanotechnology are used either in, or in close proximity to, the things that humans grow and eat. Since anyone can view the information, anyone can offer suggestions for additional projects to include or a way to improve the overall structure and approach of the database. The database also serves as an open invitation to companies working in this area to add their projects to the mix, which could help provide early publicity about a product that could have considerable consumer appeal. In addition, by allowing companies to get feedback from other scientists working in the field, industrial developers of food and agriculture innovations could, by adding their projects to the database, enjoy the benefits that accrue to software developers who follow an open-source approach to product development.

The goal of this database is to take a long-term look at food and agricultural applications for nanotechnology and assure that any risks will be proactively analyzed so that benefits can be realized.

Meanwhile, the authors will seek to offer a deeper understanding of issues raised by the research covered in this database by conducting a series of cases studies that will focus

more closely on risks and benefits. The original purpose of developing this database was to identify the subjects of these case studies. More detail about the case study selection method can be found at the end of the second section of this report.

In conclusion, the goal of this database is to take a long-term look at food and agricultural applications for nanotechnology and assure that any risks will be proactively analyzed so that benefits can be realized. While there is a tremendous opportunity with nanotechnology to "get it right," societies have missed this chance with other new technologies and, in so doing, forfeited significant social, economic, and environmental benefits.

While there is a tremendous opportunity with nanotechnology to "get it right," societies have missed this chance with other new technologies and, in so doing, forfeited significant social, economic, and environmental benefits.

Analysis of Early-Stage Agrifood Nanotechnology Research and Development

From Context to Content

As noted earlier, nanotechnology has the potential to revolutionize agricultural and food (agrifood) production. Potential applications of the technology include controlled nutraceutical delivery systems for food; on-farm applications to deliver drugs or pesticides to livestock or crops; and smart-sensing devices for agriculture-environment interactions. The most prominent agrifood nanoproducts currently on the U.S. market are nanocomposites for food packaging. These nanomaterials provide barriers to oxygen and carbon dioxide, thus protecting food quality.[21]

A recent report by Helmut Kaiser Consultancy indicates that worldwide sales of nanotechnology products in the food and beverage packaging sector were U.S. $860 million in 2004, up significantly from U.S. $150 million in 2002.[22] Products for nutraceutical delivery in foods are on the market in other countries.[23] Five out of ten of the world's largest food and beverage companies invest in some form of nanotechnology research. For example, Kraft Foods funds research at several universities and national labs through its NanoteK consortium.[24] Despite the attention to agrifood nanotechnology in industry, there have been few, if any, systematic, publicly available evaluations of research and development (R&D) in this area, and the field of agrifood nanotechnology remains largely unexplored in the public domain.

Nevertheless, the public is becoming increasingly aware of the potential for improving food via nanotechnology. One study designed to investigate the public perceptions of nanotechnology found that 6 percent of respondents listed "safer and better food" as one of the main expected benefits from the technology. This benefit was the fifth most cited. At the same time, 7 percent of respondents cited worries associated with "nanotechnology's use in food products, packaging, and agriculture."[25] This concern was the sixth most cited.

Projects in the database largely represent government-funded research, with the additional category of projects for which patents have been obtained. The database categorizes

21. For example, nanoclays dispersed in polymer matricies, such as Nanomer® nanoclays produced by Nanocor®.
22. "Study: Nanotechnology in Food and Food Processing Worldwide 2003-2006-2010-2015." Tübingen, Germany: Helmut Kaiser Consultancy, 2006. Available at http://www.hkc22.com/nanofood.html, accessed July 5, 2006.
23. For example, Canola Active, a cooking oil that contains nano-size, self-assembled structured liquids (NSSL) of approximately 30 nanometers to disperse phytosterols is on the market in Israel. See http://www.shemen.co.il/english/nutrition-health.html.
24. Gardener, Elizabeth. "Brainy Food: Academe, Industry Sink Their Teeth into Edible Nano." *Small Times,* June 21, 2002. Available at http://www.smalltimes.com/document_display.cfm?document_id=3989&keyword=brainy%20and%20food&summary=1&startsum=1, accessed July 5, 2006.
25. Macoubrie, Jane. *Informed Public Perceptions and Trust in Government*. Washington, DC: Project on Emerging Nanotechnologies, Woodrow Wilson International Center for Scholars, September 2005, p. 9 and 11. Available at http://www.nanotechproject.org/reports, accessed July 5, 2006.

projects with respect to type of research (basic, applied, or development); projected time to commercialization; techniques, topics, and research areas, as specified in a USDA report on agrifood nanotechnology[26]; sectors in the food supply chain; and their fit to well-accepted definitions of nanotechnology. Four databases[27] and five government websites[28] were searched for projects active during the years 2000 through 2005.

We do not view this version of the database as complete or the end of this project. Rather, it is a start to evaluating activities in agrifood nanotechnology in the public domain, and it will continue to benefit from outside input and contributions. We welcome feedback on the database. Please send us your comments, changes, or suggestions for additional entries.[29]

Results and Conclusions

As mentioned earlier, as of April 2006, 160 projects are included in the database. Fourteen of these projects have questionable connections to agriculture, food, and/or nanotechnology (as noted in the database entries). We erred on the side of inclusiveness and decided to keep them in this first version of the inventory.

Figures 1–3 display the number of projects that fall into each technique, topic, or USDA research category. Bioselective surfaces and nano-bio processing contain the most projects for techniques; biosensors and food bioprocessing contain the most projects for topics; and pathogen and contaminant detection and nanoscale materials science and engineering contain the most projects for USDA research categories. These results are consistent with the high number of nanotechnology projects focused on food packaging and sensing for foodborne pathogens during processing. We found very few projects that addressed USDA research categories of identity preservation/tracking and of education/workforce. By contrast, the USDA research category of environmental issues/agriculture waste is well-represented given the number of products that focus on harvesting industrial nanomaterials from biomass.

26. *Nanoscale Science and Engineering for Agriculture and Food Systems.* Washington, DC: United States Department of Agriculture, July 2003.
27. Searched databases include: USDA-Current Research Information System (CRIS), the United States Patent and Trademark Office (USPTO), EPA-Science Inventory, and NSF Awards.
28. Searched websites include NIH, DOD, DOE, DHS, and FDA.
29. Please send edits, suggestions, or additional information to Jennifer Kuzma at kuzma007@umn.edu.

Figure 1. Techniques Used in Agrifood Nanotechnology Projects

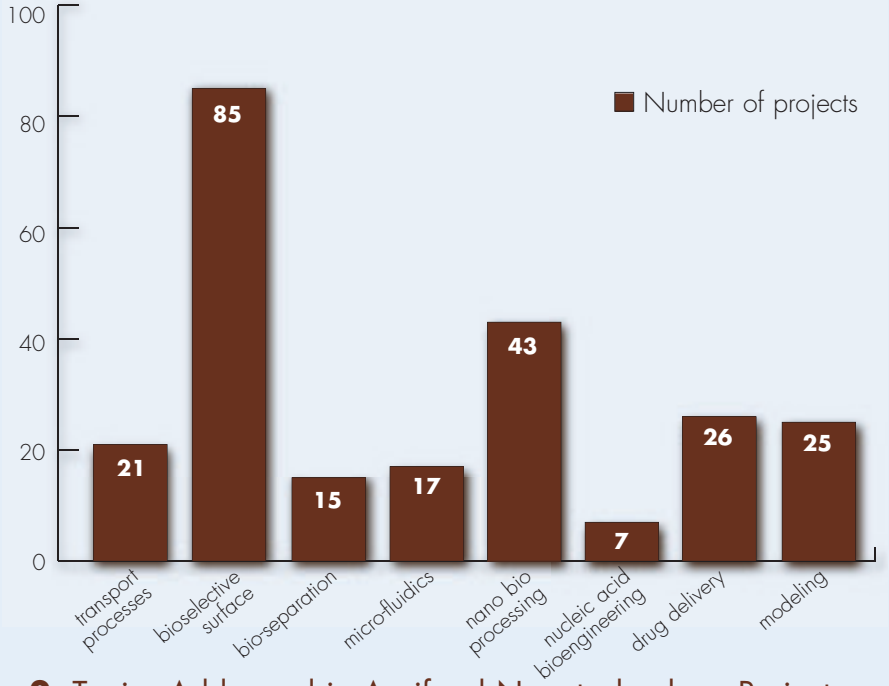

Figure 2. Topics Addressed in Agrifood Nanotechnology Projects

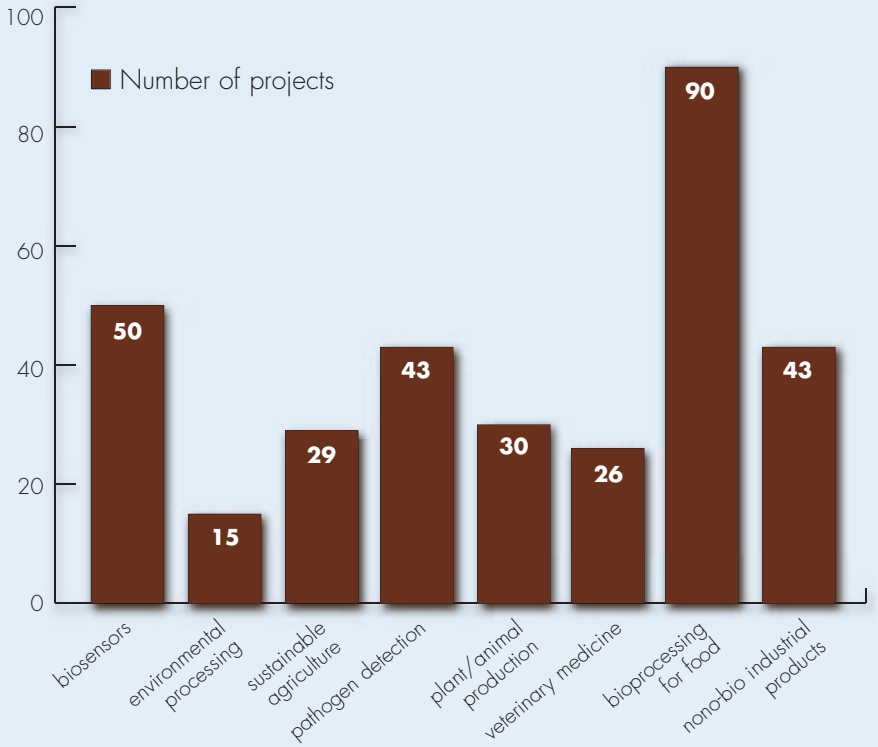

Figure 3. USDA Research Areas for Agrifood Nanotechnology Projects

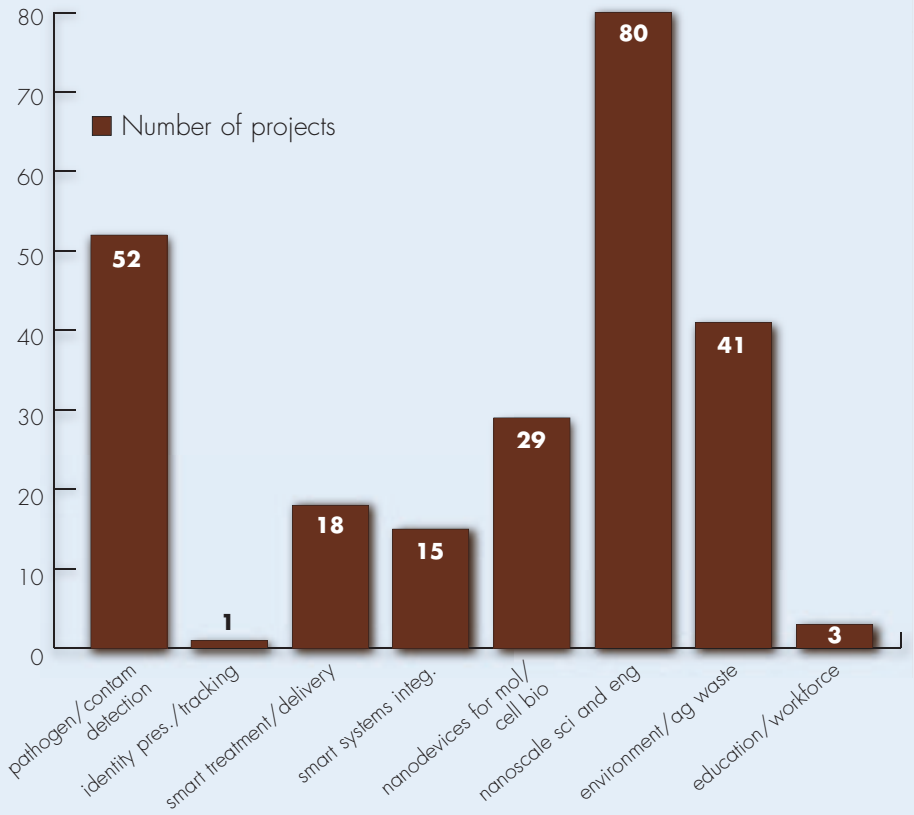

Figure 4. Type of Research in Agrifood Nanotechnology

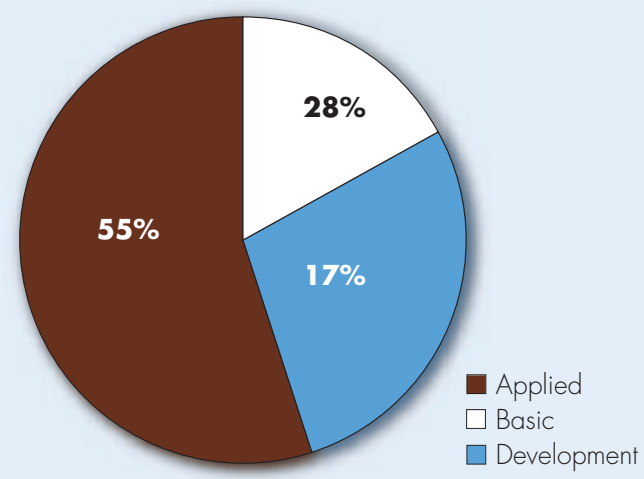

Figure 4 shows the distribution of the three types of research in agrifood nanotechnology, while Figure 5 displays the anticipated commercialization timeframe for the projects. Most projects fall into the "applied research" category (55%) and are estimated to be commercialized in 5–15 years. The majority of the "development" and "0–5 years" entries come from the United States Patent and Trademark Office (USPTO database. As shown in Figure 6, the majority of projects fall into post-harvest (47%), consumer applications (39%), or retail (27%). This again reflects an emphasis on projects related to food packaging and pathogen/contaminant detection during food processing.

Figure 5. Estimated Time to Commercialization

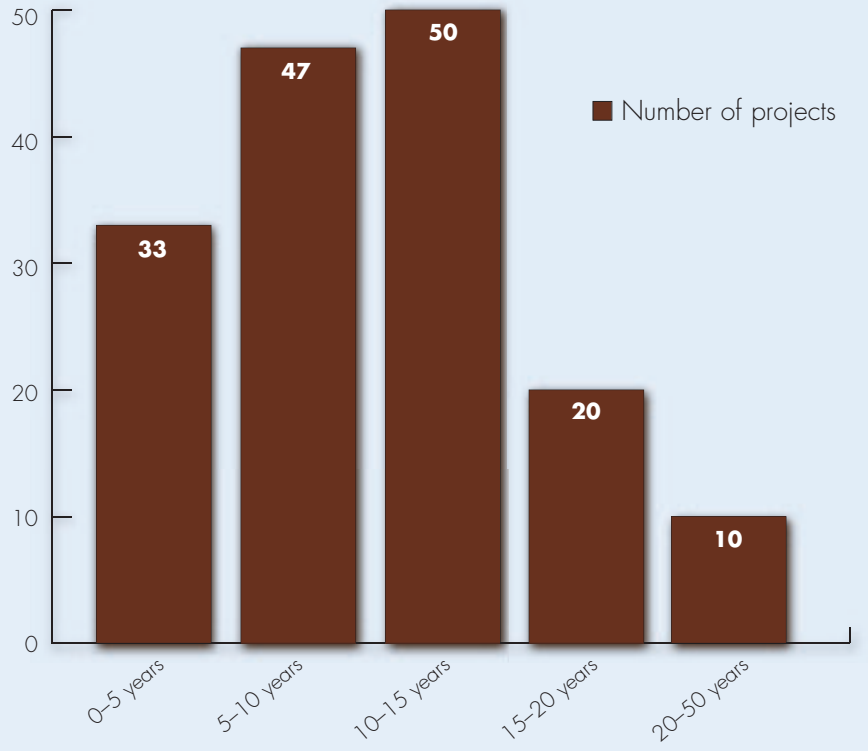

Figure 6. Sector of Food Supply Chain

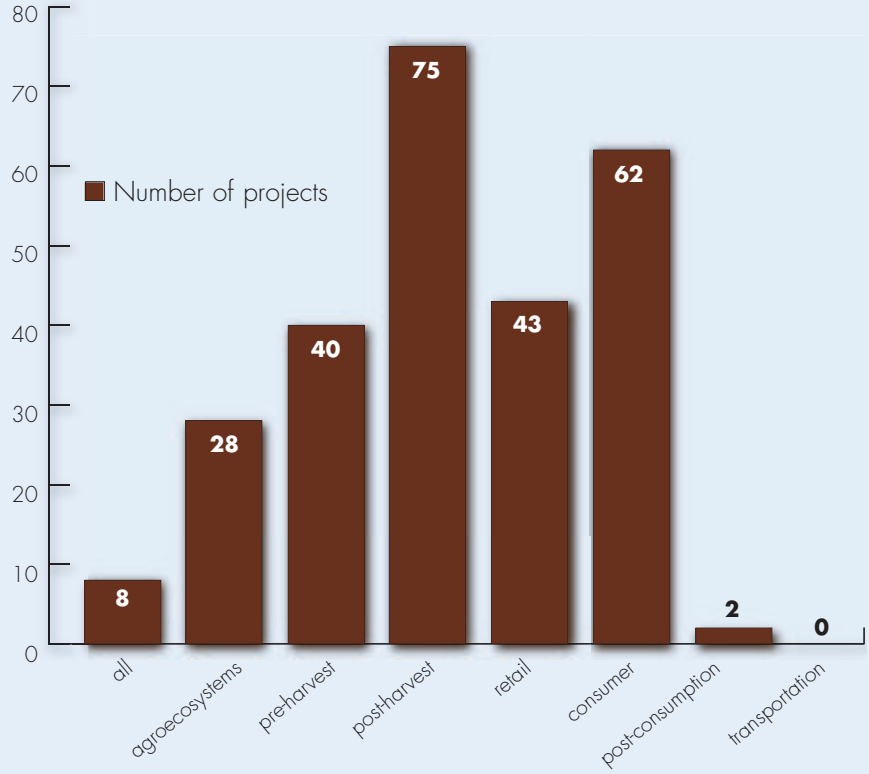

Figure 7 indicates that lab and industry workers are the primary groups who will be exposed to emerging agrifood nanotechnology applications. Consumers will also be exposed, given the number of applications in food packaging. In these cases, we did not examine whether the nanomaterials would leach from the packaging material and did not search for studies in this area. Also, in many cases, it was too difficult to determine exposure endpoints from the description of the project. Consequently, results from this analysis should be used cautiously.

Exhaustive searches for "known toxicity studies" were not conducted for each project; therefore, these results are not summarized. However, general knowledge about toxicity and exposure was used for the qualitative risk/benefit ranking. Figures 8 and 9 highlight the environmental and health results, respectively, of this ranking. It is interesting that no projects are considered to be high risk, indicating that toxic materials are not intended for wide-scale release (see methodology section). However, risks to lab and industry workers could remain high according to the ranking system used in this analysis. It will be important in future studies to analyze risks to sub-populations or different endpoints. The results in this paper should be viewed as simply a starting point for further analysis. More rigorous risk/benefit analysis for each project is needed to more accurately rank the projects.

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Figure 7. Possible Exposure Endpoints

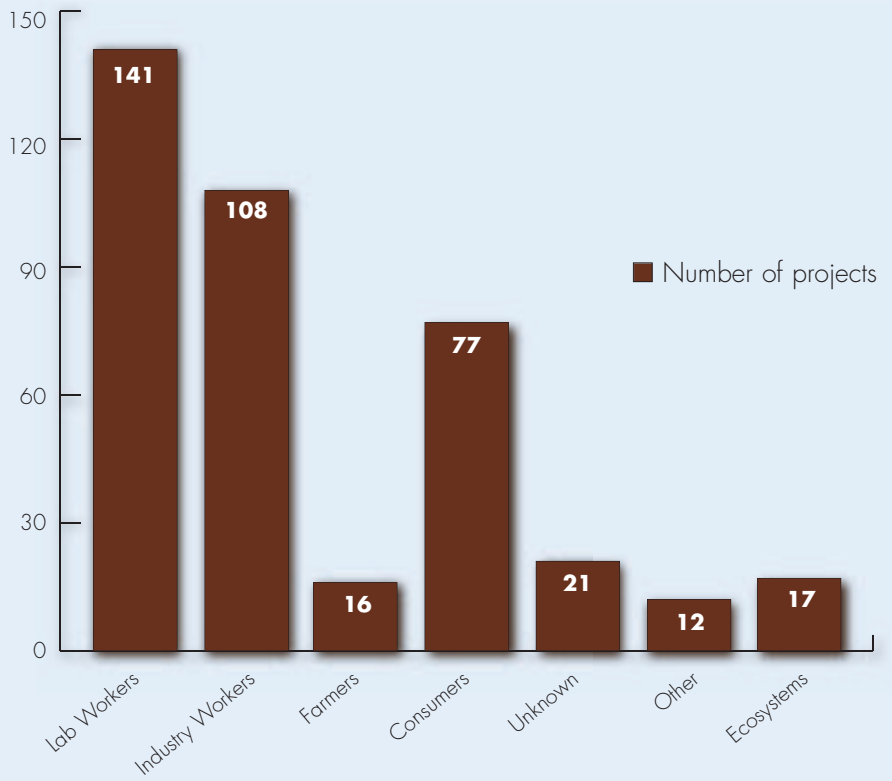


Figure 8. Environmental Risks and Benefit: Qualitative Ranking

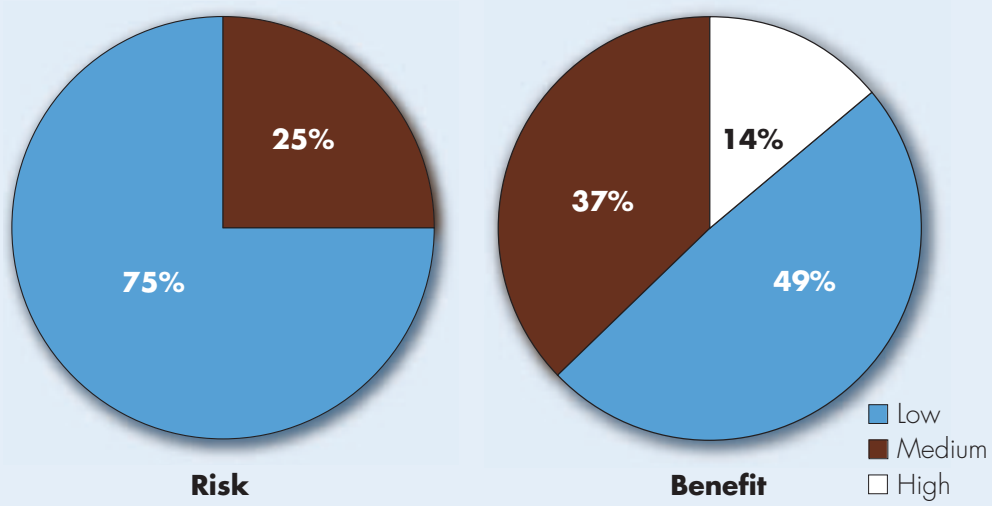
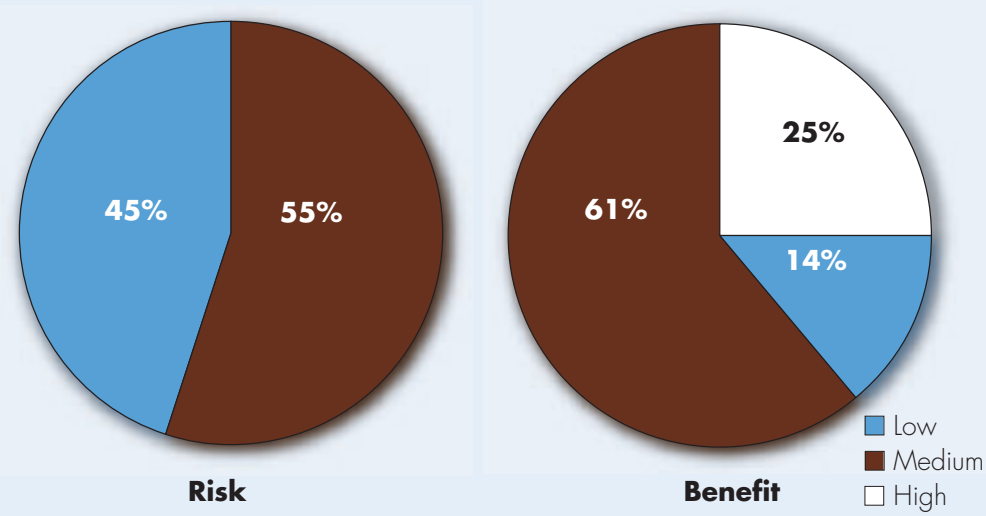


Figure 9. Health Risks and Benefit: Qualitative Ranking



Of the160 projects, 77 are projects in which research and development could lead to nanoproducts to which consumers would be exposed. Of the77 projects, 64 are classified as "medium health risk" and 13 as "low health risk" (Figure 10). Of the 17 projects leading to ecosystem exposure endpoints, four are classified as "medium environmental risk" and three as "low environmental risk" (Figure 11). When mined in this way, the database is of value in selecting priorities for safety evaluations. For example, medium-risk projects for which there will be human and/or environmental exposure endpoints should be of priority for more rigorous risk/ benefit analyses and environmental, health and safety (EH&S) research.

Figure 10. Health Risks and Benefits for Projects, including Consumers as Exposure Endpoints (n = 77)

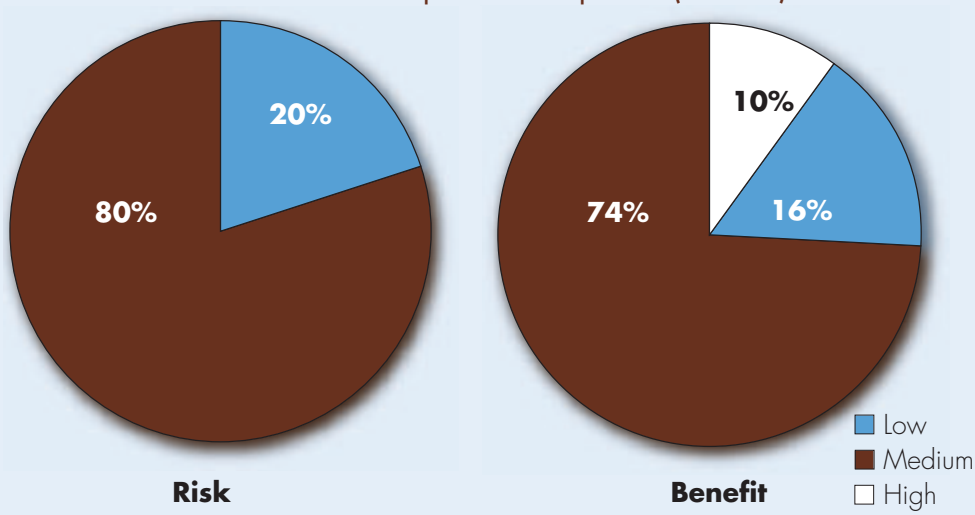


Figure 11. Environmental Risks and Benefits for Projects, including Ecosystems as Exposure Endpoints (n = 17)

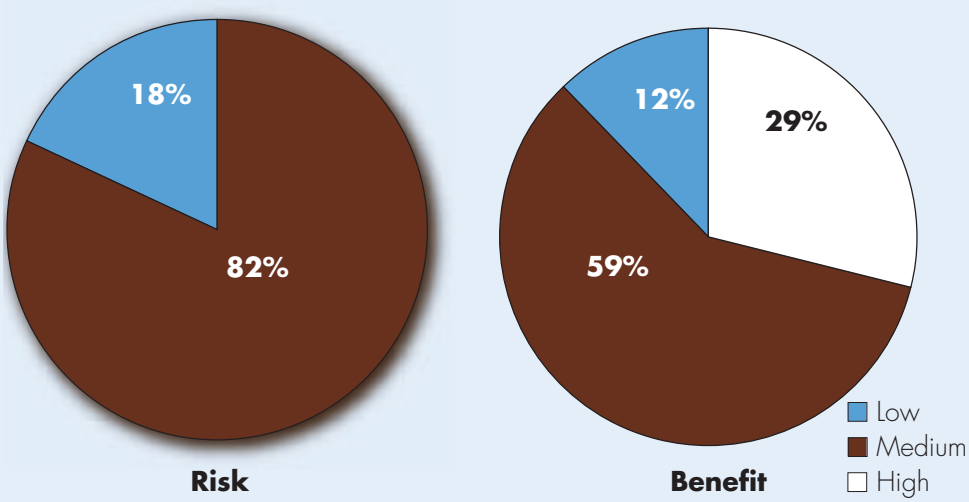
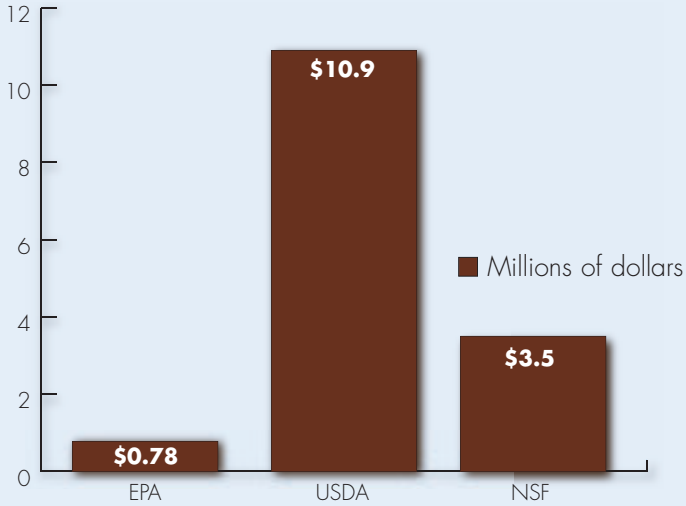


Figure 12 depicts the amount of USDA ($10.9 million), EPA ($0.78 million), and NSF ($3.5 million) extramural funding in agrifood nanotechnology between 2000 and fall 2005. The total amount of extramural funding for projects in this database across all three agencies was $15.2 million. Funding levels were not available for several projects, including some from the USDA-Current Research Information System (CRIS) database. Furthermore, some projects at these agencies may have been entirely missed, so these numbers likely are underestimates of investments in nanotechnology at USDA, NSF, and EPA. Other agency and departmental funding is not shown, as this information was not available from the searches.

Figure 12. EPA, USDA, and NSF Funding for Agrifood Nanotechnology, 2000–2005



Current and Future Work

Using this database, we have selected a draft set of case studies for subsequent risk-benefit and governance analyses. The case studies span a range of topics, research areas and techniques, timeframes, sectors, safety issues, and endpoints. Other selection criteria include:

- likelihood of products entering the marketplace in the near future;
- availability of extensive data and information on the research;
- reflection of larger social or economic issues; and
- potential to offer significant benefits.

We are currently gathering information on the draft set of case studies in order to better identify and categorize the potential human health and environmental risks and benefits. We will focus largely on the scientific and technical risk/benefit issues (e.g., human and environmental health), although we will not exclude socioeconomic issues that overlap with these.

Case studies eventually will be used to consider the following questions:

- Are there current regulatory or non-regulatory governance systems that cover the proposed applications or products? If so, what are they?
- Do these systems address the risk and benefit issues? If so, how? If not, where are the gaps?
- What are other strengths and weaknesses of existing systems?

If there currently are no systems in place for the products or the issues, what are the possibilities for developing such systems under existing legal or organizational frameworks?

This analysis is similar to one done on the products of biotechnology (i.e., genetically engineered organisms) by the Council on Environmental Quality and the Office of Science and Technology Policy (CEQ/OSTP) in 2000.[30] We will use the CEQ/OSTP analysis as a guide. Our analysis will strive to be specific as to how governance systems cover the health and environmental safety issues of emerging agrifood nanotechnology products.

In the end, the database, coupled with the proposed case studies, will begin to provide the public with information in the emerging area of agrifood nanotechnology. Once again, we welcome comments and feedback on our initial analysis. More information about the methodological approach employed in developing the database can be found in the following section.

30. *CEQ/OSTP Assessment: Case Studies of Environmental Regulation for Biotechnology*. Washington, DC: Office of Science and Technology Policy. Available at http://www.ostp.gov/html/012201.html, accessed July 5, 2006.

Methodology

Overview

We began developing the database in summer 2005 by selecting two broad search terms—"nano + food" and "nano + agriculture"—and searching four databases (USDA-CRIS, USPTO, EPA-Science Inventory, NSF Awards) and five government websites (NIH, DOD, DOE, DHS, FDA) for relevant projects. We then manually reviewed the projects for accuracy and appropriateness. We ultimately included 160 projects in the database. We then categorized each project with respect to type of research (basic, applied, or development); projected time to commercialization; and techniques, topics, and research areas, as specified in a USDA report on agrifood nanotechnology.[31] The lead author, Dr. Kuzma, then analyzed and categorized each project for potential environmental and health risks and benefits. Definitions related to each aspect of categorization are provided below, along with in-depth information about the searches of each database or website.

After the initial categorization, a majority of the principal investigators were asked to review and edit the categorizations and classifications of their projects by providing additions or corrections. Seventeen responses were received (14% response rate). A majority of the respondents completely agreed with the categorization. Others suggested only minor changes. Additional information about the principal investigator review process is provided below, as is a brief guide on how to access and use the database.

Categories for Entries

Type of Research:

Development—specific product cited largely experiments or studies to optimize product.

Applied—specific application noted, but may also lead to better understanding.

Basic—fundamental understanding is goal; specific application not stated (although there could be one in the future).

Time to Commercialization:

0–5 years—applied/development projects that directly address regulatory or product optimization issues. The applications of the work appear to be very near-term with minimal regulatory concerns or the products are already in the properties are being studied or optimized.

5–10 years—applied/development research that is based upon proven technology and for which there are no serious safety concerns.

10–15 years—applied research that is in the early stages of concept or development.

31. In this report, there is a matrix that includes thematic research and development topics such as environmental processing, pathogen detection, plant/animal transgenics/cloning, bioprocessing foods/industrial products, and sustainable agriculture on one axis, and nano-techniques such as transport processes, bio-selective surfaces, bioseparation, micro-fluidics, nano-bioprocessing, nucleic acid engineering, drug delivery, and modeling on the other. There are also eight broad categories of research: detection, identity preservation and tracking, smart treatment delivery systems, smart systems integration for agriculture and food processing, nanodevices for molecular and cellular biology, nanoscale materials science and engineering, environmental issues and agricultural waste, and education of the public.

15–20 years—applied/basic research for which applications are not specified but can be envisioned.

20–50 years—basic research for which few, if any, applications are envisioned, but for which fundamental knowledge will eventually lead to some.

Techniques:

More than one technique might be utilized in a given project (multiple boxes might be checked):

Transport processes—nanomaterials as agents for transporting chemicals, molecules, etc.

Bio-selective surfaces—nanomaterials with enhanced or reduced ability to bind or hold specific molecules and/or organisms.

Bio-separation—nanomaterials or nano-processes with the ability to separate molecules, biomolecules, or organisms.

Microfluidics/MEMs—liquid streams used to separate, control, or analyze at the nanoscale. They might have special flow properties at this scale. Microelectromechanical systems (MEMs) are also included in this category. They are devices with channels and wells, electrodes for detection, connectors, and fluidic input/output ports.

Nano-bioprocessing—use of nanoscale technology and/or biological processes to create a desired compound or material from a defined stock. The product itself may be bulk or nanoscale.

Nucleic acid bioengineering—use of DNA as building blocks to form nanoparticles or use of nanoparticles for genetic engineering.

Drug delivery—use of nanomaterials or nanomethods to deliver drugs to animals.

Modeling—use of nanotechnology to build models of systems or the modeling of nanomaterials in systems.

Topics:

The project might fit more than one topic (multiple boxes might be checked):

Biosensors—use of nanotechnology for sensors based upon biological processes or biological molecules or for detection of biological molecules, processes, or organisms.

Environmental processing—use of nanotechnology for studying environmental phenomena, removing contaminants in the environment, or remediating or reducing waste. Includes study of nanomaterials in the environment as well.

Sustainable agriculture—use of nanotechnology for reducing agricultural inputs or outputs that can harm the environment or human health (e.g., pesticides) or are in short supply (e.g., water); or for making products from agriculture in a sustainable way.

Pathogen detection—use of nanotechnology to detect pathogens in surroundings, organisms, or food.

Plant/animal production—use of nanotechnology to improve the cultivation of plants or animals, including via transgenics or cloning.

Veterinary medicine[32]—use of nanotechnology to improve animal health and/or the safety of animal-derived foods.

Bioprocessing for food—use of nanotechnology for better food processing or food quality.

Nano-bioindustrial products—use of nanotechnology for developing industrial products from agriculture or its by-products.

USDA Research Areas:

The project might fit more than one topic (multiple boxes might be checked), involving nanotechnology in the following ways:

Pathogen and contaminant detection—pathogen or contaminant detection in agriculture, food, or the environment.

Identity preservation and tracking—systems that provide producers, processors, and customers with information about the practices and activities used to produce a particular crop or agricultural product. Such systems may also provide information on the origin and movement of crops, animals, or products.

Smart treatment delivery systems—systems that deliver molecules in agricultural production or processing in time-controlled, spatially targeted, regulated, responsive, or other precise ways. Such systems could have the ability to monitor effects of delivery.

Smart system integration for agriculture and food processing—integration of a working system with sensing, reporting, localization, and control. System could be used anywhere along the farm-to-table continuum, or at multiple points.

Nanodevices for molecular and cell biology—devices based on or applied to molecular and cellular biology that separate, identify, study, modify, or sense.

Nanoscale materials science and engineering—development of novel materials through materials science and engineering. Work to better understand the behavior and properties of nanomaterials.

Environmental issues and agricultural waste—study of nanomaterials in the environment, such as in the transport and bioavailability of nutrients and pollutants. Understand transport and toxicity of nanomaterials in agricultural pollutants. Nanotechnology applied to environmental or waste issues.

Educating the public and future workforce—education about nanotechnology and nanoproducts; studies on ethical and social issues (cited in USDA report, although not reflected in USDA's short title of this research area); infrastructure support; technology transfer support; and public understanding of risks and benefits.

Sectors:

The work or research could be applied to more than one sector (multiple areas might be listed in the database):

Agroecosystems—application for or research on agricultural systems, and/or on surrounding natural systems.

Pre-harvest—application or research on the farm or in the forest, during agricultural production.

Transportation—application or research dealing with transporting agricultural or forest raw commodities or with products from the farm to the processor or retailer.

32. The authors added this category, which is not in USDA Nanoscale Science and Engineering 2003 Report.

Post-harvest—research or application after harvest, at the stage of processing the commodity or product.

Retail—research or application dealing with storage, display, etc., at the place where the product is sold.

Consumer—research or application dealing with the consumer end, such as storage and use of agricultural products in the home. This category is used for research that primarily improves the quality of the end product (e.g., better taste).

Post-consumption—research or applications for after the product is consumed. For example, food safety and illness detection.

Exposure Endpoints:

Boxes are checked if there is exposure to the following (multiple boxes might be checked):

Lab workers—most nanomaterial or particles are made or studied in the lab at some point. In most cases, lab workers will be exposed. The study of naturally occurring nanomaterials would be a case in which this box would not be checked.

Farmers—farmers are exposed if the nanomaterial, particle, or method is being used on the farm.

Ecosystems—ecosystems are exposed if the nanomaterial is (1) used on the farm (animals and plants on the farm, or the farm agroecosystem), (2) used for wide environmental applications, or (3) not disposed of properly. We assume that material used in manufacturing or the lab is disposed of properly. So, if this box is checked, it is because the material is intended at some point for environmental release.

Industry workers—industry workers will be exposed during production, manufacture, transport, processing, or at the retail/distribution stage.

Consumers—if consumers will likely come in contact with the material, this box is checked. The applications are either intended for consumer products or are left in the material as a result of production or processing.

Others—in some cases, there might be subpopulations that are specifically exposed as a result of the application or research.

Unknown—this box is checked when the description of the project is too vague, or the applications are too broad to determine who will be exposed.

Known Toxicity Records:

No—we could not easily (via a quick web search for articles) find toxicology studies on the nanomaterials cited in the project description, or the materials in question are not specified in the project description.

Yes, benign—we found studies that indicate low toxicity or hypothesize that the particles (e.g., DNA) are generally non-toxic. However, please note that toxicity is still dependent on the system tested in those studies (in vivo, in vitro, acellular endpoints), the form of the particle, and the amounts.

Yes, toxic—we found studies that indicate that the nanomaterials or materials are harmful to health and/or the environment, or the class of compounds is generally known to be toxic.

Environmental/Ecological Risks or Health Risks:

This is just a first-pass, qualitative ranking.

More information is needed on virtually all of these projects for better qualitative or quantitative risk assessment.

Low—if exposure to humans, animals or the environment is minimal, and the particles are generally non-toxic, we categorize the risk as low.

Medium—if exposure to humans, animals or the environment is minimal OR the particles are generally not-toxic, we categorize risk as medium. In this category, there are relatively benign particles that are widely used in food and agriculture. Likewise, a toxic particle that is meant to stay in the lab or processing plant could also be in this category. In the cases of nanotechnology applied to biobased products, "medium" was used for environmental or ecological risks with the question of whether harvesting and processing are done in a sustainable way (i.e., life cycle issues).

High—exposure to humans, animals or the environment is widespread and particles show toxicity or are expected to be toxic.

Environmental/Ecological or Health Benefits:

This is just a first-pass, qualitative ranking. More information is needed on virtually all of these projects for benefits assessment.

Low—application or research not meant to improve human or animal health or the environment.

Medium—application or research might improve health or the environment, but not explicitly developed for that purpose or for addressing a major societal problem.

High—application or research specifically developed to address an important societal need for improving health or the environment.

Does this fit nanotechnology?[33]

After reading the project abstract, objectives, and additional information, we are using the three criteria of the National Nanotechnology Initiative (NNI) definition to determine whether the project fits the definition of nanotechnology. If so, the box is checked. In some cases, there is not enough information to make such a determination, and we note this in the comment box.

Does this fit agrifood?

Nanotechnology should be applied to or used to study agriculture, food, forestry, or agroecosystems for this box to be checked. Sometimes the project description is vague, or the work is broad to determine whether it fits. This is noted in the comment box.

Search Process

USDA CRIS Database:

The USDA maintains a database called the Current Research Information System (CRIS) that documents and publicizes information about ongoing and recently completed research projects funded by USDA (http://cris.csrees.usda.gov/). We searched the USDA CRIS database using the following key words: "nano + food" or "nano + agriculture." Projects were limited to those active after 2000. The search was completed on August 15, 2005.

33. The National Nanotechnology Initiative lists the following three criteria for defining nanotechnology: (1) research and technology development at the atomic, molecular, or macromolecular levels, in the length scale of approximately 1-100-nanometer range; (2) creating and using structures, devices, and systems that have novel properties and functions because of their small and/or intermediate size; and (3) ability to control or manipulate on the atomic scale.

The text of each project was then searched for the words "nano + food" or "nano + agriculture" to exclude false leads as artifacts of the search terms. Initial results included many projects that did not fit agrifood nanotechnology, such as those containing the term *NaNO* (sodium nitrite) or the use of measurements at the nanoscale (e.g., nanometers, nanoliters). To be included in the survey, the project must have utilized or created materials on the nano-scale. The project must also have pertained to food or agriculture production or to agroecosystems. Once we had deemed a project relevant, we entered the project information in the database. We included a total of 90 projects from the CRIS database search. Although forestry projects arose, this was not used as a search term, so other projects funded by the USDA in this area may exist.

USPTO:

The USPTO maintains a database of patent applications that have been granted or that are pending (http://www.uspto.gov/patft/). To search the USPTO database of patent applications, we used the same key words as in the case of the CRIS database search, as well as similar criteria for selecting appropriate projects. The key words used in the search were "nano + (food or agriculture)", and a starting cut-off date of December 1, 1999 for filed patents was used. More than 600 projects contained the search terms. About 40 of them fit our definition of nanotechnology and agrifood. When there was a question as to whether a project fit, we erred on the side of including it. Due to differences in how the data are presented in each patent application and the length of the patent applications, the description given in the application was paraphrased and placed in the "objective" or "additional information" sections of the database. The search was concluded on October 14, 2005.

NSF:

The NSF website maintains an "Awards" section that provides information about NSF-funded research projects (http://www.nsf.gov/ awardsearch/). We search the "Awards" page using the following terms: "nano food" (35 projects) or "nano agriculture" (15 projects). When "nano agricultural" was substituted for "nano agriculture," the same 15 projects appeared. The search was conducted on November 11, 2005. Projects were then scrutinized for their fit to our definition of nanotechnology and agriculture and food.

EPA:

The EPA maintains the National Center for Environmental Research's webpage, which provides information about EPA-funded research projects (http://es.epa.gov/ncer/ru/index.html). We searched this webpage using the key word "nano." We found 13 projects. We then read each abstract to see whether the work was applicable to agriculture and food. None contained the keywords "agriculture" or "food." However, one had "soil" as a key word, and this was included in the database.

Additionally, we searched the Science Inventory (SI) (http://cfpub.epa.gov/si/), a searchable database of EPA science activities and scientific/technical work products, using the term "nanotechnology." All "Record Type" boxes were selected for the search, so the projects resulted from Archived and full Environmental Information Management System (EIMS) searches. The SI provides information about current or recently completed activities, providing a snapshot of EPA

science being conducted in its research laboratories and centers and program and regional offices, as well as through grants and other assistance agreements to universities and other institutions. Four entries arose from the search. One contained the keyword "soil," and it was included in the database. When the search term "nano" was used, 21 entries arose. None was found to be directly related to agriculture or food. Drinking-water projects that were found were not included in the database. Searches were conducted in December 2005.

NIH:

The NIH website was searched for "nanotechnology," and the page NIH Nanotechnology and Nanoscience Information (http://www.becon2.nih.gov/nano.htm) came up. Each of the links on this page was scanned for NIH-funded research in agrifood nanotechnology. The Nanomedicine-funded research site (http://nihroadmap.nih.gov/nanomedicine/fundedresearch.asp) was searched. No projects mentioning food or agriculture were found, although the basic science might be applicable to food and agriculture in several projects.

The Summary of Funded NIH Bioengineering Nanotechnology Initiative Small Business Innovation Research (SBIR) Grants for 2000 through 2004 was searched for the key words "food" or "agriculture." Five projects were found to contain these key words and they were added to the database. Searches were conducted in December 2005.

DOE:

The Department of Energy Office of Science site was searched for "nanotechnology." The DOE Office of Science supports nanotechnology through its Materials Sciences subprogram. The Materials Sciences subprogram was searched under "Research Programs" (http://www.science.doe.gov/bes/dms/Research_Programs/research_program.htm). Summaries of research in the national DOE labs were listed on this page. Each summary was searched for "food" or "agriculture" or "agri." No projects with these search terms were found. The DOE Basic Energy Sciences site was searched, which led to the DOE Nanoscale Science Research Centers page (http://www.science.doe.gov/Sub/Newsroom/News_Releases/DOE-SC/2006/nano/index.htm). When possible, center websites were searched for "food" or "agri." Most centers did not have searchable features on their sites. The document "Nanoscale Science, Engineering, and Technology in the DOE" (http://www.sc.doe.gov/bes/brochures/files/NSRC_brochure.pdf) was also searched. In this case, "agriculture" was found, but only in a general statement in the document that nanoscale applications could have benefits to agriculture. Searches were conducted in December 2005. No projects from DOE were added to the database.

DHS:

The Department of Homeland Security website was searched for "nano" (http://www.dhs.gov/dhspublic/). Two items were retrieved. Neither mentioned specific research projects in agriculture or food nanotechnology. The National Plan for Research and Development in Support of Critical Infrastructure Protection mentioned nanotechnology, and food/agricultural safety and security were mentioned separately in the document. Searches were conducted in December 2005. No projects from DHS were added to the database.

DOD:

Nanotechnology research awards at DOD were searched (http://www.defenselink.mil/releases/2001/b02232001_bt079-01.html). None contained the key words "food" or "agri" in the title. The Office of Naval Research nanotechnology site was also searched for "food" and "agri" (http://www.nanosra.nrl.navy.mil/). No specific research projects on agrifood nanotechnology were found. Searches were conducted in December 2005.

FDA:

FDA's website was searched using the term "nanotechnology," which led to its nanotechnology homepage (http://www.fda.gov/nanotechnology/). When the site was searched for "nanotechnology research," several Powerpoint presentations came up indicating that FDA does research in this area through its centers. The content of these presentations was reviewed. Research projects at FDA seem to focus on biological effects of nanomaterials and nanomaterials. No specific projects were found that focused on research and development in agrifood nanotechnology. Some of the general toxicity research will apply to agrifood nanotechnology products, however. Searches were conducted in December 2005.

Principal Investigator Review and Validation of the Entries

The majority of principal investigators (n=121, those for whom we could find contact information) were sent entries for their projects and the definitions of the categories (provided at the beginning of this section). They were asked to review the classification of their research and to make additions or corrections. We received 17 responses (14% response rate); of these, 11 completely agreed with the categorization. Other principal investigators asked for minor adjustments to their entries. In one case, the time to commercialization was decreased from 10–15 years to 3–5 years. In three cases, additional categories of techniques, topics, or research areas were added (however, none was removed). In one case, a principal investigator supplied additional information on the nature of the nanomaterials that allowed for a more appropriate classification of the risks and benefits. In another case, the principal investigator indicated that the majority of her work is not in nanotechnology, although the project in the database states that nanomaterials will be made in the laboratory. Changes suggested by principal investigators were incorporated into the database.

How to Use the Agrifood Nanotechnology Database

Available at: http/nanotechproject.org/50 Users may interact with the database in two ways. First, each project can be viewed in its entirety as an individual record. Second, several topical reports have been generated around specific criteria, including Risks and Benefits, Sectors and Research Areas, Topics and Techniques, Toxicity and Endpoints, and Time to Commercialization.

NOTE: A Windows computer with Microsoft Access 2000 or greater installed is necessary to open the database.

Unzipping and Opening the Database:

1. Double-click on the zipped file and select "Extract All Files" from menu on the left.

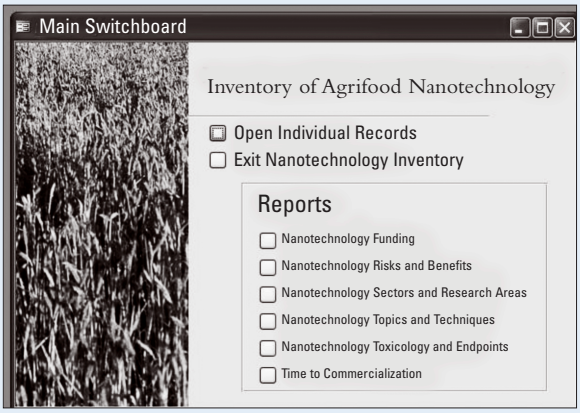
2. When the Extraction Wizard opens, click "Next."

3. Click on the "Browse" button, select where you would like to save the database and click "Next." Then click "Finish."

4. Navigate to the extracted folder and double-click on the file labeled "Inventory of Agrifood Nanotechnology.mdb."

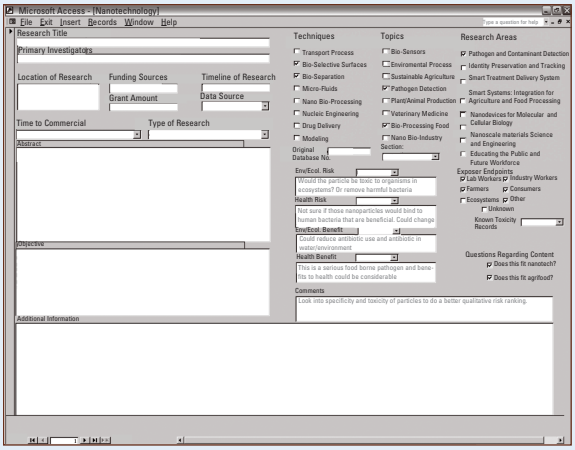
5. If a Security Warning message appears, click "Open."

6. As shown below, the opening page of the database will have several search options.

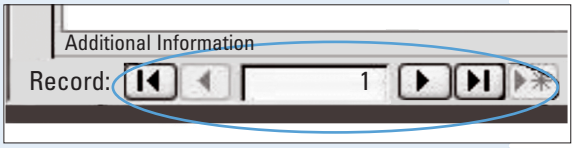


Navigating Through the Database Records:

1. Selecting "Open Individual Records" will open a form containing all the information collected and the criteria used in our study (see sample below).



2. The buttons on the bottom left of the screen are used to navigate through the records.



Opening and Printing Reports:

1. Selecting any of the reports listed will open the respective report.

2. Navigating through the report is identical to the process described above.

3. To print the document, select the File Menu and click "Print."

Please submit any edits, suggestions, or additional information about the projects listed in this database to Dr. Jennifer Kuzma at kuzma007@umn.edu.

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