Agriculture, Food, and Water Nanotechnologies for the Poor:

Opportunities and Constraints

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"*Nanotechnology* is research and development that involves measuring and manipulating matter at the atomic, molecular, and supramolecular levels at scales measured in approximately 1 to 100 nanometers (nm) in at least one dimension."[1]

Materials at such small scales often exhibit different electrical, magnetic, optical, mechanical, and other physical properties from their bulk material counterparts, leading to the development of potentially revolutionary technologies in a variety of industries, including agriculture and food. By increasing productivity, reducing postharvest loss, improving product quality,[2] increasing the competitiveness of agricultural producers, and improving market access,[3] advances in nanotechnology may present new opportunities to improve the livelihoods of the poor.[4] But nanotechnology may also create new risks.

Investments in agriculture and food nanotechnologies carry increasing weight because their potential benefits range from improved food quality and safety to reduced agricultural inputs and improved processing and nutrition.[5] While most investment is made primarily in developed countries, research advancements provide glimpses of potential applications in agricultural, food, and water safety that could have significant impacts on rural populations in developing countries.[6]

Despite their promise, agricultural and food nanotechnologies, especially those that could reduce poverty or increase food and nutrition security, will likely face many challenges in each step of development—from investment in research and development (R&D) to adoption and use—before being commercialized and used by the rural poor. Many of these obstacles appear in the development of any new technology, but there are also issues specific to nanotechnology: intellectual property rights (IPR), the management of safety and environmental risks in the presence of wide uncertainties, and possible market displacement effects induced by these technologies, among other concerns.[7] This brief presents a review of the potential opportunities and challenges of using nanotech applications for agriculture, food, and water in developing countries.

Potential Benefits of Nanotechnology for the Poor

Potential nanotechnology applications currently in the R&D pipeline have the potential to make agriculture more efficient, increase yields and product quality, and thereby increase nutritional benefits. Developed countries are using or testing nanosensors and nanoagricultural chemicals, nanoparticles for soil cleaning and nanopore filters, nanoceramic devices, and nanoparticles.[8] An increasing number of applications are expected for food and agriculture uses, including nanosensors, potentially capable of detecting chemical contaminants, viruses, and bacteria; nano–delivery systems, which could precisely deliver drugs or micronutrients at the right time and to the right part of the body; as well as nanocoatings and films, nanoparticles, and quantum dots.[9]

Several reports have touted agricultural and food nanotechnology's great potential in developing countries.[10] Promising nanotechnology applications address low use efficiency of agricultural production inputs and stress of drought and high soil temperature.[11] Nanoscale agrichemical formulations can increase use efficiency and decrease losses into the environment.[12] Nanoporous materials capable of storing water and slowly releasing it during times of drought could also increase yields. Researchers have shown that applying nanotechnology to reduce the effects of aflatoxin (a human toxin) increases the weight of food animals.[13] The potential for nanotechnology in agriculture continues to grow; Box 1 lists future applications with a significant potential to affect agricultural production, food safety and nutrition, and water safety.

Key Challenges Ahead

Research and Development Investment for the Poor

Among developing countries, China, Brazil, and India have heavily invested in nanotechnology, while smaller developing countries lag behind.[30] Some of these smaller countries are developing capacity or setting up national programs.[31] Other countries reportedly have local nanotech research teams.[32] Still, only China, Brazil, India, Iran, Thailand, and Malaysia seem to have a program focused on agriculture or food. Several others, like South Africa, include a specific focus on water quality.[33]

Whether in large or small countries, garnering public support for new agricultural technologies always proves challenging. First, attracting support for and commitment to long-term investment in expensive, potentially risky, or uncertain research is difficult, especially with changes in governments and donor priorities. Second, public-sector research is not usually connected to developing a product. Third, bringing researchers from different disciplines together with regulatory and deployment specialists is necessary but often difficult. All these challenges (and more) must be overcome to transform a concept into a tangible product or technology that gets regulatory approval in a country and is adopted by the user community.

In the case of nanotechnology, developing countries face larger barriers than developed countries.[34] Clearing the many hurdles in the private sector requires enabling infrastructure, basic capital, and sufficient economic incentives to invest in agricultural and food nanotechnology—all of which are hard to come by in the developing world. The uncertainties of investment and uptake of technologies make it trickier for domestic companies in developing countries to invest in long-term R&D. Larger companies and multinationals may also see small, developing-country markets as unprofitable.

Apart from funding, proponents of nanotechnology must also overcome the lack of human capacity, especially in the public sec-

Box 1—Agriculture, food, and water nanotechnologies

1. Agricultural Production
   - **Nanopesticides and nanoherbicides**
     Pesticides inside nanoparticles are being developed that can be timed-release or have release linked to an environmental trigger.[14] Combined with a smart delivery system, herbicide could be applied only when necessary, resulting in greater production of crops and less injury to agricultural workers.
   - **Nanofertilizers**
     Nanofertilizers could be used to reduce nitrogen loss due to leaching, emissions, and long-term incorporation by soil microorganisms.[15] They could allow for selective release linked to time or environmental condition. Slow-controlled-release fertilizers may also improve soil by decreasing toxic effects associated with fertilizer overapplication.
   - **Nanosensors**
     Nanosensors may detect contaminants, pests, nutrient content, and plant stress due to drought, temperature, or pressure. They may also potentially help farmers increase efficiency by applying inputs only when necessary.
   - **Nanofeed additives**
     Chicken feed containing nanoparticles that bind with harmful bacteria could help reduce food-borne pathogens.[16] Nanoclays can ameliorate aflatoxin's deleterious effects on poultry.[17]
   - **Smart drug-delivery systems**
     Smart delivery systems can detect and treat an animal infection or nutrient deficiency and provide timed-release drugs or micronutrients.[18]
   - **Nanocoatings**
     Self-sanitizing photocatalyst coating for use in poultry houses with nano–titanium dioxide could be used to oxidize and destroy bacteria in the presence of light and humidity.[19]
   - **Zeolites for water retention**
     Zeolites are naturally occurring crystalline aluminum silicates that can significantly improve the water retention of sandy soils and increase porosity in clay soils.
2. Food Safety and Nutrition
   - **Enhanced barriers to microbial contamination or spoilage**
     Barriers can reduce opportunity for microbial contamination by keeping bacteria away from food or preventing conditions that allow bacteria to grow. Nanocomposites used in food and beverage containers provide effective barriers to gas transmission.
   - **Detection of food-borne pathogens or spoilage organisms**
     Nano-based methods of detecting harmful pathogens are being developed for several pathogens: a nanobiosensor can identify the presence of *E. coli* and prevent the consumption of contaminated foods;[20] similarly, nanosensors can indicate the deterioration of foods due to spoilage microorganisms or other factors.
   - **Nano-based veterinary treatments**
     A nanoadditive for animal feed can deactivate aflatoxin, deoxynivalenol, and zealalenone mycotoxins in animal feed.[21] Nanoparticles can also remove food-borne pathogens in the gastrointestinal tracts of livestock.[22]
   - **Detection of pesticides, heavy metals, or other chemical contaminants**
     Several nano-based biosensors have been developed to detect contaminants, such as crystal violet or malachite green concentrations in seafood and parathion residues or residues of organophosphorus pesticides on vegetables.[23]
3. Water Safety
   - **Filtration**
     Nano-enabled water treatment techniques incorporating carbon nanotubes, nanoporous ceramics, and magnetic nanoparticles can be used to remove impurities from drinking water and could potentially remove bacteria, viruses, water-borne pathogens, lead, uranium, and arsenic, among other contaminants.[24] Magnetic nanoparticles could be used to filter water at the point of use to remove nanocrystals and arsenic.[25] Nanoparticle filters can be used to remove organic particles and pesticides from water.[26]
   - **Removal or detoxification of harmful pollutants**
     Affordable arsenic removal can be done by using synthetic clay.[27] Zinc oxide nanoparticles could help remove arsenic using a point-of-source purification device.[28] Nanoscale zero-valent iron and other nanomaterials (nanoscale zeolites, metal oxides, carbon nanotubes, and fibers) can be used to remediate pollutants in soil or groundwater.[29]

tor and in less developed countries.[35] Developing countries could send people to developed countries for training, but this might lead to "brain drain," especially if countries like the United States decide to offer permanent residency to nanotechnology graduates.[36] With limited resources and capacity, especially in agriculture, research prioritization should be done strategically, with the objective of funding programs with applications that have the maximum benefit–risk ratios for the poor.

Cost and Access

Intellectual property rights, innovation, and technology access: In private-sector development, economic incentives, such as intellectual property rights (IPR), play a critical role in the innovation process in a globalized world. Patents provide incentive for research and investment, but their use still generates significant criticism. Enforcing IPR—and, more specifically, patents—can create barriers to entry and raise the cost of products for consumers, thereby contributing to a growing divide between developed and developing economies.

The number of international and US nanotechnology patents is rapidly increasing.[37] A large majority of these patents originates from nanotech-leading developed countries.[38] In the developing world, so far, only large emerging economies have produced patented technologies. If this pattern continues, it may block the use of some promising technologies in the developing world.[39] Patents may also result in less competition and higher technology prices, even if more competition exists in nanotechnology than in other fields.[40] The existence of "broad" patents covering essential methodological tools and technologies needed to handle or analyze nanomaterials could also stifle innovation in the developing world.[41]

On the other hand, the absence of any form of IPR protection could reduce the incentive for private companies to invest in developing countries, and discourage agricultural technology investment, which would ultimately keep useful technologies from those who would benefit from them the most. In the longer run, the use of any nanotech applications may be conditional on IPR. Patents themselves are not a prerequisite for obtaining the benefits of research. Alternatives to patents, like research prizes directed toward public goals, could help advance food and agricultural nanotechnology for developing countries and poor users. Market segmentation strategies could reach poorer users while preserving commercially viable enterprises. Licensing agreements are another alternative. Also, key agricultural technologies developed by the private sector have been effectively transferred to developing countries using trade secrets to protect the rent of innovation, as seen in the case of poultry breeders.

Supply-and-demand constraints: Ultimately, the access to and affordability of technologies will determine whether the poor will use them. Many factors may block access, including limited market access, lack of knowledge and information, and credit constraints.[42] The final prices will depend on transaction costs and the generating organization's distribution capacity. Limited infrastructure and means of communication, lack of educational programs, and financing constraints can keep new technology out of the poor's hands. Implementing safety regulations, while potentially facilitating technology use, may also impose significant costs on developing nations.

On the other hand, the users' demand for a new technology will ultimately determine the technology's success. The use of many nanotechnologies does not require technological expertise, but the final users need to at least know the technologies exist, what their purpose is, and how they should be used. Sellers can transmit basic information either directly or indirectly through extension agents or informed peers. Users' attitudes toward nanotechnologies will depend on their knowledge of them and any preconceived ideas or feelings they may have about them. Currently, studies on acceptance and willingness to adopt nanotechnologies are much more common in the developed world than in the developing world. This apparent information asymmetry may increase the likelihood of a "nano divide": if consumers in developed countries drive research, funding sources will continue to focus on their demands and not necessarily on those of the poor.

Risks, Regulations, and Acceptance

Environmental and human-health risks: Using nanomaterials is not inherently risky—for instance, traditional foods contain many nanoscale materials (such as proteins found in milk, fat globules found in mayonnaise, carbohydrates, DNA, and so on)—but the use of certain engineered nanoscale materials in agriculture, water, and food may have risks for human use and consumption, for the environment, or for both.[43] The lack of sufficient scientific knowledge about key risk-assessment factors, such as nanoparticle toxicity, bioaccumulation, exposure information, or ingestion risks, causes the most concern.[44] A relatively small share of funding goes to risk research, and that money supports research focused on nonfood or agricultural materials, suggesting that this lack of knowledge will persist.[45]

Countries will likely react to this uncertainty about risk in different ways. In Japan, South Korea, or among members of the European Union, a precautionary approach, which assumes that uncertainty or data gaps on risks should not prevent regulatory action, may already be apparent. In contrast, countries like the United States and emerging large economies seem to put more emphasis on the technology's potential and use existing knowledge to create risk regulations for end products. Other developing countries seem to be in between, looking at the potential but also waiting to learn more about the risks.

Risks certainly do matter, and should be accounted for (see Regulations below), but some developed countries' excessive focus on risk in the nanotechnology debate could discourage the application of potentially important nanotechnology in the developing world.[46]

Regulations: Several high-level panels have recommended approaches to nanotech risk regulation. In the case of food, the Science and Technology Committee of the UK House of Lords has suggested including a mandatory pre-commercialization assessment using the methods supported by a research investment effort in risk assessment and detection methods.[47] The European Food Safety Agency supports the use of conventional risk assessment while acknowledging the limited knowledge on exposure to nanofood applications.[48]

Developing countries should prioritize building on existing institutional capacity when creating regulations. In particular, they could take advantage of the similarities between nanotech regulatory systems and biotech regulatory systems.[49] Though nanotech and biotech have significant differences, lessons can be learned from the challenges observed in biosafety, such as the need for transparency, predictability, and public education.[50] Countries should account for the potential costs of compliance with regulatory approvals. The lack of risk assessment capacity and porous borders (in Sub-Saharan Africa, for example) should also encourage countries to form regional groups.

Risk perceptions and market acceptance: Risk perceptions are critical to the future acceptance of nanotechnology globally.[51] Despite the general lack of knowledge, the public in developed countries is still fairly positive about nanotechnology's potential.[52] Yet, consumers tend to be more averse to nanofood applications than other nanotechnology uses.[53] Perceived benefits and health risks (among other things) affect acceptance, meaning consumers do not associate all products with the same risk levels.[54] Risk communication strategies should pay particular attention to the messenger and the target of the message.[55]

External factors could also play a role in shaping future acceptance in the key markets that will largely affect the future of nanotechnologies worldwide. Vocal nongovernmental organizations supporting a ban on nanotechnology use in food and agriculture may prove influential, pushing toward reduced commercialization globally.[56] Such an outcome could further widen the technology divide.[57] The possible introduction of labeling requirements on nano-products in certain developed countries could also affect technology deployment and regulations in developing countries.[58]

More generally, food companies' decisions to use or avoid nanotechnology will help determine the future of nanofood and related products.[59] Certain large food companies have already decided to avoid publicly declaring that they base products on nanotech for fear of consumer backlash.[60] Consequently, this limits knowledge of which applications the food sector is developing and using.[61] While many food companies support increased consumer awareness on nanotechnologies, and some of them have developed private stewardship schemes, maintaining secrecy could preemptively force nanofood products out of the market and decrease the likelihood of adoption of related technologies in developing countries.[62]

Market Risks

Three types of economic risks may also play a role in nanotechnologies' expansion. First, import regulations could create barriers to entry for nanotech products. As in biotech, trade policies can influence risk-averse policymakers in developing countries.[63] Second, nanotechnology applications could have negative economic effects on the poor by increasing productivity in the developed countries adopting those technologies and depressing commodity prices.[64] Third, certain innovative nanotechnology applications (including nanotextiles and synthetic rubber) could act as substitutes for agricultural commodities, having potentially disastrous economic effects on commodity-dependent developing countries.[65] While nano-substitutes are serious concerns that call for anticipatory responses, they should be examined and addressed individually. For instance, other factors could compensate for a shift in demand due to nanotextiles, like the increased demand for natural-fiber products in developed countries. A case-by-case approach should be used to assess and manage economic risks.

Conclusions and Research Needs

Although discrete indications of enthusiasm exist for nanotech and agriculture in developing countries, proponents must overcome many challenges to ensure that the most promising nanotechnologies actually reach the poor.[66]

Little research has targeted developing-country needs and, in particular, the needs of the poor, which has created critical gaps in the scientific understanding of ways to improve the situation of the poor (both as producers and as consumers). Public scientists working in this area have kept a relatively narrow focus on certain applications and may not be aware of the needs of the poor and how to ensure uptake in a developing-country situation. Insufficient information exists about the potential economic benefits and risks associated with nanotech adoption in developing countries. Prioritization exercises should be conducted at the national level to communicate needs to the scientific, government, and donor communities. Ex ante assessment of specific technologies could help governments to anticipate potential safety, social, and economic effects. Governance options, including intellectual property rights and the design of regulatory frameworks critical for the future use of the technology, also need more research.

The Consultative Group on International Agricultural Research (CGIAR) could play a significant role in these areas—between the private and public sectors—and help redirect development to nanotechnologies that the poor can use to improve agricultural productivity and ensure food and water safety. The following actions could be taken by the CGIAR to begin this redirection:

- Conduct research and produce and diffuse information on how nanotechnology applications can be used to improve agricultural yields, decrease food spoilage, or improve water quality at the farm or household level.
- Develop and encourage the use of nanotechnology applications to support agricultural and food policy and regulatory efforts in developing countries (for example, create hazard maps by using data from nanotechnology-based sensors).
- Conduct risk analysis so decisionmakers understand the cost effectiveness of using certain nanotechnology applications to improve food and water safety compared to other technologies.
- Provide ex ante and ex post impact evaluations of specific nanotech applications as a support for funding and policy decisions.
- Conduct research on the critical issues related to nanotechnology governance and help overcome some of the funding, capacity, access, risk, and regulatory challenges outlined in this brief.

Because nanotechnology is still in its infancy, focused research, development, and funding could potentially redirect nanotech efforts toward useful goals for agriculture and sustainable development.

NOTE: Due to space constraints, it is not possible to include the full list of endnotes in this brief. However, the full reference list is available online at www.ifpri.org/sites/default/files/publications/bp019notes.pdf.

FOR FURTHER READING

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