Responsible Development, Social Science, and the National Nanotechnology Initiative (NNI): A Workshop to Explore Future Intersections

National Nanotechnology Coordination Office, Washington, D.C.
July 24, 2024
Summary Report

Introduction

Since its inception, the National Nanotechnology Initiative (NNI) has emphasized the importance of responsible development. For example, the Nanotechnology Environmental and Health Implications (NEHI) Working Group has coordinated federal activities related to the understanding and managing of potential adverse impacts of nanomaterials on human bodies and natural ecosystems. While environmental, health, and safety research remains crucial, opportunities exist for the NNI to expand and strengthen its attention to other areas of responsible development.[1] These societal dimensions of responsible development offer key contributions to the NNI's mission, such as highlighting the critical role of public perceptions and trust in technology adoption,[2] exploring methods of participatory technology assessment,[3] and engaging diverse stakeholders to inform innovation pathways.[4]

The NNI has a history of supporting extramural social science research related to nanoscience and engineering. Most notably, from 2005-2015, the National Science Foundation (NSF) funded Centers for Nanotechnology in Society (CNS) at Arizona State University (ASU) and at the University of California, Santa Barbara (UCSB). Totaling over $23M, these centers facilitated a wide array of social science research that advanced knowledge and created new tools and frameworks for science communication, foresight of socio-technical systems, governance of

[1] https://doi.org/10.1007/s11051-018-4210-x
[2] http://www.jstor.org/stable/4314956
[3] https://www.sciencedirect.com/science/article/pii/S0040162521004066
[4] https://onlinelibrary.wiley.com/doi/abs/10.1002/hast.1320

emerging technologies, and the integration of science, social science, and the humanities in education and training. In the meantime, scholars of science and technology policy, STS (science, technology, and society), and related fields have applied and expanded social science insights - many of them learned through the activities of the NNI - to other emerging technologies, such as biotechnology, synthetic biology, and most recently, artificial intelligence. In this context, three key questions arise for the NNI:

1. How can existing social science tools, developed by focusing on anticipatory governance and upstream interventions, adapt to a more mature nanotechnology field?
2. What new challenges and opportunities have emerged in nanotechnology research and development that could benefit from innovation in social science frameworks, methodologies, and concepts?
3. How can the NNI maintain and expand on its vibrant network of social science experts who can participate in interdisciplinary efforts that are central to the culture of nanotechnology research and development?

The National Nanotechnology Coordination Office (NNCO) sought to address these questions by convening a workshop with experts in social science who intersect with the responsible development of nanotechnology and other emerging technologies.[5] The agenda (see Appendix 1) included an orientation to the NNI, brief introductions to a number of application domains of nanotechnology, and a presentation about the National Science and Technology Council's recently released "Blueprint for the Use of Social and Behavioral Science to Advance Evidence-Based Policymaking."

Ten social scientists were invited to contribute their expertise to the workshop. While all had experience conducting research on emerging technologies, few specialized in nanotechnology. This was purposeful, in order both to attract new scholars to the field and to expand the scope of social science approaches intersecting with the NNI. Each expert presented a flash talk to introduce a tool, concept, approach, or methodology that might contribute to social science research relevant to emerging nanotechnologies (see Appendix 2).

Following the flash talks by social science experts, representatives from federal agencies that participate in the NNI introduced four case studies of emerging nanotechnologies: nanomedicine, advanced batteries, nanotechnology-enabled agrochemicals and food packaging, and 3D printing and additive manufacturing (see Appendix 3). Small-group discussions focused on these four case studies. Social science experts, nanotechnology case study leaders, and interested members of the public brainstormed new intersections between social science and nanotechnology research and development with the goals of i) integrating social science into future visions of interdisciplinary research, development, and training, and ii) reinvigorating networks that connect the NNI to the social science community. Pursuing such goals strengthens the foundations of the NNI's commitment to responsible development by

[5] https://www.nano.gov/socialscienceworkshop

improving alignment between innovation and public values and increasing the positive social impacts of nanotechnology research and development.

This report presents highlights from this workshop, providing a resource for federal agencies to consider strategies to integrate social science methodologies and approaches in calls for interdisciplinary research. This work also aims to inspire the social science community to identify case studies within the nanotechnology field that show great promise for advancing theory and practice in the responsible development of emerging technologies.

Insights for the National Nanotechnology Initiative

The most apparent insight from the workshop was the energy and enthusiasm expressed by both social science experts and federal nanotechnology leaders in considering the intersection of their communities. Conversation flowed freely, new ideas were generated, and the benefits of integrating social science into nanotechnology research and development initiatives were clear to all workshop attendees. These types of interactions matter, and they are enriched by the presence of disciplines often excluded from technical discussions about initiatives to promote and guide nanotechnology innovation.

Discussion highlights included motivations for integrating social science expertise, strategies to implement social science approaches, and perspectives on evaluation (for more detailed and case-specific discussion summaries, see Appendix 4).

1. Motivations

- **1.1. Move beyond seeking public acceptance**: Some experts imagine engagement as a tool to fill public knowledge deficits in order to calm unreasonable fears and objections. Current social science suggests that this model fails to build trust and misunderstands societal concerns. A more ambitious vision considers “public acceptance” as a minimal state, with more ambitious goals of community endorsement, stakeholder support, or public participation.
- **1.2. Balance technological hype**: Visions for emerging technologies, especially by developers and funders, often include a good deal of optimism and even hype. Social science engagement and reflexivity activities can provide pragmatic balance and insight into unintended consequences.
- **1.3. Recognize sociotechnical systems:** Most nanotechnology innovations enter complex systems that are as much organizational and political as technical.[6] Innovation thus represents an opportunity to revisit assumptions about what is considered “fixed” or “fluid” in the spaces where technologies may thrive or fail.
- **1.4. Expand the breadth of expertise**: The complexity of problems and solutions suggests the need for broad and deep knowledge. Rethinking what counts as expertise can create opportunities for engaged groups to shape technological design and direction.

[6] http://link.springer.com/10.1007/s11051-014-2492-1

1.5. **Anticipate regulatory complexity**: Existing regulatory frameworks for emerging nanotechnologies often implicate multiple regulatory agencies - ranging from the U.S. Department of Agriculture (USDA) to the Environmental Protection Agency (EPA) to the Food and Drug Administration (FDA) to the Consumer Product Safety Commission (CPSC). Social science perspectives that focus on governance more broadly create opportunities to bring multiple agencies and regulatory perspectives together to pursue a more integrated approach to safety, health, and the public good.

2. Strategies

2.1. **Identify public values**: In the U.S. context, market forces primarily dominate innovation pathways. Social science methods for identifying public values and community interests and needs offer some balance to ensure that government attention to research and development is given to both economic growth and societal benefit.

2.2. **Expand design constraints**: While it can be challenging to consider how best to integrate social science approaches in established patterns of research and development, the common understanding of design constraints offers a practical model. Just as economic viability and end-user safety represent constraints for innovation, so too could societal values such as sustainability, equity, technological access, cultural respect, workforce development, or privacy.

2.3. **Conduct upstream public, stakeholder, and community engagement**: The traditional engagement of social science, especially communication or marketing experts, at the downstream end of nanotechnology innovation misses key opportunities early on in technological development. Integrating public and community priorities more upstream creates the opportunity for shaping problem formulation and design criteria at the same time that technological constraints are at play.

2.4. **Diversify perspectives**: Innovation systems are often constrained by the assumptions of experts who take initial conditions for granted.[7] Social science methods to incorporate more diverse voices in problem formulation and design choice create opportunities for creativity and more transformative innovation. For example, definitions of stakeholders could expand to include people that are skeptical of a potential technology.

2.5. **Improve communication strategies**: Social scientists can help determine public perceptions of emerging technologies, including concerns and questions that can be addressed strategically and respectfully. Such efforts must account for a communication environment stressed by increasing patterns of misinformation and disinformation.

3. Evaluation

3.1. **Metrics for responsible development**: Typical metrics for research and development involve counting patents and publications or tracking market success. Social science methods offer opportunities to measure other values such as responsiveness to

[7] https://doi.org/10.1080/09537325.2015.1129399

community needs, alignment with public values, fair distribution of risks and benefits, or promotion of equity.

3.2. **Interdisciplinary peer review**: While federal funding programs focused on technological research and development often rely on technical subject matter experts, expanding that pool of reviewers to social scientists with expertise in the societal dimensions of emerging technologies could infuse funding decisions with broader perspectives better aligned with public priorities and values.

The final discussion generated specific ideas for the NNI and its federal agencies to pursue to continue the momentum of the workshop. Building off newly involved social scientists, the NNI could host a webinar series focused on intersections of nanotechnology and social science. Such events could help grow and formalize a network of social science experts interested and available to engage with the NNI. With respect to existing international collaborations, the Communities of Research (COR) program, which connects nanotechnology researchers from the European Union and the U.S., could expand to include a new COR focused on social science or societal implications.

At the institutional level, social scientists could be invited to study and analyze the structure and culture of the NNI to inform strategic planning, which could promote consideration of responsible development priorities beyond environmental, health, and safety dimensions of societal benefit. Experiments in research funding strategies may also be warranted. For example, calls for proposals that traditionally target only natural and physical scientists could require or incentivize inclusion of social scientists. Further upstream, social science perspectives might contribute to the design of funding calls and strategies, such as the Basic Research Needs (BRN) at DOE, which creates reports on technologies that guide requests for proposals.

Finally, participants recognized the value of creating more opportunities like the workshop, where nanotechnology experts and social scientists get to talk with each other - not at each other - and build relationships and understanding. Such interdisciplinary activities lower the barriers to productive collaborations that provide the foundation for the NNI's support for responsible development.

APPENDIX 1

Responsible Development, Social Science, and the National Nanotechnology Initiative (NNI): A Workshop to Explore Future Intersections

Agenda | July 24, 2024

8:30 Registration and coffee

9:00 Welcome and introductions

- Dr. Branden Brough, NNCO Director
- Dr. Quinn Spadola, NNCO Deputy Director
- Dr. Jason Delborne, AAAS Science and Technology Policy Fellow

9:30 Presentation on the "Blueprint for the Use of Social and Behavioral Science to Advance Evidence-Based Policymaking" - Kei Koizumi, Special Assistant to the President and Principal Deputy Director for Science, Society and Policy at the White House Office of Science and Technology Policy (OSTP)

9:55 "Ripples of the NNI: How Nanotechnology Inspired Responsible Research and Innovation (RRI) Policy in the European Union" – Clare Shelley-Egan, TU Delft

10:30 Social science flash talks (6)

12:00 LUNCH

12:45 Social science flash talks (4)

1:30 NNI case study introductions

- Nanomedicine
- Advanced batteries
- Nanopesticides and food packaging
- 3D printing / additive manufacturing

2:30-2:55 Case study small group discussions - Round 1

3:00-3:25 Case study small group discussions - Round 2

3:30-3:50 Case study small group discussions - Round 3

3:55-4:15 Case study small group discussions - Round 4

4:20 Plenary discussion

5:00 Adjourn

APPENDIX 2

Social Science Flash Talks: Tools, Concepts, Approaches, and Methodologies

Daemmrich, Arthur (Arizona State University)
Director of the Consortium for Science, Policy, and Outcomes
"Chemical Risk, Testing, and Regulatory Cultures"

With shifting dynamics in the global chemical industry, exemplified by China's rising dominance in production and capital investment, the way that we understand chemical risk, test for safety, and design our regulatory cultures has evolved over the past two decades. The historical formula of understanding risk as hazard x exposure struggles to account for the pervasiveness of exposure and the politics inherent in testing regimes that, practically speaking, cannot keep up with the increasingly complex chemical environment. Potential solutions include community involvement in the design of test programs and new governance models that prioritize community decision-making over individual consent.

Ghilani, Jessica (University of Pittsburgh)
"Science Communication, Misinformation, and Trust"

The rise of digital disinformation, amplified by algorithmic platforms, poses a significant challenge in the contemporary information landscape. Studying these dynamics requires distinguishing between misinformation - erroneous information shared without intent to deceive - and disinformation, which is deliberately misleading. In the social media environment, algorithms prioritize content for engagement, often exacerbating confirmation bias - the tendency to put more trust and confidence in information that confirms existing beliefs - and creating filter bubbles that entrench users in isolated information ecosystems. The resulting echo chambers not only undermine public trust in accurate information but also contribute to the pervasive spread of falsehoods across digital platforms.
Zimdars and McLeod, 2020; Ghilani, 2020

Nelson, John P. (Georgia Institute of Technology)
"Public Values Mapping and Science Policy Assessment"

How might we evaluate science and technology policies through the lens of public values? Societal goals like public health, economic prosperity, and national security are often cited to justify science policies, yet the actual assessment of these policies tends to focus more on outputs like publications, patents, and startups. Public Values Mapping (PVM), a framework for aligning science policy evaluation with broader societal goals, offers an approach that allows for prospective and retrospective analyses both to identify public values and to assess public values effects. PVM articulates public values-focused research questions, which can be answered with methods including tracking of indicators, scenario planning, case studies, and public engagements.
Bozeman 2018, Bozeman & Sarewitz 2011, Nelson 2021

Evans, Sam Weiss (National Security Commission on Emerging Biotechnology) "Making Science More Responsive to Society: Lessons from Experiments in Governance" *While technical realities tend to dominate our attention, the sociotechnical context of research includes institutional structure and priorities, economic incentives, career advancement metrics, cultural and ethical priorities, and research networks. Making science more responsive to society thus invites attention to this complexity, illustrated by governance experiments that integrate social and ethical considerations into scientific and technological research. The International Genetically Engineered Machines (iGEM) competition, DARPA's Safe Genes program, and the Responsive Science working group all served as testbeds for embedding societal concerns into the research process. Sociotechnical context profoundly shapes the questions researchers ask and the innovations they pursue, and there is incredible value in encouraging research teams to "ask one more question."*
Hartley, Sarah (University of Exeter, UK) "Stakeholder Engagement and Risk Assessment" *Risk assessment is a process involving multiple decisions and opportunities for engagement. While regulators play an advisory role, technology developers typically conduct risk assessments, with very limited public consultations that traditionally occur at the end of the process. Alternatively, integrating stakeholder engagement in the risk assessment process creates opportunities for interdisciplinary collaboration and knowledge co-production. Stakeholders are domain experts and knowledge holders, not just populations with diverging interests and diverse perspectives. Ultimately, the goal is to acknowledge the politics embedded in risk assessment and use social science methods to create more inclusive, socially-responsive decision-making processes.* Hartley et al., 2022; Hartley et al., 2023
Grieger, Khara (North Carolina State University) "Online Stakeholder Engagement" *Online platforms offer opportunities to facilitate stakeholder engagement that is less resource intensive, more convenient for participants, and less geographically limited in comparison with traditional engagement activities. A study focused on gathering insights on nanotechnology and responsible innovation used online asynchronous participation, which allowed stakeholders to provide feedback through questionnaires, case study reviews, and discussion boards. Key findings indicate that stakeholders prioritized reducing environmental and safety risks and expressed higher confidence in responsible innovation within agricultural nanotechnology compared to food applications. While the platform proved resource-efficient and accessible, challenges included the lack of real-time, in-person interactions and the significant up-front investment required for development and hosting of the platform.* Grieger et al., 2022; Ruzante et al., 2022; Merck et al., 2022
Tomblin, David (University of Maryland) "Participatory Technology Assessment: An Alternative Public Input" *Participatory technology assessment (pTA) offers an alternative approach to public engagement in science and technology decision-making. Unlike traditional methods such as public comments or stakeholder hearings, pTA aims to bridge democratic gaps by involving underrepresented groups and fostering mutual learning between the public, experts, and*

decision-makers. The process involves co-creating forums, preparing participants with background information, and facilitating interactive sessions to gather diverse perspectives that can influence policy and governance. Key outcomes include mapping public priorities and values, identifying areas of agreement, increasing the public's understanding of the complexity of science and technology policy, anticipating emerging issues, and discovering unexpected connections. The Expert and Citizen Assessment of Science and Technology (ECAST) Network has worked to socialize, train, innovate, and evaluate pTA since 2011.
ECAST Network, Tomblin et al. 2017

Udu-gama, Natasha (American Geophysical Union - Thriving Earth Exchange)
"Community Science"

AGU's Thriving Earth Exchange facilitates collaborations between scientists and communities to address local issues based on community-defined priorities. The approach democratizes science by centering marginalized communities and co-creating solutions that are directly relevant to their needs. Key elements include building trust through equitable partnerships, capacity-building for both scientists and community members, and focusing on sustainable, long-lasting impacts. Community science helps communities become more resilient, generates new research questions and approaches, increases public support for sciences, and helps scientists hone skills and prepare for diverse careers. The initiative emphasizes that science is a human right, aiming to generate research that not only advances knowledge but also contributes to a more just and sustainable society.

Palmer, Megan (Gingko Bioworks)
"Engineering Biology at Social Scales"

Governance and science policy experiments attempt to escape models that are technology driven and reactive to realize models that are need driven and proactive. To do so, scientists can partner with scholars and practitioners of law, political science, and science and technology studies (STS) or, more ambitiously, form hybrid collaboratives of practitioners of socio-technical systems engineering. Success requires committed leadership, diverse expertise, dedicated resources, research and/in practice, iteration and innovation, and a focus on culture. Experiments include SynBerc - a major NSF effort in synthetic biology that dedicated 25% of resources to research and strategy on social aspects; iGEM - an international competition that engaged 80,000 students from 65 countries over 20 years with incentives for excellence and innovation in social responsibility (not just compliance); and Ginkgo Bioworks - a startup company that emerged from iGEM and institutionalized "caring" into their innovation ecosystem.

Shelley-Egan, Clare (Delft University of Technology, Netherlands)
"Interrogating Integration: Formulating a Quantum and Society Approach"

TU Delft is part of the Action Line for Ethical, Legal and Societal Aspects (ELSA) of Quantum Delta NL, which is the national programme for the development of quantum technologies in the Netherlands. One aspect of TU Delft's focus is on addressing integration challenges made visible through previous ELSA initiatives: 1) de facto arrangements of disciplinary boundaries, funding patterns, and power asymmetries; 2) ELSA requirements that lack guidance for articulation and operationalization; and 3) systemic and cultural undervaluations of ELSA components. In response, the proposed approach emphasizes co-creation and collaboration

in the early stages of problem formulation, institution building, and normative commitments; wrestling with underpinning assumptions and expectations by participants and the funding agency; and recognizing the different methodologies and epistemologies of the various involved disciplines.
Ethics of Quantum Technologies Research Team; Shelley-Egan & Vermaas 2024

APPENDIX 3

Nanotechnology Case Studies

Nanomedicine

- Dr. Jermont Chen, Program Officer in the National Institutes of Health (NIH), National Institute of Biomedical Imaging and Bioengineering (NIBIB), Division of Discovery Science and Technology (Bioengineering).

- Dr. Carolina Salvador Morales, Program Director in the NIH for the National Cancer Institute (NCI) Division of Cancer Treatment and Diagnosis' Nanodelivery Systems and Devices Branch

Dr. Chen presented a nanoparticle-based gene delivery system that uses the blood to circulate and deliver lipid nanoparticles carrying cargo. The blood-based delivery system was more efficient at delivering gene editing cargo for cystic fibrosis treatment than those delivered by the current airway methods (which have 28 failed clinical trials). He then described a second nanoparticle-based system where nanoprobes were designed to enhance the bioimaging of tumors in the presence of cancer enzyme activity, resulting in a single-cell imaging visualization tool. Dr. Salvador-Morales presented a case study of nanomaterials-based biosensors for wearable devices that can enable therapeutic drug monitoring, biochemical sensing to diagnose several diseases including the sleep apnea-hypopnea syndrome (OSAS) disorder, diabetes and kidney failture, and chemical biomarker discovery (e.g., susceptibility, diagnostic, response, safety, prognostic and predictive biomarkers).

Advanced Batteries

- Dr. Amanda Haes, Program Manager for Separation Science in the Chemical Sciences, Geosciences and Biosciences Division of the Office of Basic Energy Sciences, Office of Science, U.S. Department of Energy (DOE)

- Dr. Mikhail (Misha) Zhernenkov of the Scientific User Facility Division of the Office of Basic Energy Sciences at DOE

The DOE representatives presented three examples of how nanotechnology may enable advanced batteries with higher performance, greater safety, less dependence on critical minerals, and better recyclability: supramolecular organo-ionic (ORION) electrolytes for solid state batteries that enable direct cathode recycling; ether-based electrolyte for lithium-ion batteries that operates with natural graphite with high-capacity retention; and the spin coating of alumina nanopowder to enhance the electrochemical kinetics of potassium metal batteries.

Agriculture and Food

- Dr. Hongda Chen, National Program Leader for Bioprocess Engineering and Nanotechnology at National Institute of Food and Agriculture (NIFA), US Department of Agriculture (USDA)

- Dr. Raymond P. Briñas, Review Chemist in the Office of Food Additive Safety (OFAS), Center for Food and Applied Nutrition (CFSAN), US Food and Drug Administration (FDA)

Dr. Chen described how the application of nanoscale sulfur can increase nutritional content, reduce disease severity, and improve yields. He also discussed plant virus-like nanopesticides for precision farming that increase agrochemical efficiency and protect the environment. Dr. Briñas introduced nanotechnology-enabled food packaging to improve mechanical, thermal, antimicrobial, and barrier properties that extend shelf life and improve food safety. Examples included polymer nanocomposites that outperform microcomposites and nanosensors that enable intelligent packaging.

3D Printing and Additive Manufacturing

- Dr. Jay Vietas, Chief of Emerging Technologies in the Division of Sciences Integration at the National Institute for Occupational Safety and Health (NIOSH)

Dr. Vietas described developments in 3D printing and additive manufacturing. Nanomaterials are foundational to many 3D printing filaments which can include metals, polymers, ceramics, composites, and concrete. Yet, hazards exist such as particulate and VOC emissions remain concerns for accessible and affordable fused filament printersuser environments, leading NIOSH to publish “Approaches to Safe 3D Printing: A Guide for Makerspace Users, Schools, Libraries, and Small Businesses”[8] This guidance reflects the importance of considering the decentralized landscape for manufacturing made possible by this technology, leading to the use of 3D printers in private homes, schools, and community libraries.

[8] https://www.cdc.gov/niosh/docs/2024-103/default.html

APPENDIX 4

Intersections of Social Science with Nanotechnology Case Studies

All workshop participants were invited to join small-group discussions of how social science concepts, ideas, approaches, and methods might inform research and development related to the nanotechnology case studies. The following sections offer examples of the kinds of potential contributions imagined by social science experts, federal agency leaders, and other workshop attendees.

Advanced Batteries

1. **Upstream Integration of Societal Considerations**: Social science can guide the integration of societal challenges early in the research and development process, even when technological questions are still forming. This would disrupt existing patterns of conducting basic energy science research within programs that typically do not include any social science expertise (although values of sustainability have begun to infiltrate this culture). It also raises questions of how much to invest in social science research and activities prior to proof of concept for a new technology.

2. **Lifecycle Assessment and Supply Chain Ethics**: Social science research can contribute to understanding the ethical implications of supply chains for battery components and lifecycle assessments, including the environmental and community impacts of critical mineral extraction for energy storage. This analysis can inform decisions, for example, about whether to prioritize more efficient extraction methods or alternative materials in battery development.

3. **Public Perception and Communication Strategies**: Social scientists can help navigate public perception issues related to energy technologies, such as how the framing of a material (e.g., lithium as a chemical) can influence acceptance or resistance. Importantly, these are not simple vocabulary questions but rather point to the potential to build social capital around how to define and solve various problems related to energy storage.

4. **Responsibility and Liability in Technology Development**: Social science tools such as scenario planning and reflexive engagement can address questions of responsibility and liability in technology development. These approaches can help determine who is accountable for potential harms, shaping both the design process and policy responses to emerging energy technologies.

5. **Consumer and Worker Safety Considerations**: Social science can provide insights into how new energy technologies impact people’s lived experiences, including safety concerns for consumers and workers. For example, understanding how firefighters approach safety in the

context of electric vehicles highlights the importance of integrating human factors into battery design and deployment decisions.

Agriculture and Food

1. **Early and Upstream Integration of Social Science**: Engaging social scientists and stakeholders at the upstream stages can help identify potential societal challenges, such as equity, food sovereignty, and public trust, ensuring that technological advancements align with societal needs.

2. **Consumer Perception and User Experience**: Social science research can offer insights into consumer behavior, public perception, and trust. For example, what does labeling language like "use by/sell by/best by" mean to consumers? And how do they make sense of priorities like food security and food sovereignty?

3. **Equity and Access in Technology Adoption**: Social science can help address questions of equity in the distribution and access to nanotechnology-enabled solutions, such as ensuring that innovations reach small farmers and marginalized communities.

4. **Cultural and Ethical Considerations**: Social science can help navigate cultural practices, ethical concerns, and the socio-political context of food production. For instance, in discussions about food security and waste reduction, social science perspectives highlight the importance of considering cultural norms and preferences, as well as the goals of food sovereignty and community resilience.

5. **Life Cycle Assessment and Responsible Innovation**: Social science plays a crucial role in assessing the long-term sustainability and ethical implications of agricultural and food nanotechnologies through life cycle assessments (LCA) and responsible innovation frameworks. This includes evaluating environmental impacts, regulatory compliance, and how intellectual property rights affect access to agricultural and food technologies.

Nanomedicine

1. **Ethical Considerations and Equity in Design**: Social science can guide the integration of equity, justice, and redistribution into the design of nanomedicine technologies. For example, addressing racial/ethnic and socioeconomic status disparities in healthcare access, ensuring that designs consider the needs of diverse populations, and proactively building equity into medical devices from the outset can prevent biases and promote fairness.

2. **Public Perception and Misinformation**: Social science can help navigate the complex landscape of public perception, misinformation, and disinformation. The "weaponization" of scientific terms and the influence of charlatans can undermine the credibility of nanomedicine. By engaging social scientists early and for the duration of the research, developers can better

anticipate and mitigate public fears, ensuring that accurate information is communicated effectively.

3. **Balancing Information with Human Well-being**: Social science research can inform how to balance the benefits of nanomedicine with potential drawbacks, such as information overload or anxiety caused by wearable health technologies. Understanding how much information people want, how they use it, and what stressors it introduces are crucial considerations for designing user-friendly and supportive technologies.

4. **Stakeholder Engagement and Contextual Needs**: Social science emphasizes the importance of understanding the contextual needs of patients and other stakeholders when developing nanomedicine technologies. Involving stakeholders early in the development process ensures that devices are designed with real-world applications and are sensitive to the needs and preferences of end-users. Iterative engagement that spans the research and development lifecycle promotes evaluation of potential short- and long-term impacts of technological innovations and accountability for physical, emotional, and psychological health.

5. **Privacy and Data Ethics**: As nanomedicine increasingly involves wearable devices and data collection, social science can inform critical discussions around data privacy, the ethical use of information, and the societal implications of extensive monitoring. Addressing these issues upfront helps avoid potential abuses, ensures informed consent, and maintains public trust in nanomedicine innovations.

3D Printing and Additive Manufacturing

1. **Stakeholder Engagement and Public Involvement**: Social science emphasizes the importance of engaging a wide range of stakeholders early in the development process. Understanding who the stakeholders are, what their concerns might be, and how they can contribute to the development of 3D printing technologies is crucial in considering applications to the construction industry (e.g., 3D printed homes), public health (e.g., personal protective equipment), aerospace and space exploration, and distributed manufacturing. Importantly, stakeholders bring not only their perspectives and values, but also their knowledge and experience, which can complement that of traditional experts.

2. **Ethics and Social Impact Considerations**: Social scientists can help identify and address potential ethical issues related to 3D printing, such as the production of firearms, environmental impacts, and the implications for workforce displacement. For example, while 3D printing may create new levels of accessibility for widespread personal production, it could also lead to the generation of enormous amounts of waste material requiring disposal and management.

3. **Workforce Development and Equity**: Understanding the implications of 3D printing on job markets and the skills needed for future workforce development is essential. Social science can guide efforts to ensure that educational resources and training are available to equip workers with the necessary skills for design, use, and repair, particularly in underrepresented or rural

communities and among women who may feel less welcome in spaces focused on tools and production.

4. **Regulatory and Safety Concerns**: Social science can inform discussions around the regulation of 3D printing, particularly regarding health and safety standards. This includes exploring how technologies can be designed to minimize risks to users and the environment (e.g., VOC production), how regulatory frameworks can be developed to ensure safe and ethical use, and how liability is assigned when such systems implicate a mixture of hardware, software, and user behavior. While many 3D printing practices are well underway, new applications with ingot metal and metal powders serve as a reminder that many regulatory decisions will need to be made.

5. **Vision for Public Good and Innovation Pathways**: Social scientists can help articulate a vision for the future of 3D printing that prioritizes public good. This involves asking critical questions about the societal goals of 3D printing, such as whether it should be widely available in homes or concentrated in community spaces, and how it can be used to solve community problems rather than just serving market-driven interests. For example, while the marginal cost of production may be higher in 3D printing than importing goods from other countries, national security and supply chain reliability may position 3D printing as an important backup system for the production of key materials, goods, and supplies (e.g., personal protective equipment).