Agriculture and Nanotechnology: National Infrastructure Readiness. 1

David Berube
  dmberube@ncsu.edu
  Prof. Science and Technology Communication and Affiliated Prof. Climate Change and Society, NCSU

Ben Whitley
  Parallax Advanced Research

Anne Wangari Njathi
  Pepperdine University

Jacob Jones
  North Carolina State University

Maude Cuchiara
  North Carolina State University

Folasewa Olatunde
  North Carolina State University

Perspective

Keywords:

Posted Date: April 17th, 2024

DOI: https://doi.org/10.21203/rs.3.rs-4219468/v1

License: ☒ This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Additional Declarations: No competing interests reported.
Abstract

Agriculture will face many challenges in the next 25 years, including water, population demands, supply chain disruptions, storage, safety, and distribution. Whether discussing smart farming, genetically modified seeds, or alternatives to traditional productivity enhancements, such as insecticides, herbicides, fungicides, and fertilizers, it is all about increasing resiliency by broadening the options for the industry. One of the platform technologies that may offer solace could be nanotechnology especially given the temporal variables involved. We may need to act quickly, so we must prepare to do so. In addition, we must not avoid viable solutions while searching for the silver bullet. There may be none. The following gleans expert opinions from the different stakeholder communities in nanotechnology and agriculture disciplines. Our approach involved diverse sampling and analysis in producing a modicum of information to help inform debates over nanotechnology and agriculture. Put simply; these are observations and suggestions for those who participated.

1.0 Introduction

The intersection of agriculture and nanotechnology is currently sitting at a crossroads. Agriculture will face many challenges in the next 25 years, including water, population demands, supply chain disruptions, storage, safety, and distribution. Whether discussing smart farming, genetically modified seeds, or alternatives to traditional productivity enhancements, such as insecticides, herbicides, fungicides, and fertilizers, it is all about increasing resiliency by broadening the options for the industry. One of the platform technologies that may offer solace could be nanotechnology especially given the temporal variables involved. We may need to act quickly, so we must prepare to do so. In addition, we must not avoid viable solutions while searching for the silver bullet. There may be none.

The following gleans expert opinions from the different stakeholder communities in nanotechnology and agriculture disciplines. Our approach involved diverse sampling and analysis in producing a modicum of information to help inform debates over nanotechnology and agriculture. Put simply; these are observations and suggestions for those who participated. They are not definitive and do not represent the beliefs and sensibilities of our home academic institutions or the agencies that supported this work.

2.0. Context

The United States Biden-Harris administration has set four priorities for the USDA to lead globally. Each priority represents a challenge tied to the state of national agriculture, including Equity, Climate Change, Food and Nutrition Security, and More, Better, and New Market Opportunities. A brief overview of each priority/challenge follows.

The USDA (2022) has turned its attention to farmers, ranchers, and forest landowners who experienced discrimination in previous iterations of the USDA's farm lending programs. A series of national legislation, including Executive Order 13985, American Rescue Plan Act, and Inflation Reduction Act, have directed
funds and attention to “incorporate equity into farm, family and food programs...including fortifying civil rights where improvements need to be made” (EO 13985 2022), “support land, capital, and market access,” and “Cultivate the next generation of diverse food and agriculture professionals” (USDA, 2022).

Climate change will inevitably affect these newly trained professionals. The USDA (2022) claims that implications will spread beyond agriculture districts into surrounding American communities through shifting weather patterns and the frequency and severity of storms, floods, droughts, and wildfires.

The Food and Nutrition Security priority has led the USDA to focus on how food availability can be altered to combat structural racism and connect healthy, safe, and affordable food sources to all Americans to promote optimal health and well-being.

The supply chain will be prioritized to assist the Food and Nutrition Security priority by transforming infrastructure and critical supply chains to build resilience against threats and disturbances and provide local and regional food systems with export opportunities.

The global agriculture market captures the supply chain’s ability to move food between continents, creating a consequential thread between the United States’ actions and its international partners. The *World Food and Agriculture Statistical Yearbook 2021* should capture the overarching extent of agricultural distribution (FAO, 2021). This yearbook presents two interesting facets: pandemic effects and US presidential election year.

This manuscript examines shared institutional facilities and infrastructures’ roles in preparing nanoscience to be optimized for evolving needs implications shortly. By cumulating experts in the fields of nanotechnology and agriculture, we south to determine how well this interdisciplinary group is training the current and next generations of researchers by making available top-notch, shared research facilities from selected Research-1 (R1) universities like those in the National Nanotechnology Coordinating Infrastructure or (NNCI) to help resolve concerns from stakeholders about roles to be played by nanotechnology and agriculture.

The NNCI is the current manifestation of the nanotechnology infrastructure program supported by the U.S. National Science Foundation (NSF). Prior embodiments of the program include the National Nanofabrication Users Network (NNUN) and the National Nanotechnology Infrastructure Network (NNIN).

The NNUN consisted of two “full service” hub facilities at Cornell (the Cornell Nanofabrication Facility) and Stanford (the Stanford Nanofabrication Facility), in association with specialized facilities at Howard University, Pennsylvania State University, and the University of California at Santa Barbara. It began in 1993.

The NSF supported nanoscience infrastructure again in 2004 by launching the NNIN program, building upon the NNUN, and expanding the network to 14 universities encompassing a broader technology scope in particular areas of nano-characterization and simulation resources. The network provided on-site and remote access for users, from academia, small and large industry, and government, to advanced top-
down patterning and processing and bottom-up synthesis and self-assembly, comprehensive integration capabilities for multi-step processes, state-of-the-art characterization for hard and soft materials, the development of tools and techniques, and a wide web and computation infrastructure in support of nanotechnology.

Once again, in 2015, the NNIN was followed by the NNCI, which consists of 16 primary sites with 27 institutional partners. Eight former NNIN sites are part of the newer NNCI network. Like the NNIN, the NNCI offers access to advanced nanotechnology resources across various nanotechnology areas. In the renewal proposals for the NNCI sites in 2020, the NNCI proposed to establish “Research Communities,” which are externally facing working groups of NNCI faculty, staff, and other volunteers that seek to advance specific nanotechnology opportunities that are of national interest, e.g., microelectronics and environmental science.

The RTNN proposed the Research Community for Nanotechnology Convergence and, in 2021, began work on an initial topic of Nanotechnology to Address Food and Nutrition Security. The NNCI program sunsets in 2025, and the NSF has yet to announce a subsequent initiative. However, a workshop entitled: Workshop on Nanotechnology Infrastructure of the Future has been announced for September 11–13, 2023.

All these nanotechnology infrastructure initiatives are or were part of the National Nanotechnology Initiative (NNI), officially launched in 2000 and first funded in FY2001. The NNI is associated with over thirty federal departments, independent agencies, and commissions.

The authors of this manuscript are, or have been, faculty, staff, and student researchers of the Research Triangle Nanotechnology Network (RTNN), one of the 16 NNCI sites. The RTNN combines the three major R-1 universities in North Carolina’s Research Triangle region: Duke University, the University of North Carolina at Chapel Hill, and North Carolina State University.

Somewhat unique among the 16 sites of the NNCI, the RTNN proposed and was supported to research the societal and ethical implications of nanotechnology (SEIN). Uniquely, our SEIN work centered on nanotechnology infrastructure networks’ role in our society rather than evaluating implications surrounding all things nanotechnological.

As a self-described “convergence initiative hub,” part of the mission research of the RTNN is to involve examining and accelerating how different disciplines engage in interdisciplinary research to address especially difficult global challenges. Work at the intersection of nanotechnology and agriculture is related to several difficult global challenges, e.g., climate change, phosphorus, nitrogen pollution, and food and nutrition security.

Under a “convergence initiative,” part of the mission of the RTNN is to examine how different disciplines engage in interdisciplinary research to address especially difficult global challenges.
3.0. Literature review

The literature suggests there will be many demands placed on the agricultural industry in the near future from a very broad set of drivers (How to feed the World-2050 2009; House of Lords, Science and Technology Committee 2010; World Resources Report 2019; Morgan Stanley 2021 and The U.S. Department of Agriculture’s Interagency Agricultural Projections Committee 2022).

This manuscript focuses on challenges rather than developments in nanotechnology and agriculture. For information on current developments, consider Fraceto et al. 2016; Schari and Kowshik 2018; Hen, Den, and Hwang 2019; Sunil and Chore 2020; and Usman et al. 2020.

For predictions and projections related to nanotechnology and food, see Angle 2019; Biswas et al. 2020; Ahmed et al. 2022; and especially the Future Market’s Technology Report on the AgTech Market 2023.

Many criticisms have surfaced regarding whether nanotechnology applications in food and agriculture can be engaged responsibly (see Cummings et al. 2021 and Grieger et al. 2021) and sustainably (Prosad et al. 2017 and Yi, Wang, and Gilbertson 2018).

Reservations and drawbacks associated with agricultural nanotechnology in general (Chigh 2021 and Singh and Packirisamy 2023), to microorganisms (Joshi et al., 2019), to pollinators (Hooven et al., 2019), etc. For a list of food products containing nanoparticles, you might wish to investigate the Center for Food Safety’s database (2023).

While we have yet to vet many of these sources, they are included here for your records.

4.0 Research protocols

Research protocols involving soliciting expert advice on any topic are immensely problematic. The highly qualified experts in the subject field may be unavailable due to a myriad of important responsibilities. Expert solicitations must compete with all the other demands on their time. Unfortunately, much of the literature suggests that experts agreeing to participate in a solicitation exercise may not be truly representative of the field from which they are drawn. Experts are busy, and those who agree to participate may exaggerate their qualifications and expertise (see Cherry 2022). In addition, experts are pelted with a multitude of correspondence from social science researchers; some have installed firewalls or politely ask to pass. As such, we search for them at professional meetings and scan lists of grant recipients and journal article authorships to find them. Finally, the sample sizes make quantitative research nearly impossible, so we find creative ways to fathom any consensus. This limits the authority of our findings. Nonetheless, the process may yield early predictors that are the basis for research questions and hypothesis building (see Ayyub 2001).

Given these reservations, the RTNN site explored the intersection between the two distinct fields of nanotechnology and agriculture. The specificity of this intersection requires knowledge bridging both
disciplines to multiple spheres of influence, including public, private, and government. A mixture of sampling and mixed methodologies was implemented to provide participants with various approaches to describe their insights on the field’s past and future opportunities, including opportunities for under-represented populations and under-represented subject areas.

4.1. Sampling.

There are two primary samples: attendees at the conference and the transcriptions of discussions in breakout rooms and email-based solicitations for semi-structured interviews.

Subject-matter experts were gathered from convenience samples. Additional expert sampling, both the researchers’ and grantees’ subsets, were added following low response rates from the conference experts’ sampling. Each expert sample followed similar exclusion criteria outlined below to ensure the integrity of subject-matter experts across all three sample populations.

4.1.1. Sampling for conference attendees and their breakout sessions’ transcriptions.

The RTNN, in collaboration with three other NNCI sites, NCI-SW, SDNI, and KY Multiscale, and an NSF AccelNet project called Accelerate Integration of Engineering and Agricultural Research using Artificial Intelligence (AI2EAR) hosted the first open, public-facing workshop in the Research Community programs on March 9, 2021, which was called, “Nanotechnology for Food and Nutrition Security.” The Workshop was hosted online on the Zoom platform, as travel limitations were still prevalent during the pandemic that persisted through 2021. The event was broadly announced to national listservs, on various NNCI websites and highlighted in multiple email promotions that reached several thousands of recipients. The workshop activities were undertaken under IRB approval so materials and transcripts could be retained for research. After the workshop, all of the attendee’s workshop participants at the March 9th, 2021, Nanotechnology for Food and Nutritional Security workshop held on the campus of North Carolina State University at the Hunt Library were invited to the next stage of research, i.e., to provide an interview (see 4.1.2.1). Workshop attendees sought out the opportunity to discuss nanotechnology through the lens of food security or agriculture, meaning they were knowledgeable or, at the least, engaged across both disciplines. Thus, no exclusion criteria were applied to the workshop attendee population.

Given the convergence of expertise in nanotechnology and agriculture debates, we hosted a workshop. The workshop involved 158 participants. During the workshop, participants were separated into four different breakout sessions. The sessions were labeled: pests and pathogens, water and fertilizers, crops and animals, and food products, and each was run twice. The assignments were made by giving the participants their first and second choices at registration. Each participant was assigned a topic session but was optional to follow their assignment and could visit whatever session they preferred. We solicited conference participants through several mechanisms (see section 4.1.1).
Participants, upon online registration, were asked what workshop topics interest them. These results were used to create the specific workshop breakout room topics and the assignment of the participants in each room. As the conference moved forward, its hosted discussions were taped, and content was analyzed to generate findings.

Each session had a moderator and a scribe. The moderators were selected from RTNN staff to keep the session on topic and attempted to ensure no single individual or the same individuals dominated the discussion. The scribe took notes in various ways involving tablets, portable computers, and whiteboards.

The top five occupations/positions in the Workshop population represented 76% of the conference population - “faculty member” 32.9% (n = 53), “research scientist” 18.0% (n = 29), “staff member” 11.2% (n = 18), “graduate student” 8.1% (n = 13), and “government agency employee” 5.6% (n = 9). The attendees’ institutional affiliation included “academia” (95%, n = 153), “government” (22%, n = 35.4), “industry” (21%, n = 33.8), “non-profit” (9%, n = 14.5) and “other” (6%, n = 9.7). The 161 registered attendee list was scrubbed to remove duplicates and undeliverable emails, narrowing the sample to 158 solicited attendees and generating a response rate of 5.1% (n = 8), necessitating an expanded sample pool.

4.1.2. Sampling for semi-structured interviews.

There are many approaches to take with soliciting samples for expert semi-structured interviews. We can use standard indices to decide who may or may not qualify as an expert. This approach was mongrelized so we could include a broader group of stakeholders. Furthermore, there was no consensus on which index was considered an index of experts among the staff and those with whom we interacted, as we learned informally during the conference. In addition, a substantial body of literature indicts traditional approaches to establishing the “expert” credential in expert solicitations, such as the Dunning-Kruger effect\(^2\) (Cherry, 2022).

4.1.2.1. Soliciting interviews with the conference attendees – Interview sample set one.

All attendees at the March 9th, 2021, Nanotechnology for Food and Nutritional Security Workshop held on the campus of North Carolina State University at the Hunt Library were invited to provide an interview. Workshop attendees sought out the opportunity to discuss nanotechnology through the lens of food security or agriculture, meaning they were knowledgeable or, at the least, engaged across both disciplines. Thus, no exclusion criteria were applied to the workshop attendee population.

Participants for the conference were solicited by email to participate in a semi-structured interview. Samples were broken into groups of up to 10 people to prevent a mass email from being filtered as spam by a server. Each group was contacted twice, with a 10-day gap between each solicitation.

The ten-day lay period was used between solicitations to target participants returning from summer travels. As mentioned above, each participant from the conference received the “First Solicitation Letter”
4.1.2.2 Soliciting supplemental interviews with “Researchers” – Interview sample set two.

Convenience Sample Two was organized to locate subject experts through research publications on Google Scholar or ResearchGate. The sample frame search parameters included a date range from January 1st, 2010, until August 5th, 2022, and the required keywords “nanotechnology,” “agriculture,” and “United States” within the publication text body. Abstracts were then used as an additional exclusionary filter by removing any publications not containing both terms “nanotechnology” and “agriculture/environment” in the abstract text. The term “environment” was deemed acceptable as agricultural processes rely on elemental cycles representing the broader definition of an environment (OECD 2023).

To ensure the validity of insights about the United States of America, any authors whose corresponding addresses or their sponsoring institution’s addresses were outside the North American continent were
excluded, thus including bordering countries.

When more than three authors contributed to a single publication, only the first three were invited to establish expert-level insights and validity further. Convenience Sample Two included 58 authors, resulting in a 6.9% (n = 4) response rate.

4.1.2.3. Soliciting supplemental interviews with “Grant Recipients” – Interview sample set three.

Grant Recipients of United States-sponsored organizations or federal departments were considered for Convenience Sample Three. Grant databases available online through the NSF and United States Department of Agriculture (USDA) were searched using the same required keywords - “nanotechnology” and “agriculture” - previously used in Convenience Sample Two, including abstract filtering. The term “United States” was not applied to the grant recipient search because United States sponsorship inherently orients research to be an asset to the nation. Grants must have been awarded between January 1st, 2010, and August 5th, 2022. The principal investigator and their second and third co-investigators were invited to interview. Convenience Sample Three acquired 138 potential participants with a response rate of 5.8% (n = 8).

5.0 Scheduling

Scheduling was quite a challenge in this project. While little was done in scheduling the conference breakout rooms’ transcriptions, scheduling the semi-structured interviews was challenging.

5.1. Scheduling transcriptions.

No special efforts were used to schedule transcriptions from the conference. They were recorded as part of the breakout sessions. The transcription process was done by The “live closed caption” - notated as LiveClosedCaption or “LCC.” The text was available immediately after recording, while the “transcript” - notated as PostTranscript or “PC” was processed by Zoom’s third-party The research associate scrubbed each PostTranscript of participant identifiers and replaced names with randomized numbers generated by Google Range Randomizer. In addition, the text body was reviewed by the research associate against the audio recording to correct any mistranscribed text. Responses were then transferred to Google Sheets based on their question number to aggregate themes and statistical analysis.

5.2. Scheduling semi-structured interviews.

The interview schedule (see Appendix A on the RTNN webpage [https://www.rtnn.ncsu.edu/]) was designed by the authors and administered by the research associate. Each consenting participant who signed up for an appointment slot received a private Zoom link requiring an authenticated passcode to join their interview.
The interview schedule required a verbalized “yes” by each participant to confirm they understood they could abstain from answering any question and had the opportunity to stop the interview at any time. Before beginning, participants were allowed to ask any questions. The interview consisted of ten questions divided into two sections. The first six questions used a 1–10 Likert scale where ten (10) was the highest and one (1) was the lowest. Questions seven and eight required ranking agricultural challenges over a ten and 25-year period, respectively. Questions nine and ten inquired about the overall interaction of the fields of nanoscience and agriculture. The interview concluded by offering participants a copy of the finalized research findings and allowing for any questions. The interview was designed to run 5–10 minutes. However, the time was not capped at 10 minutes to enable participants time to respond thoughtfully.

All interviews were recorded via Zoom. The Zoom feature “live closed caption” was turned on for each interview to provide an additional transcription increasing reliability. This allowed for a comparison between both transcripts produced by Zoom to identify any missing text not captured by one transcript. This decision increased the accuracy of transcripts before analysis.

6.0 Methods

Since linkages known as attributions are used rather than any form of causality in the following, we employed the principles of “Grounded Theory” to make sense of these data sets. Grounded theory is a systematic methodology largely applied to qualitative research conducted by social scientists. The methodology involves the construction of hypotheses and theories through data collection and analysis (Glaser & Strauss, 1967; Dey, 1990). This is one of the very early steps in analysis and is highly inductive.

All the information collected and analyzed in this project received IRB approval before collecting, analyzing, and reporting the findings.


A word cloud (or a tag cloud) is a visual representation of words. Cloud creators are used to highlight popular words and phrases based on frequency and relevance. They provide quick and simple visual insights that can lead to a more in-depth analysis of frequency and relevance (Heimerl et al., T., (2014).

We used WordClouds.com (a free online word cloud generator) to produce the following word clouds for all transcribed discussions from the conference breakouts.

As a result, we used simple cloud analysis. Heimerl et al. 2014 developed the prototype of the Word Cloud Explorer that relies entirely on word clouds as a visualization method. It equips them with advanced natural language processing, sophisticated interaction techniques, and context information. We show how this approach can effectively solve text analysis tasks and evaluate it in a qualitative user study. (Atenstaedt, 2017; Heimerl, Lohmann, Lange, & Ertl 2014).
Each set of uncoded responses was used to generate a word cloud based on the frequency of keywords using a free word cloud. This generator was used due to its ability to edit cloud output and recognize word collections – i.e., *agricultural pesticides*. This specific ability steps beyond a display of word frequency typically seen in Wordles. The researchers filtered word cloud texts to remove all unrelated words to the field of nanotechnology or agriculture, such as “challenge,” “things,” and “great ideas.” Each cloud was limited to 20 words produced through the algorithm.

6.2. **Conversational analytics (Boonstra, 2020).**

Semi-structured interviews are a method of research used most often in the social sciences. While a structured interview has a rigorous set of questions that do not allow one to divert, a semi-structured interview is open, allowing new ideas to be brought up during the interview as a result of what the interviewee says (Brinkman et al., 2018; Knott et al., 2022).

Interviews are generally coded, and terms of importance are highlighted to produce a theory and theme. This process is called “Conversational Analytics” (Boonstra, 2021).

Conversational analytics uses artificial intelligence, specifically Natural Language Processing (NLP), to derive data from conversations and respond appropriately. Conversational analytics, used in Alexa™ and chatbots, are AI-powered, automated, and fast. It is also scalable and can take on huge amounts of data. This takes the burden away from your teams. It also can reduce processing and error-fixing costs attached to manual analysis.

7.0 **Results**

We collected results from two separate events: a workshop with some control over the registered participants and a set of semi-structured interviews with total control over the interviewees. All the transcripts came from conference attendees. The first set of interviews also came from the conference attendees. The second and third sets of interviewees were supplemental to the conference attendees. All the samples from these events were selected as experts.

7.1. **Findings from conference transcripts.**

Before each session, the participants were asked to self-identify their disciplines and their levels of understanding of the subject for discussion. There were eight sessions run in two sets of four. Participants could participate in up to two each.

The transcripts were run through the Wordcloud generator (wordclouds.com). “Sentiment analysis”[4] analyzes digital text to determine if the emotional tone of the message is positive, negative, or neutral. This is often used to understand consumer preferences, i.e., complaints. The benefits of sentiment analysis include improving customer service through customer experience analysis (Thelwell, 2020).

When evaluating a text document’s sentiment (positive, negative, neutral), research shows that human analysts tend to agree around 80-85% of the time. This is the baseline we (usually) try to meet or beat.
when training a sentiment scoring system. Sentiment analysis focuses on the polarity of a text (positive, negative, neutral).

In non-consumer settings, sentiment analysis is of little utility except to establish the tenor of a text or, in our case, the tone of the breakout meetings. All the sessions were neutral in sentiment except for one, which was positive.

In non-consumer settings, sentiment analysis is of little utility except to establish the tenor of a text or, in our case, the tone of the breakout meetings. All the sessions were neutral in sentiment except for one, which was positive.

The confidence level for the Word Cloud from Sessions 1 & 2 on water and fertilizers (Figure 1) was 0.814, and the sentiment was neutral. Two of the top five terms (frequency and relevance) were future need (frequency: 9x and relevance 0.870) and real-time (frequency 7x and relevance .0745). The three remaining terms in the top five were next question, and things. The word things had the highest frequency (32x) and lowest relevance (0.527). From the top five terms

The confidence level for the Word Cloud from Sessions 1 & 2 on crops and animals (Figure 2 above) was 0.536, and the sentiment was neutral. Three terms in the top five were facilities (69x; 0.319 relevance), data (57x, 0.220), and technology (51x, 0.239). The remaining top terms in the top five were questions (109x, 0.527) and time (58x, 0197).

For the Word Cloud from Sessions 1 & 2 on pests and pathogens (Figure 3), the sentiment was neutral (0.96 confidence). The terms in the top five could have been more informative (questions, time, toby, facilities, and pathogens). The top term was associated with the title of the breakout session (pathogens). The only term with a high frequency and relevance was toby (34 times relevance 0.578).

Three of the top five terms in frequency and relevance were facilities (63 times, 0.422 relevance) and people (60 times, 0.652 relevance). Three terms: food, questions, and things were present in the top five by frequency. The term appearing most often was the word “food.” The sentiment, however, was positive (0.96 confidence).

In general, 75% of the participants were self-identified academics who ranked themselves slightly and extremely familiar; 74% were from wet labs; 47% were engaged in basic research, and over 40% used shared facilities regularly. They claimed the largest obstacles were a need for more public education and research infrastructure and funding. Their highest priority is interdisciplinary education and workforce training. They found current facilities and sufficiency in the topic (slightly and somewhat inadequate), but they do not see a need for changes in the existing facility. Current data issues mean machine learning assists decision-making.

As such, the following observations were derived from the texts recorded by participants from the breakout “reporting out” presentations at the end of the meeting. They were validated by email with the participants found in the acknowledgments.
The workshop involved a final session whence the participants reported on issues raised in the breakout sessions. The workshop strongly focused on NNCI facilities in resolving nanotechnology and agriculture challenges; hence it is unsurprising that many of their remarks were about facilities per se. They included the following:

- The USDA should find a way to join NNCI and have a unique food-focused center/location. The convergence of academic research and industrial product development is a corequisite to translating research into manufacturable products and scale-up and ensuring that societal needs are met. In general, this may require better record-keeping and resolve to balance data ownership and data sharing. The NNCI should be solution driven and include farms and fields co-located with the instrumentation and facility expertise needed to converge with the growers and those working in the agricultural sector.

- The NNCI facilities are not well situated to think about going into the field and need to continue to reach out to non-traditional disciplines, e.g., by focusing on specific topics like food security and describing what their facilities can do TODAY to support the needs of these research areas. The facilities should embrace system-level thinking.

- The NNCI facilities may need to ask, "How can we use our tools and expertise to support research in this area? This may require a shift in promotional/marketing strategies because we mostly promote based on tools (e.g., TEM or ALDtool) or general capabilities (e.g., nanofabrication, film deposition, microscopy).

- NNCI could improve staff expertise with plant-based systems and even new degree programs where nanotechnology, biotechnology, and agriculture converge, focus some effort on “real-time” measurements in dynamic environments as well as create and enhance sample prep facilities needed to deal with biological tissue, roots, plants, soil, etc.

- NNCI should include a "concierge mechanism" or LIAISON that could be housed within a shared facility, which could facilitate gaps: 1) on their research side, they may not know the possibilities if they do not know the capabilities of the instrumentation, 2) new degree programs, e.g., in ag-data or ag science data analytics, 3) communication across fields of science to accept the shared language more quickly. It would be a tall task for an individual to do this - perhaps a social scientist specializing in STEM communication or an ag field person who can talk to diverse stakeholders.

- NNCI facilities should promote interdisciplinarity, encouraging technical staff to become more proficient at working with researchers from other disciplines and thinking about training or educational programs to teach our nanotechnology capabilities to folks from other fields.

- NNCI could newly engage critical stakeholders in non-traditional-nano areas in future planning activities, especially industry, to help guide our thinking. For example, artificial intelligence can be an integrated part of several deployable systems using nanotechnology (e.g., controlled and sustained release of water, fertilizers, and pesticides, optimization over time, customization to different parts of the world, etc.

7.2. Findings from semi-structured interviews.
IRB-approved data were collected from all participants, n=20, and aggregated onto spreadsheets by their respective questions. Responses to questions 1-6 that utilized the 1-10 Likert scale were analyzed separately from the open-ended questions 7-10. This section will review results in an ordinal method separating the quantitative and qualitative nature of the interview questions.

7.2.1 Quantitative Responses that began the semi-structured interviews.

Questions 1-6 utilized a Likert scale of 1-10 to describe the field of agriculture and nanotechnology. One was the lowest score, and ten was the highest. The values run from 1.00 in very light blue through 10.00 in very deep blue. This color-coded legend for Questions 1 through 6 charts is the same.

Full results are in Appendix B and were created by data imported into Qualtrics and can be found on the RTNN web page. The format of Qualtrics’ software provided a clean foundation to present semi-structured interviews without sacrificing the ability to deliver qualitative data.

The interviewee was given a 7-option Likert scale. The darker the shade of blue, the closer the answer was to superior. The number before the parenthesis is the rank order of the Likert ordinal chosen by the interviewee. The percentage who chose the value is within the parenthesis, followed by the number of experts. If you ask why one or more of the pie charts have more slices than others, that is simply because none of the interviewees selected that number on the Likert scale for that question. This was a small sample of expert interviews, and these things happen. Next, to understand what the expert semi-structured surveys expressed, evaluate the pie chart by how deep the shade of blue dominates the charts.

Question 1 (Figure 5) investigated the quality of USA scholarship at the intersection of nanotechnology and agriculture since 2010. **On a scale of 1-10, with ten being superior, how would you rate the quality and extent of USA scholarship at the intersection between nanoscience and agriculture since 2010?** The responses (n=18) ranged from 2 to 8, with a mean of 5.72 and a standard deviation of 1.79. The frequency, 7 (n=5), was within one standard deviation of the norm. This data could be interpreted to suggest that the scholarship over the last decade at the intersection of nanotechnology and agriculture is of “moderate” quality.

Question 2 (Figure 6, below) remained focused on nanotechnology and agriculture since 2010 but targeted the US government’s investment in research partnerships. **On a scale of 1-10, with ten being superior, how would you rate the US government’s investment in research partnerships at the intersection between nanoscience and agriculture since 2010?** The range decreased from the first question to span the value set 3-8 despite two additional responses (n=20). However, the mean remained consistent at 5.70, with a standard deviation of 1.87. The frequency, however, was split between the scores of 4 (n=5) and 8 (n=5). Respectively, the lower frequency was within one standard deviation, and the upper frequency was outside one standard deviation. The split frequencies lead to a polarized interpretation of the quality of USA investment in research partnerships at the intersection of nanotechnology and agriculture.
Questions 3 (Figure 7) and 4 (Figure 8) addressed similar subject matters at the intersection between nanoscience and agriculture since 2010 but diverted to the institutions being questioned. Question 3 targeted “(non-university) research lab-related investments” (On a scale of 1-10, with ten being superior, how would you rate the USA government (non-university) research lab-related investments at the intersection between nanoscience and agriculture since 2010?) whereas question 4 inquired about “university research facilities, laboratories, and equipment” (On a scale of 1-10, with ten being superior, how would you rate the government investment in university research facilities, laboratories, and equipment at the intersection between nanoscience and agriculture since 2010?) Due to this relative yet distinct difference, the responses ranged between questions 3 (n=14) and 4 (n=20). Question 3 responses ranged from 2 to 7 with a 4.29 mean. The 5 (n=6) frequency was within one standard deviation (SD=1.44) above the average. Question 4 acquired a greater range from 2 to 10, averaging 5.30. Unlike question 3, the 4 (n=6) frequency was one standard deviation (SD=2.35) below the average.

Questions 5 (Figure 9) and 6 (Figure 10) had parallel structures and inquired about the critical importance of work at the intersection between nanoscience and agriculture for the “general welfare of the USA” (On a scale of 1-10, with ten being critically important, how would you rate the importance of work at the intersection between nanoscience and agriculture for the general welfare of the USA over since 2010?) Moreover, “welfare of the USA economy” since 2010 (On a scale of 1-10, with ten being critically important, how would you rate the importance of work at the intersection between nanoscience and agriculture for the welfare of the USA economy since 2010?), respectively. Both questions acquired an equal number of responses (n=20) and ranged from 3 to 10.

However, they differed in their means, with question 5 being valued at 8.15, 1.85 points below the frequency of 10 (n=6) - yet within one standard deviation (SD=1.88). Question 6 had a greater distribution of responses that lowered the mean to 7.40, 1.6 points below the frequency of 9 (n=5). The frequency was within the standard deviation of 2.24.

7.2.2. Qualitative Responses.

Questions 7-10 were open-ended, and participants were encouraged to provide opinions and insights. Each participant’s response was transposed into a Google Sheet for coding and analysis. Answers to questions 7 and 8 were broken further to reflect the researcher’s request to “rank five challenges over a ten or 25-year outlook”, respectively. As such, the five challenges were viewed as separate responses for analysis.

These responses were recorded and transcribed by Zoom. They were transferred to an Excel spreadsheet, where they were aggregated. Some challenges are ordered below, but the ordinal nature of these suggestions was not significant, even with an abbreviated version of Krustal Wallis; since the sample was small, the distributions did not have sufficiently similar variabilities (Krustal, 1952).

7. If you were asked to rank the top five challenges confronting agriculture over the next ten years, what would you rank as the top five? Which would rank first and most challenging?
Over the next ten years, interviewees listed the challenges mostly following in this order: climate change, water, pesticide use and resistance, productivity and efficiency, and finally, genetic engineering and genetically modified crops.

8. If you were asked to rank the top five challenges **confronting agriculture** over the next 25 years, what would you rank as the top five? Which would rank first and most challenging?

Over the next 25 years, interviewees listed the challenges mostly in this order: climate change, productivity and efficiency, water, pesticide use and resistance, genetic engineering, and genetically modified foods.

9. In general, what are the greatest challenges for work **at the intersection of agriculture and nanoscience**?

Regarding the convergence and intersection of nanotechnology and agriculture, interviewees listed the challenges mostly in this order: (1) research funding, (2) a lack of emphasis from government regulatory and commercial entities, (3) a lack of focused training in nanotechnology and agriculture, (4) a general under-investment in land grant schools, and (5) science should direct STEM efforts toward agriculture.

10. What problems in the future of agriculture, if any, **can be addressed** by investing in nanoscience over the next 25 years?

This question asked the experts to prioritize what **CAN** be accomplished with adequate investment. In other words, what were the “lower-lying” fruits? They mostly listed these in this order: (1) engineer crops for climate resistance, (2) engineer crops to be more water efficient and develop materials to promote advances in irrigation, and (3) use advances in nanotechnology to improve the use of fertilizers and nutrients, specifically addressing pesticide resistance and fertilizer alternatives, such as phosphorus.

8.0. Results

The Workshop transcripts from both the Wordles and the reports from the breakout sessions support the general conclusion that much work is still to be done if an infrastructure network is to demonstrate resilience in responding to some of the demands and challenges confronting agriculture.

8.1 Conference transcripts.

We had transcripts, and we ran the text through a Wordle program. We checked for frequency and relevance as well as sentiment. We learned a little about the samples involved, but the breakout sessions focused on terms like facilities, data, and technology. The notes from the breakout groups concur with the discussions in the breakout rooms. Stakeholders, including the U.S.D.A. and farmers, need to be involved. Our facilities may not be optimally situated to address agricultural needs, and we need to learn what platform and instrument needs the agricultural interests may have. Interdisciplinarity seems worthwhile.
on many levels, including education and agricultural data analysis. More agricultural scientists must be encouraged to use the facilities, and staff may need to be trained to assist them.

8.2 Semi-structured interviews.

Taken as a whole, the interviews generated a picture of an infrastructure network that may need to be prepared for the agricultural community’s needs, especially when the interviewees began answering the open-ended questions. They found the greatest challenges in terms of climate change and genetic engineering. Specifically, they emphasized water needs, fertilizer issues, and pesticide management—the sample called for research funding priority, including training. When asked what we could do today – they called for both the engineering of crops to be climate resistant and water efficient and direct nanotechnology into the fields of fertilizers and nutrients.

9.0. Limitations

The limitations included self-selection on the part of participants throughout. We asked them to attend a conference, and we asked them to be interviewed. They had to agree to participate before we collected and distilled their opinions. While we made efforts to ensure the samples were experts, we cannot attest to the levels of expertise per se. Some of the breakout sessions indicated concerns about the dominance of academics at the workshop when it might have been a stronger sample with much stronger food industry participation.

As mentioned above, expert solicitation is a difficult research activity because experts are busy. They are experts, and their intellectual property is valuable to many stakeholders. Some experts are better than others, so we use whatever research tools we can to reach the experts willing to make themselves available to help fashion a thoughtful response to the challenges at hand at the confluence of agriculture and nanotechnology.

10.0. Conclusions

We found many conclusions to be drawn from the opinions expressed by our samples. We assigned a scribe to each breakout group for the conference, and they reported to the meeting as a group. These reports were instrumental in coalescing general attitudes toward how prepared we might be for agricultural setbacks in the decades ahead. Those challenges were bulleted (above) from the analysis of transcriptions from the conference sample. This group was well-informed about the current NNCI infrastructure, and some of the samples had experienced actual lab-based shortcomings that they reported as challenges.

The quantitative semi-structured interview results indicate that we have mixed results regarding supporting the convergence of nanotechnology and agriculture. In some instances, so little is known about some facilities supporting infrastructure that the sample could not report their opinions. We did not prod for a score in those instances and accepted their response as “do not know.”
The qualitative results from the semi-structured interviews could not be more consistent among the sample: climate change will be the most important challenge for converging nanotechnology and agriculture.

Declarations

Author Contribution

DMB Primary author and secondary editor; BW Primary editor, graphs and tables; JJ: Tertiary editor; FO; Copy editor; MC: Internal reviewer.

Data Availability

Primary data will appear on the RTNN web page. The RTNN, in collaboration with three other NNCI sites, NCI-SW, SDNI, and KY Multiscale, and an NSF AccelNet project called Accelerate Integration of Engineering and Agricultural Research using Artificial Intelligence (AI2EAR) hosted the first open, public-facing workshop in the Research Community programs on March 9, 2021, which was called, “Nanotechnology for Food and Nutrition Security.” The Workshop was hosted online on the Zoom platform, as travel limitations were still prevalent during the pandemic that persisted through 2021. The event was broadly announced to national listservs, on various NNCI websites and highlighted in multiple email promotions that reached several thousands of recipients. The workshop activities were undertaken under IRB approval so materials and transcripts could be retained for research. After the workshop, all of the attendee’s workshop participants at the March 9th, 2021, Nanotechnology for Food and Nutritional Security workshop held on the campus of North Carolina State University at the Hunt Library were invited to the next stage of research, i.e., to provide an interview (see 4.1.2.1). Workshop attendees sought out the opportunity to discuss nanotechnology through the lens of food security or agriculture, meaning they were knowledgeable or, at the least, engaged across both disciplines. Thus, no exclusion criteria were applied to the workshop attendee population.

References


Footnotes

1. This work was made possible in part by collaboration across several grants from the National Science Foundation (NSF), ECCS-2025064 (Research Triangle Nanotechnology Network), ECCS-2025490 (Nanotechnology Collaborative Infrastructure-Southwest), ECCS-2025075 (Kentucky Multiscale Manufacturing and Nano Integration Node), ECCS-2025752 (San Diego Nanotechnology Infrastructure) and OISE-2020459 (A12EAR). The findings reported below are not definitive and do not represent the beliefs and sensibilities of our home academic institutions or the National Science Foundation. Special gratitude is extended to Kevin M. Walsh, Professor of Electrical and Computer Engineering, J. B. Speed School of Engineering, University of Louisville, and Paul Westerhoff, Regents Professor, School of Sustainable Engineering and the Built Environment, Arizona State University, for their notes from the conference.

2. The Dunning-Kruger effect is a type of cognitive bias in which people believe they are smarter and more capable than they are. Essentially, low-ability people do not possess the skills needed to recognize their own incompetence.

3. Word clouds (text clouds or tag clouds) work in this way: the more a specific word appears in a source of textual data (such as a speech, blog post, or database), the bigger and bolder it appears in the word cloud. A word cloud is a collection, or cluster, of words depicted in different sizes. The bigger and bolder the word appears, the more often it’s mentioned within a given text and the more important it is.

4. Sentiment analysis is the process of analyzing digital text to determine if the emotional tone of the message is positive, negative, or neutral. Today, companies have large volumes of text data like emails, customer support chat transcripts, social media comments, and reviews. Companies use the insights from sentiment analysis to improve customer service and increase brand reputation.

Figures
Figure 1

Word Cloud from Sessions 1 & 2 for the Water and Fertilizers Breakouts.
Figure 2

Word Cloud from Sessions 1 & 2 for Crops and Animals Breakouts
Figure 3

Word Cloud from Sessions 1 & 2 Pests and Pathogens Breakouts

Figure 4

Word Cloud from Sessions 1 & 2 Food Products Breakouts.
Figure 5

Responses to Question 1; options 1 and 10 were not selected.

Figure 6

Responses to Question 2; options 1, 2, 5, 9, & 10 were not selected.
Figure 7

Responses to Question 3; options 1, 8, 9 & 10 were not selected.

Figure 8

Responses to Question 4; options 1 & 7 were not selected.
Figure 9

Responses to Question 4; options 1, 2 & 4 were not selected.

Figure 10

Responses to Question 5; options 1, 2 & 5 were not selected.