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Research Paper

Responsible innovation of nano-agrifoods: Insights and views from U. S. stakeholders

Khara D. Grieger [a,b,*], Ashton W. Merck [a,b], Maude Cuchiara [c], Andrew R. Binder [b,d], Adam Kokotovich [b,e], Christopher L. Cummings [b,f], Jennifer Kuzma [b,g]

[a] *Department of Applied Ecology, North Carolina State University, USA*
[b] *Genetic Engineering and Society Center, North Carolina State University, USA*
[c] *Department of Materials Science and Engineering, North Carolina State University, USA*
[d] *Department of Communication, North Carolina State University, USA*
[e] *Department of Forestry and Environmental Resources, North Carolina State University, USA*
[f] *Gene Edited Foods Program, Iowa State University, USA*
[g] *School of Public and International Affairs, North Carolina State University, USA*

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ABSTRACT

To date, there has been little published work that has elicited diverse stakeholder views of nano-agrifoods and of how nano-agrifoods align with the goals of responsible innovation. This paper aims to fill this research gap by investigating views of nano-agrifoods, how well their development adheres to principles of responsible innovation, and potential challenges for achieving responsible nano-agrifood innovation. Using an online engagement platform, we find that U.S. stakeholder views of responsible innovation were dominated by environmental, health, and safety (EHS) contexts, considerations of societal impacts, opportunities for stakeholder engagement, and responding to societal needs. These views overlap with scholarly definitions of responsible innovation, albeit stakeholders were more focused on impacts of products, while the field of responsible innovation strives for more “upstream” considerations of the process of innovation. We also find that views of nano-agrifoods differed across applications with dietary supplements and improved whitening of infant formula viewed least favorably, and environmental health or food safety applications viewed most favorably. These findings align with the larger body of literature, whereby stakeholders are expected to be more supportive of nanotechnology used in agricultural applications compared to directly within food and food supplements. Overall, participants indicated they held relatively neutral views on research and innovation for nano-agrifoods being conducted responsibly, and they identified key challenges to ensuring their responsible innovation that were related to uncertainties in EHS studies, the need for public understanding and acceptance, and adequate regulation. In light of these results, we recommend future research efforts on EHS impacts and risk-benefit frameworks for nano-agrifoods, better understanding stakeholder views on what constitutes effective regulation, and addressing challenges with effective regulation and responsible innovation practices.

1. Introduction

The use of nanotechnology and engineered nanomaterials in food and agriculture (termed nano-agrifoods) may provide numerous benefits to health, the environment, and society. For example, nano-pesticides and nano-fertilizers aim to improve crop productivity through more efficient agrochemical delivery mechanisms (Kumar et al., 2019; Sampathkumar et al., 2020), and nano-vaccines may provide superior vaccine delivery in animal husbandry practices (Renu et al., 2020). In addition, nano-emulsions may improve food nutritional values (Prakash et al., 2018), while nano-scale food additives may improve food properties such as color and texture (Hwang et al., 2019). However, concerns have also been raised regarding their potential impacts and unintended consequences (Grieger et al., 2016a, 2016b, McClements and Xiao, 2017, Grieger et al., 2019, Li et al., 2019, Cummings et al., 2021). Today, after nearly two decades of research programs dedicated towards understanding nano-safety and risks, there are still extensive uncertainties and data gaps that impede the formation of concrete

* Corresponding author at: 100 Eugene Brooks Avenue, Campus Box 7617, Raleigh, NC 27695-7617, USA.
E-mail address: kdgriege@ncsu.edu (K.D. Grieger).

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conclusions regarding the risks of most nanomaterials (Oomen et al., 2018; Grieger et al., 2019), including those in food and agriculture sectors. In addition to impacts on health and safety, there are also uncertainties in terms of how publics including consumers may perceive the use of nano-agrifoods, particularly given previous experiences with other novel agrifood technologies that faced considerable public consternation (Zhang et al., 2016). Recent studies have shown that perceptions and attitudes of nanotechnology are still forming (Parisi et al., 2015, European Chemicals Agency (ECHA), 2020, Feindt and Poortvliet, 2020, Joubert et al., 2020), and questions remain on how best to achieve transparency regarding the use of nanotechnology in agrifood sectors while also ensuring trust among stakeholders (Capon et al., 2015; Grieger et al., 2016a, 2016b).

As an approach to minimize potential risks and maximize benefits to society, the responsible development of nanotechnology has been a top priority, especially in the U.S. and the European Union (European Commission (EC), 2020, National Nanotechnology Iniatitive (NNI), 2020, Organisation for Economic Co-operation and Development (OECD), 2020). The U.S. National Nanotechnology Initiative (NNI) has designated the responsible development of nanotechnology as one of four strategic areas, largely focused on understanding environmental, health, and safety (EHS) impacts as well as ethical, societal, and legal implications, including understanding of stakeholder perceptions, attitudes, and views (National Nanotechnology Iniatitive (NNI), 2020). The responsible development of nano-agrifoods may be especially important to pursue given that consumers and other stakeholders may have heightened risk perceptions of nanotechnology used in food and agricultural products compared to other application areas (e.g., medicine, electronics, automotive) (e.g., (Kato-Nitta et al., 2019, Porcari et al., 2019, European Chemicals Agency (ECHA), 2020, Joubert et al., 2020)). At the same time, the concept of responsible innovation goes beyond the safe and responsible development of emerging technologies, by attempting to (better) couple research and innovation with societal needs and expectations through iterative engagement processes that occur more "upstream" (Stilgoe et al., 2013, von Schomberg, 2013, Macnaghten et al., 2014, Bogner and Torgersen, 2018). Stilgoe et al. (2013) define responsible innovation as "taking care of the future through collective stewardship of science and innovation in the present," based on four main pillars: i. *anticipation*, to anticipate potential impacts and effects; ii. *inclusion*, to include diverse perspectives and actors; iii. *reflection*, to reflect on one's motivations and assumptions; and iv. *responsiveness*, to respond and/or adapt to e.g., new information, stakeholder values, concerns. In addition to Stilgoe et al.'s definition of responsible innovation, others have proposed slightly different definitions, some of which have included other parameters such as openness, transparency, sustainability, care, and ethical acceptability (Blok et al., 2015, Burget et al., 2017, Owen and Pansera, 2019, Fraaije and Flipse, 2020).

Within this context, understanding and evaluating stakeholder perceptions and views of nano-agrifoods not only helps achieve NNI's goal of responsible nanotechnology development but it also adheres to best practices of responsible innovation more broadly. Over the past two decades, numerous studies have investigated perceptions and attitudes of nano-agrifood applications (Siegrist and Keller, 2011, Yue et al., 2015a, 2015b, Steenis and Fischer, 2016, Chang et al., 2017, Chuah et al., 2018). Among other findings, several authors have highlighted the importance of trust between stakeholders and the need for transparent information in attitudes and perceptions of nano-agrifoods (Siegrist et al., 2007a, 2007b, Besley, 2010, Giles et al., 2015). Other studies have suggested that clear communication efforts are needed on the benefits of nano-agrifoods in order to address potential stakeholder concerns (Steenis and Fischer, 2016; Chang et al., 2017). While this valuable body of literature has assessed factors that underpin perceptions, attitudes, and levels of acceptance of nano-agrifoods, there is little published work that has elicited stakeholder views of nano-agrifoods and of how nano-agrifood products align with the goals of responsible innovation. In addition, stakeholder views of nano-agrifoods and responsible innovation may likely differ between sectors (e.g., agricultural practices vs. within food products) as well as between stakeholder groups (Scheufele et al., 2007; Siegrist et al., 2007a, 2007b; Gupta et al., 2015; Yue et al., 2015a, 2015b; Steenis and Fischer, 2016). If nanotechnology and nanomaterials are to improve food and agriculture practices and be achieved through responsible development and innovation, then a clearer understanding of how different stakeholders perceive nano-agrifoods according to how well they are responsibly innovated is needed. Therefore, this paper aims to fill this research gap by investigating stakeholder perceptions and views of nano-agrifoods, how well their development adheres to principles of responsible innovation, and potential challenges for achieving responsible nano-agrifood innovation. Key outcomes from this study are relevant for researchers, innovators, industry, policy-makers, and other stakeholders involved and/or interested in ensuring responsible innovation and development of nanotechnology applications in food and agriculture sectors.

2. Methodology

We investigated stakeholder perceptions of nano-agrifoods using an online engagement platform, as a part of a larger U.S. Department of Agriculture (USDA), National Institute of Food and Agriculture (NIFA)-funded grant focused on societal implications and responsible innovation of nanotechnology in food and agriculture (Grant No. No. 2019–67023-29855; PI = Grieger, CoPI = Kuzma). To conduct the online stakeholder engagement study, we developed the engagement platform, identified and invited stakeholder participants, conducted the study using a series of questionnaires and case studies, and analyzed the results. While we have previously provided an overview of the process to develop the online stakeholder engagement platform and topics investigated in Ruzante et al. (2021), this paper is the first to report on processes used to elicit stakeholder perceptions of responsible nano-agrifood innovation alongside resulting outcomes of these stakeholder views.

2.1. Development of stakeholder engagement platform

We developed the online engagement study using the CMNTY platform (www.cmnty.com/) (Ruzante et al., 2021). CMNTY is an online platform that supports a variety of different modalities to engage participants in a virtual setting. We developed the platform in a way to elicit perceptions and responses from study participants using a mixed-method approach that relied on both quantitative (i.e., Likert-type scale from 1 to 5) and qualitative (i.e., open-comment fields) questions. The engagement platform included a home-landing page, electronic consent form, questionnaires, open forum discussion board, and chat function (see Fig. S1 in the Supplementary Information (SI) for a screenshot of the home page). After we developed all content for the study, we tested the platform functionalities and subsequently revised the platform content to improve the quality of the study for participants.

2.2. Development of questionnaires

We developed questionnaires consisting of open-ended, Likert-type scale, semantic differential, and ranked-order questions according to three themes: 1. Views of responsible innovation, 2. Responsible innovation and nano-agrifood case studies, and 3. Challenges to nano-agrifood responsible innovation (Table 1). Section 2 in the SI provides the full list of questions posed to participants, and Fig. S2 provides a screenshot of the questionnaires used in the online stakeholder platform.

Participants first completed two open-ended questions on their views of responsible innovation (Q1–2). Next, participants responded to an open-ended question on practices to ensure responsible innovation of nano-agrifoods (Q3). Participants also indicated how much they agreed or disagreed to a series of statements regarding responsible innovation

Table 1
Questions posed to study participants regarding nano-agrifoods and responsible innovation (RI), categorized by theme.

Theme	Question
1. Views of RI	1. In your own words, what do you think it means to innovate responsibly? In other words, what does it mean to conduct research and development in a responsible way? (Open-ended) 2. Similarly, in your own words, what does it mean to NOT innovate responsibly? (Open-ended) 3. Regarding nanotechnology innovations in food and agriculture, what practices should researchers pursue to ensure that they innovate responsibly? (Open-ended) 4. How much do you agree with the following statements? (Likert-type scale) • Maximizing stakeholder engagement leads to better nanotechnology policy • Reflecting on the underlying purposes, motivations, and uncertainties that surround nanotechnology products is important • Considering potential environmental and social implications of nanotechnology products is important in all stages of research • The nanotechnology innovation process should respond to public attitudes or values • The innovation process should respond to public attitudes or values, even if this means delaying, modifying, or terminating a nanotechnology project • Innovators should consult with consumer and environmental advocacy groups during research and development in nanotechnology • There should be a standard of at least 10% of public funding for research in nanotechnology that goes to environmental, social, legal, and ethical implications research • Social scientists, environmental and health risk analysts, and ethicists should be involved from the early stages of nanotechnology innovation
2. Views of Nano-agrifood Case Studies*	5. Please indicate your level of agreement with the following statement: The nanotechnology application described in this study is an example of responsible innovation (Likert-type scale) 6. Please rank the nano-agrifood case studies in descending order according to how best they adhere to your definition of responsible innovation (1 = Most responsibly innovated; 5 = Least responsibly innovated) 7. What were the three most important factors that influenced your ranking? (Open-ended) 8. Please rate the case study on the following traits: • Responsible - Irresponsible • Useful - Useless • Safe – Unsafe • Superior to alternatives – Inferior to Alternatives • Beneficial – Not beneficial • Not Risky - Risky 9. Please rate the case study on the following traits: • How potentially hazardous is this product to human health? (“Not at all-” to “Extremely hazardous”) • How potentially beneficial is this product to human health? (“Not at all-” to “Extremely beneficial”) • How potentially hazardous is this product to the environment? (“Not at all-” to “Extremely hazardous”) • How potentially beneficial is this product to the environment? (“Not at all-” to “Extremely beneficial”) • To what degree is there a societal need for this product? (“Not at all” to “There is an extreme need”) • To what degree does the product provide equitable distribution of benefits? (“Completely unequitable-” to “Completely equitable-”) • To what degree does the product provide equitable distribution of risks? (“Completely unequitable-” to “Completely equitable-”)
3. Views of RI Challenges	10. How much do you agree with this statement: Currently, food and agriculture nanotechnology is being conducted responsibly? (Likert-type scale) 11. Overall, what do you think is the most important challenge that needs to be overcome to achieve responsible innovation for nanotechnology used in food and agriculture? (Open-ended)

Likert-type scale: 1 = Strongly disagree; 2 = Disagree; 3 = Neither Agree nor Disagree; 4 = Agree; 5 = Strongly agree.
Note: *Questions listed in order for presentation and analysis purposes. See SI for questions listed in order in which they were presented to study participants.

and nano-agrifoods, using a scale from 1 (Strongly disagree) to 5 (Strongly agree) (Q4), following an approach previous developed by Roberts et al. (2020) that evaluated stakeholder attitudes of responsible innovation of biotechnology. Next, participants reviewed five nano-agrifood case studies that spanned food, agriculture, and veterinary medicine sectors (See SI for full details) and responded to a series of questions regarding their responsible innovation (see Q5–9). Using a Likert-type scale from 1 (Strongly disagree) to 5 (Strongly agree), participants were asked if the nano-agrifood case study was an example of responsible innovation (Q5). Participants ranked the case studies in descending order according to how well they adhered to responsible innovation (Q6), followed by an open-ended question on the factors that influenced their response (Q7). Participants were also asked to rate the case studies according to bipolar semantic differential scales (using a scale 1–10), with opposite traits on each end of the spectrum (e.g., “not at all hazardous to human health” vs. “extremely hazardous to human health”) (Q8–9). These questions were partially based on the Societal Risk Evaluation Scheme previously developed and applied to synthetic biology products (Cummings and Kuzma, 2017) and positioned the responses on alternating poles to reduce biases in responses (e.g. to avoid having all “good” responses be on the left side, and “bad” responses on the right of the spectrum). Finally, participants provided their final views of nano-agrifoods and responsible innovation, where they were asked if food and agriculture nanotechnology is being conducted responsibly using a Likert-type scale (Q10), and what is the most important challenge that needs to be overcome to achieve responsible innovation of nano-agrifoods (Q11). All questions posed to the participants are shown in Table 1 according to theme for presentation and analysis purposes.

2.3. Development of nano-agrifood case studies

As mentioned, participants reviewed five case studies of food and agriculture products that use nanotechnology and/or contain engineered nanomaterials to gain insights on views and perceptions of different nano-agrifoods (see Section 2 in SI for full case study descriptions). These case studies were based on real-world products that are on the market or are in the final stages of research and development. Each case study contained i) a description of the general context and purpose of the product, ii) how the product uses nanotechnology and/or nanomaterials, and iii) the potential risks and anticipated benefits of the product. The case studies included the following, which represented a range of nano-agrifood products across agriculture, food, and veterinary medicine sectors:

Case Study A: Fresh Cut Fruit and Surface Browning, which utilizes lemongrass nano-emulsions to prolong shelf lives of fresh cut fruit;

Case Study B: Laying Hens and Salmonella Infection, which utilizes chitosan nanoparticle-encased *Salmonella* antigens for an oral vaccine for laying hens;

Case Study C: Dietary Supplements and Micronutrient Copper, which utilizes copper nanoparticles as a dietary supplement;

Case Study D: Fruit and Citrus Greening Disease, which utilizes zinc oxide nanoparticles to combat citrus greening disease; and.

Case Study E: Infant Formula and Aesthetic Appearance, which utilizes titanium dioxide nanoparticles as a color additive in infant formula.

2.4. Stakeholder participant identification and recruitment

Potential study participants were identified through the peer-reviewed literature (e.g., journal article publications on nano-agrifoods accessed through NC State's online article retrieval system), conferences and workshops, USDA's Current Research Information System (CRIS) database, as well as the research team's networks within nanotechnology, food science, agriculture, veterinary medicine, and governance areas. We aimed to include participants from diverse affiliations and sectors in the U.S., including U.S. academic institutions, industry, non-governmental organizations (NGOs), think-tanks, advocacy groups (including consumer and environmental advocacy groups), as well as government agencies (Ruzante et al., 2021). We identified a total of 466 potential participants and invited them to partake via email in the online stakeholder engagement study. IRB approval was obtained from the PI's institution (NC State, IRB protocol 19,207) prior to reaching out to participants. As an incentive, a $100 honorarium was offered to participants who completed all platform activities. In total, 466 stakeholders were invited to participate in the study, 69 responded and agreed to participate, 21 participants responded but did not agree to participate, 24 participant emails were not delivered (bounced back or returned), 1 person was found to be deceased, and the remainder (351) did not respond to our invitation. Out of the 62 participants who agreed to participate in the platform, 55 participants completed all tasks and activities, and therefore the total number of participants who partook in this study was 55. The distribution of these study participants according to sectors are as follows: academia ($n = 19$, 34.5%), government ($n = 9$; 16.4%), industry ($n = 10$, 18.2%), NGOs/think-tanks ($n = 7$, 12.7%), and NGOs/advocacy (n = 10, 18.2%). Participants were required to create an account to access the online engagement platform, sign a consent form, and agree to terms of conditions (i.e., study expectations, behavioral norms) prior to starting any engagement activities. To create an account, the participants provided an email address and chose a username. We also asked participants to use non-identifiable usernames to ensure anonymity among participants and to promote an inclusive space (e.g., reducing or eliminating power imbalances between participants).

2.5. Conduct stakeholder platform

Once all of the platform content was developed, tested, and finalized, the study was conducted during a three-week period in late October and early November 2020. The research team monitored the platform daily during the study period to ensure that activities were being conducted and there were no technical issues. During the study, the research team did not participate in or facilitate platform activities or interfere with participants partaking in the study. After the study was completed, the platform was closed so that participants were no longer able to access the online site. All participants received emails to thank them for their participation and provide details on how to receive their honorarium for completing all study activities.

2.6. Analysis of results

After the completion of the study, we analyzed the responses to the questionnaires. For the Likert-type scale, semantic differential scale, and ranked-order questions, we calculated univariate descriptive statistics, including mean and standard deviation, of responses from the 55 participants who completed all study activities. The mean scores and standard deviations were then plotted. For the open-ended response questions, we exported responses from the CMNTY platform and used Dedoose qualitative software to code the responses using descriptive coding and subcoding (Saldaña, 2013). In this process, we read through the participant responses and assigned parent and child codes to overarching themes related to definitions and practices of responsible innovation, factors that influenced participant judgements of nano-agrifoods, as well as challenges to achieve responsible nano-agrifood innovation. The final list of codes represented key themes that emerged from responses to these open-ended questions. We also identified exemplary responses for codes to present in the results.

For a subset of questions that measured stakeholder responses to traits of being responsible, useful, safe, superior to alternatives, beneficial, and not risky using semantic differential scales (Q8), we further investigated whether there were statistically significant differences in our participants' responses across case studies. We selected only this subset for investigations of statistical significance for two reasons. First, our study aimed to investigate views of nano-agrifoods and responsible innovation primarily on a qualitative basis, and therefore we judged these questions as the only suitable ones for statistical analysis. Second, stakeholder responses to the aforementioned questions largely resulted in consistent patterns throughout different questionnaires in our study (as discussed in subsequent sections). To investigate if statistically significant differences were observed in this subset of questions, we first used responses from 51 participants who completed every item within the questionnaire, as four individuals did not respond to all questions within the questionnaire. After assessing measure reliability across multiple responsible innovation traits (Cronbach's alpha results: case A $\alpha = 0.90$, case B $\alpha = 0.92$, case C $\alpha = 0.88$, case D $\alpha = 0.90$, case E $\alpha = 0.89$), we created composite variables used in analyses to assess statistical differences in general views among participants across the case studies. Finally, we performed statistical analyses to test for differences in participant responses to Q8.

3. Results

Stakeholder responses to the 11 questions listed in Table 1 are shown in the following sections, organized by themes of views of responsible innovation, views of nano-agrifood case studies, and views of responsible innovation challenges.

3.1. Views of responsible innovation

3.1.1. What does it mean to innovate responsibly?

When asked "In your own words, what do you think it means to innovate responsibly?" (Q1), participants largely framed responsible innovation within EHS contexts as well as considering societal impacts (Fig. 1A). The most commonly mentioned theme was to *Consider studies on environmental, health, and safety (EHS)*, mentioned by 64% of participants and exemplified by the stakeholder quote: "it means carefully and comprehensively considering the potential social, health, and environmental impacts associated with the innovation and ensuring that actual and potential near-term and longer-term negative impacts are mitigated to the extent feasible." The second most mentioned theme to what it means to innovate responsibly was to *Consider societal impact,* mentioned by 36% of participants and exemplified by the stakeholder quote "I also think we need to consider the impacts of an innovative development on the different stakeholders." The third most frequently mentioned theme was to *Not harm human health and/or the environment,* mentioned by 22% of participants and exemplified by the quote "[to] do nothing that could cause irreversible harm to public health or the environment." We note here, and expand more in the discussion, that this emphasis on evaluating the "downstream" impacts of nano-agrifood products runs counter to foundational principles and practices of responsible innovation as defined in the science and technology policy and studies literature that emphasize more "upstream" engagement with

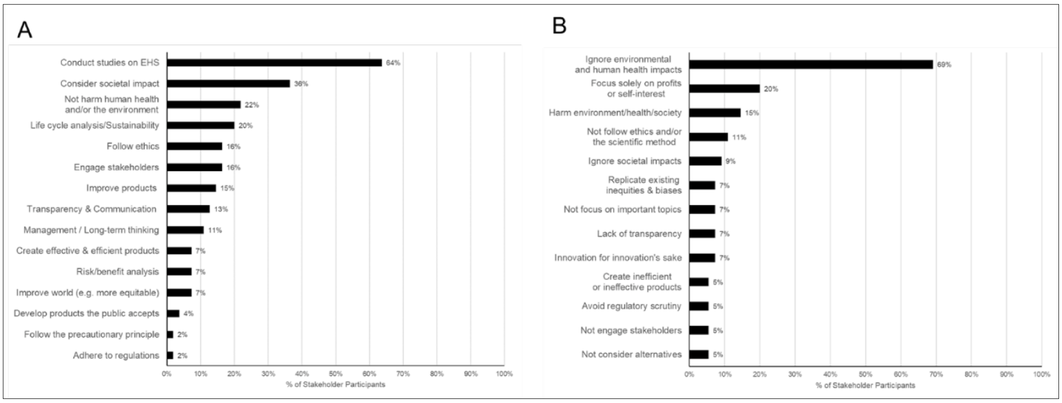

Figure 1. Views of responsible innovation according to stakeholder participants. A: Responses to "In your own words, what do you think it means to innovate responsibly? In other words, what does it mean to conduct research and development in a responsible way?" B: Responses to "Similarly, in your own words, what does it mean to NOT innovate responsibly?" EHS = environmental, health, and safety.

Fig. 1. Views of responsible innovation according to stakeholder participants. A: Responses to "In your own words, what do you think it means to innovate responsibly? In other words, what does it mean to conduct research and development in a responsible way?" B: Responses to "Similarly, in your own words, what does it mean to NOT innovate responsibly?" EHS = environmental, health, and safety.

stakeholders (Stilgoe et al., 2013; Carvalho and Nunes, 2018).

Other themes mentioned by stakeholder participants included concepts of *Conduct sustainability and/or life cycle analysis* (mentioned by 20% of participants), *Follow ethics* (16%), *Engage stakeholders* (16%), *Improve products* (15%), *Improve transparency & communication* (13%), and *Consider long-term planning and/or management* (11%). In addition, some stakeholders mentioned that to innovate responsibly meant to *Create effective & efficient products*, *Conduct risk/benefit analysis*, and *Improve the world* (e.g., more equitable solutions) – all mentioned by 7% of participants - as well as *Develop products the public accepts* (4% of participants), *Follow the precautionary principle* (2%), and *Adhere to regulations* (2%). We note here that some of these themes relate to the principles and practices of responsible innovation (as cited in Stilgoe et al., 2013). For example, the anticipation of consequences that occur "upstream" of development relates to themes of *Follow the precautionary principle* and *Consider long-term planning and/or management*. However, other stakeholder-identified definitions of responsible innovation again focus on "downstream" impacts of products, such as *Create effective & efficient products* and *Improve the world*.

3.1.2. What does it mean to NOT innovate responsibly?

When asked "Similarly, in your own words, what does it mean to NOT innovate responsibly" (Q2), participants also largely considered EHS contexts (Fig. 1B). For example, 69% of participants indicated that to not innovate responsibly meant to *Ignore environmental and human health impacts*, as described by a participant as "Conducting research just aiming at innovation and achievement, and ignoring the impacts on the environment and society, such as generating pollutions, doing harm to humans, animals, plants, etc." The second most mentioned theme to what it means to not innovate responsibly was to *Focus solely on profits or self-interest*, mentioned by 20% of participants and exemplified by the quote "Irresponsible innovation is myopically looking at either the bottom line, very short-term benefits, or efficacy of technology without looking at the bigger picture." The third most frequently mentioned theme was to *Harm environment, health, and/or society*, mentioned by 15% of participants and exemplified by "You undertake an activity simply because you can, with little or no regard for implications on humankind or the environment." Other themes that emerged included *Not follow ethics and/or the scientific method* (11% of participants), *Ignore societal impacts* (9%), and *Replicate existing inequities & biases*, *Not focus on important topics*, *Lack of transparency*, and *Conduct innovation for innovation's sake* – all mentioned by 7% of participants. Other themes included *Create inefficient or ineffective products*, *Avoid regulatory scrutiny*, *Not engage stakeholders*, and *Not consider alternatives* – all mentioned by 5% of participants.

3.1.3. What are practices of responsible innovation?

Similar to results shown in Fig. 1A and B, participants also largely framed responsible innovation practices within contexts of EHS studies, when asked "Regarding nanotechnology innovations in food and agriculture, what practices should researchers pursue to ensure that they innovate responsibly" (Q3). The stakeholder responses to Q3 are show in Fig. S3 in SI, as they are complementary to results shown in Fig. 1 above. The most commonly mentioned theme in terms of the practices researchers should pursue to ensure responsible innovation was to *Consider studies on EHS*, mentioned by 67% of participants, as exemplified by the stakeholder quote "Consider impact of nanomaterial on environment, toxicity and safety, human health." The second most commonly mentioned practice was *Engage stakeholders* (31% of participants), as exemplified by the quote "A range of stakeholders should be involved from the outset to consider the benefits, costs, and risks of research." The third most mentioned practice was *Improve transparency & communication* (16% of participants), as exemplified by the quote "Full transparency on the presence of nanomaterials in any food or agriculture product." Other practices mentioned include *Reflect on goals* (13% of participants), *Inform innovation with consumer values & concerns* (11%), as well as *Implement adaptive management/research*, *Adhere to regulations*, *Analyze risks* vs. *benefits, Collaborate interdisciplinary*, *Consider sustainability/efficiency*, and *Follow ethics* – all mentioned by 9% of participants. Other themes that emerged included *Consider societal impacts* (5%), *Life cycle assessment/systems thinking* (5%), *Ensure access to innovations* (4%), *Improve monitoring* (4%), *Compare to conventional agriculture* (2%), *Follow good scientific practice* (2%), and *Use precautionary principle* (2%).

3.1.4. Views of responsible innovation pillars

Participants were then asked to respond to a series of statements related to the pillars of responsible innovation (following Stilgoe et al., 2013), that was previously developed and used to probe stakeholder attitudes towards the principles and practices of responsible innovation of biotechnology (Roberts et al., 2020) (Q4). In our study, stakeholder responses to the quantitative Likert-type questions regarding EHS contexts were more positive than responses to other questions that reflected other areas of responsible innovation from the scholarly literature; aligning with stakeholder responses to open-ended questions on views of responsible innovation discussed above (Fig. 2, Table S1 in SI). For instance, nearly all participants agreed or strongly agreed with the following, in descending order of agreement: i) "Considering potential environmental and social implications of nanotechnology products is important in all stages of research" (98% of participants) (related to pillar of *anticipation*); ii) "Reflecting on the underlying purposes, motivations, and uncertainties that surround nanotechnology products is important" (95%) (related to *reflexivity*); and iii) "Maximizing stakeholder engagement leads to better nanotechnology policy" (93%) (related to *inclusion*). Further, 84% of participants agreed or strongly agreed with "Social scientists, environmental and health risk analysts, and ethicists should be involved from the early stages of nanotechnology innovation" (*inclusion*) and 76% agreed that "Innovators should consult with consumer and environmental advocacy groups during research and development in nanotechnology" (*inclusion*). In addition, 62% of participants agreed or strongly agreed with "There should be a standard of at least 10% of public funding for research in nanotechnology that goes to environmental, social, legal, and ethical implications research" (adhering to *anticipation* and *inclusion*) as well as "The nanotechnology innovation process should respond to public attitudes or values" (*responsiveness*). Finally, only 49% of participants agreed or strongly agreed with "The innovation process should respond to public attitudes or values, even if this means delaying, modifying, or terminating a nanotechnology project" (*responsiveness*), which was the statement that had the greatest amount of disagreement from participants (18%). We note here that these results align with previous studies of stakeholder views of responsible innovation applied to biotechnology sectors, as Roberts et al. (2020) found stakeholders were less willing to implement *responsiveness* practices if it means delaying innovation, and therefore there was less agreement among stakeholders towards this pillar of responsible innovation compared to other pillars.

3.2. Views of nano-agrifoods case studies

3.2.1. Case studies adhering to responsible innovation

After reading through five case studies of nano-agrifoods, participants were asked to indicate their level of agreement that the case studies were an example of responsible innovation using a scale from 1 to 5 (1 = Strongly disagree; 5 = Strongly agree) (Q5). Across the case studies, D (Zinc oxide nanoparticles to combat citrus greening) received the highest mean score of agreement (Mean (M) = 3.64, Standard deviation (SD) = 0.97), closely followed by B (Nanoparticle-encased *Salmonella* vaccine; M = 3.49, SD = 1.03) and A (Lemongrass nanoemulsions for fresh cut fruit; M = 3.25, SD = 0.97) (Fig. 3, Table S2). The case study that had the least level of agreement that it is an example of responsible innovation was case study E (Titanium dioxide nanoparticles in infant formula, M = 1.58, SD = 0.92) followed by C (Nano-copper as dietary supplement, M = 1.87, SD = 0.79) (Fig. 3, Table S2).

A similar pattern of results was found when participants were asked to rank the case studies according to how best they adhere to their definition of responsible innovation, using a scale from 1 (most responsibly innovation) to 5 (least responsibly innovated) (Q6). Across all participants, case study B (Nanoparticle-encased *Salmonella* vaccine) was ranked highest overall in terms of most adhering to responsible

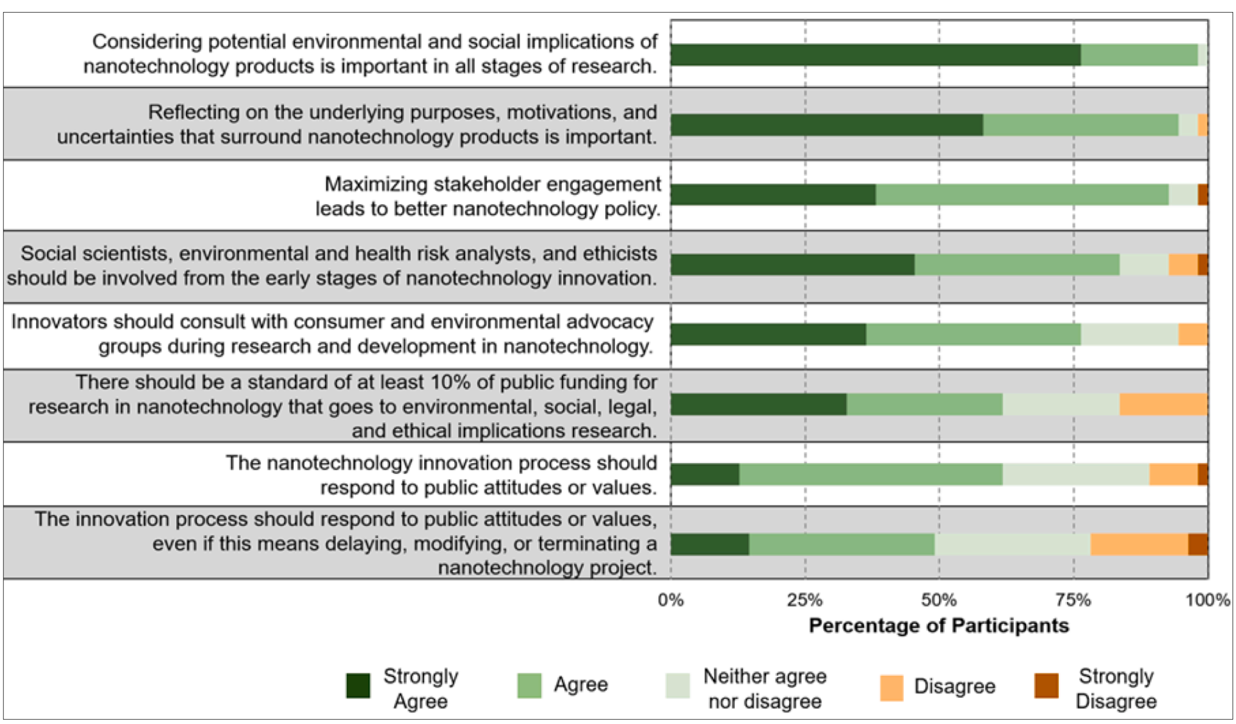

Figure 2. Views of responsible innovation pillars within nanotechnology context. Responses to "How much do you agree with the following statements?" Table S1 in SI provides percentages of participants who agreed/disagreed with each statement. Questions were based on Roberts et al. (2020) and are presented here in descending order of agreement ("strongly agree" and "agree" combined).

Fig. 2. Views of responsible innovation pillars within nanotechnology context. Responses to "How much do you agree with the following statements?" Table S1 in SI provides percentages of participants who agreed/disagreed with each statement. Questions were based on Roberts et al. (2020) and are presented here in descending order of agreement ("strongly agree" and "agree" combined).

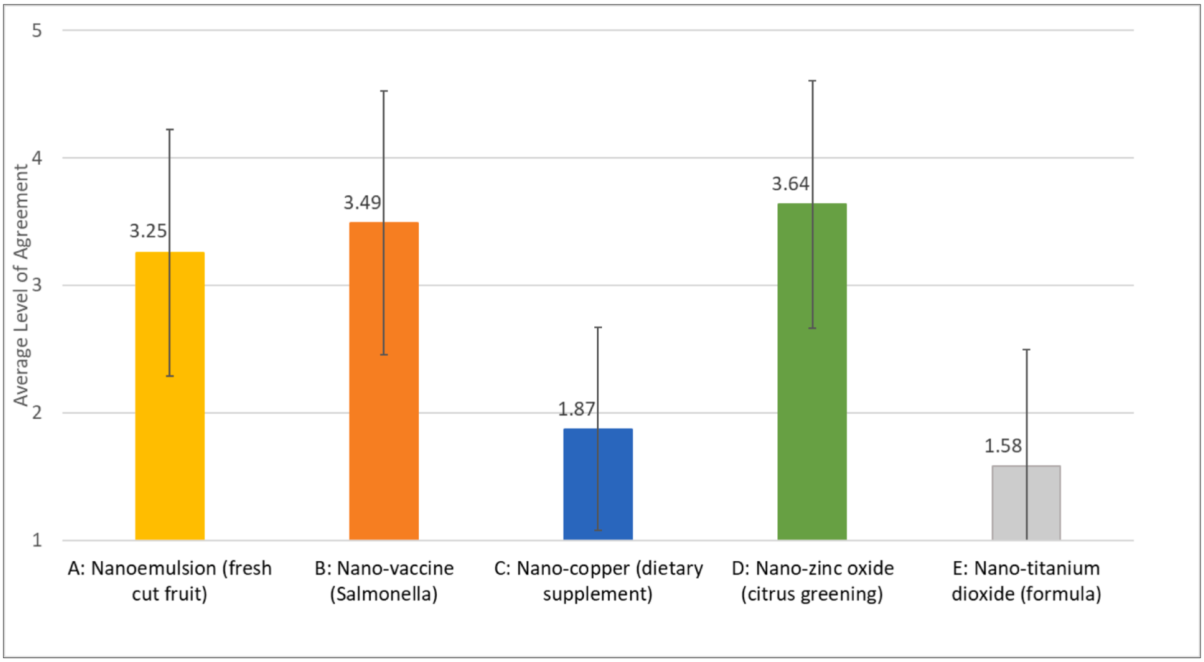

Figure 3. Views of nano-agrifood case studies as examples of responsible innovation. Responses to "Please indicate your level of agreement with the following statement: The nanotechnology application described in this study is an example of responsible innovation" (1 = Strongly disagree, 5 = Strongly agree).

Fig. 3. Views of nano-agrifood case studies as examples of responsible innovation. Responses to "Please indicate your level of agreement with the following statement: The nanotechnology application described in this study is an example of responsible innovation" (1 = Strongly disagree, 5 = Strongly agree).

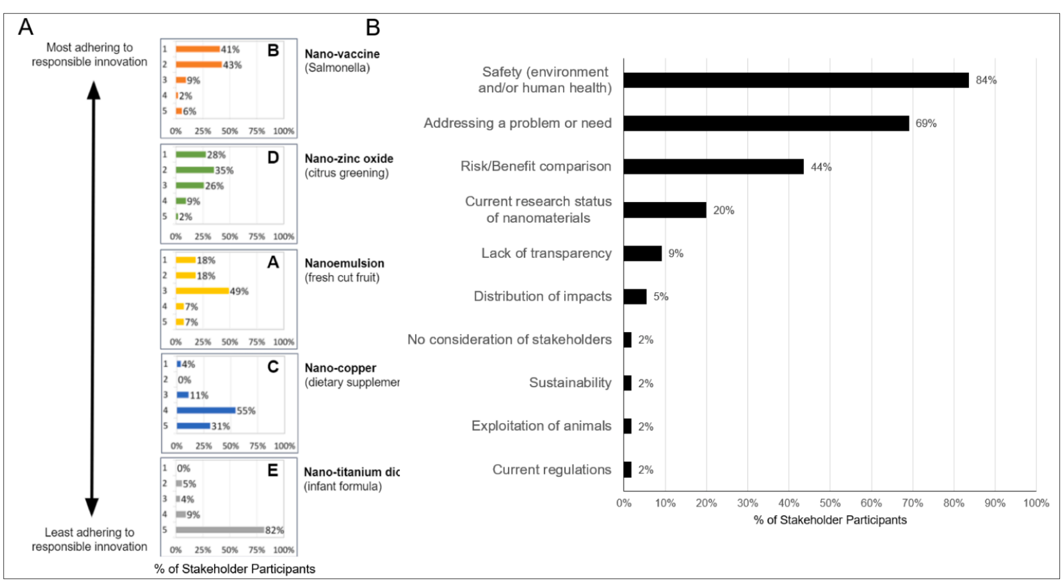

Figure 4. Ranking of nano-agrifood case studies according to how well they adhere to responsible innovation and factors that influenced rankings. A: Participant responses to "Please rank the nano-agrifood case studies in descending order according to how best they adhere to your definition of responsible innovation" (1=Most responsibly innovated; 5 = Least responsibly innovated). B: Participant responses to "What were the three most important factors that influenced your ranking?"

Fig. 4. Ranking of nano-agrifood case studies according to how well they adhere to responsible innovation and factors that influenced rankings. A: Participant responses to "Please rank the nano-agrifood case studies in descending order according to how best they adhere to your definition of responsible innovation" (1 = Most responsibly innovated; 5 = Least responsibly innovated). B: Participant responses to "What were the three most important factors that influenced your ranking?"

innovation, as 41% of participants ranked it as the most responsibly innovated case study and 43% of participants ranked it as the second most responsibly innovated case study (Fig. 4A). Next, case study D (Zinc oxide nanoparticles to combat citrus greening) was ranked second highest in terms of adhering to responsible innovation, as 28% of participants ranked it as most adhering, 35% ranked it as second most adhering, and 26% of participants ranked it as third most adhering case study. Case study A (Lemongrass nanoemulsions for fresh cut fruit) was ranked next, as 49% of participants ranked it as third most responsibly innovated case study, followed by case study C with 55% of participants ranking it as the fourth most responsibly innovated case study. Finally, case study E was overwhelmingly ranked as least adhering to responsible innovation, whereby 82% of participants ranked it last. These results also align with previous studies that nanotechnology for food and agriculture is more acceptable when it addresses important health, nutrition, and safety issues as opposed to more aesthetic characteristics such as taste or appearance (Brown and Kuzma, 2013, Brown et al., 2015, Yue et al., 2015a, 2015b).

When asked to provide the top three most important factors that influenced participant rankings of the case studies (Q7), participants largely cited EHS impacts – a finding that aligns with results reported in *3.1. Views of Responsible Innovation.* For example, 84% of stakeholder participants indicated that *Safety (environment and/or human health)* was one of the three most important factors that influenced their rankings of the nano-agrifood case studies (Fig. 4B). This theme was exemplified by the stakeholder quote "how thoroughly was the product studied for potential public health and environmental adverse effects, what did the results show about the potential to cause such effects, what are the uncertainties surrounding the evaluation of such effects." In addition, participants also indicated that their rankings were based on *Addressing a problem or need*, mentioned by 69% of participants, as exemplified by the stakeholder quote "Necessity of the product developed. Benefits versus the Risks. In some cases (for example the salmonella vaccine) the innovation development really serves a purpose of filling a problem that exists where some segment of the society may benefit greatly from in other cases, the development of the innovation is completely unnecessary, and is not likely to be publicly acceptable (i.e., using titanium dioxide in infant formula)." *Risk/Benefit comparisons* were the third-most mentioned theme (44% of participants) and exemplified by the stakeholder quote "Risk/Benefit comparison" and "my perceived risk vs. reward," followed by *Current research status of nanomaterials* (20% of participants) as exemplified by the stakeholder quote "whether there has already been research showing a negative effect, whether additional research is continuing." Other themes that influenced participant rankings included *Lack of transparency* (9%), *Distribution of impacts* (5%), as well as *No consideration of stakeholders*, *Sustainability*, *Exploitation of animals*, and *Current regulations* – all of which were mentioned by 2% of participants.

3.2.2. Views of case studies according to responsible innovation traits

When asked to rate the nano-agrifood case studies according to traits of responsible, useful, safe, superior to alternatives, beneficial, and not risky using differential semantic scales (scored 1–10, Q8), participant responses revealed a consistent pattern. Results show that case studies D (Zinc oxide nanoparticles to combat citrus greening), B (Nanoparticle-encased *Salmonella* vaccine), and A (Lemongrass nanoemulsions for fresh cut fruit) were consistently viewed more favorably than case study C (Nano-copper as dietary supplement) and E (Titanium dioxide nanoparticles in infant formula) (Fig. 5, Table S3 in SI). Overall, case study E was rated as the least favorable case study across the differential rating scale questions in Q8. This finding is also consistent with results from Fig. 4A in which participants overwhelmingly ranked case study E as

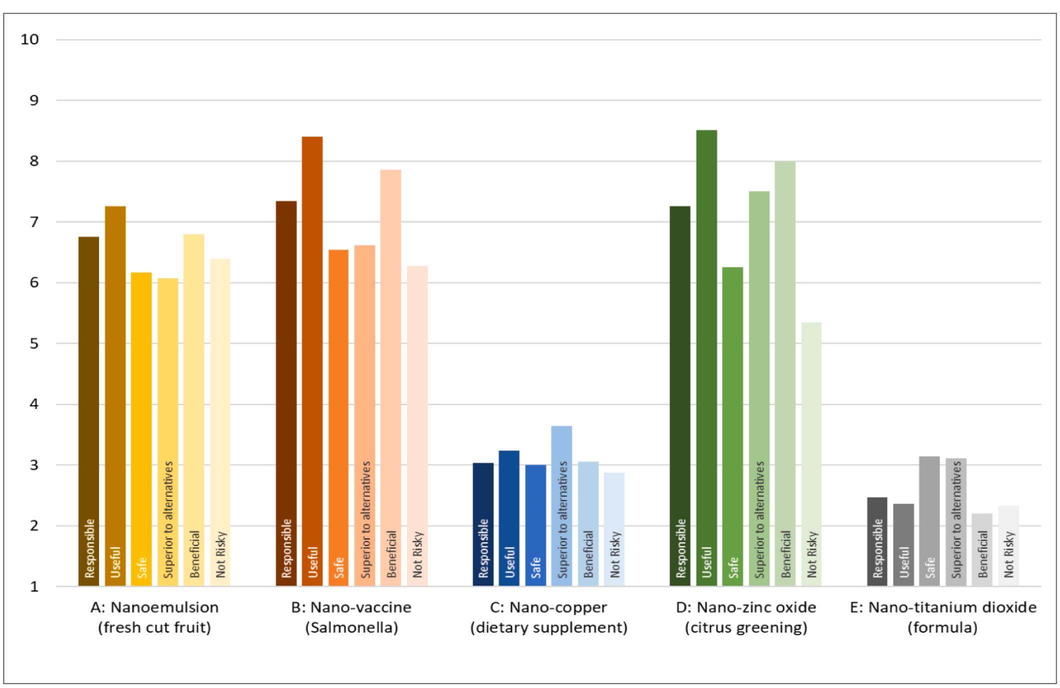

Figure 5. Views of nano-agrifood case studies, according to traits of responsible, useful, safe, superior to alternatives, beneficial, and not risky. Participant responses to "Please use the slider to rate the application of nanotechnology described in this case study on the following traits. Use the slider to indicate your response based on your own judgment" (Scale 1-10).

Fig. 5. Views of nano-agrifood case studies, according to traits of responsible, useful, safe, superior to alternatives, beneficial, and not risky. Participant responses to "Please use the slider to rate the application of nanotechnology described in this case study on the following traits. Use the slider to indicate your response based on your own judgment" (Scale 1–10).

least responsibly innovated out of all case studies. These findings of stakeholder views of case studies according to responsible innovation traits were confirmed by statistical analyses using the Kruskal-Wallis Test, a non-parametric equivalent of an ANOVA with pairwise comparisons (Gibbons, 2011) in SPSS version 26 (see full details in Tables S3-S4 in SI). Across these traits (responsible, useful, safe, superior, beneficial, not risky), case studies D, B, and A were rated much more favorably than case studies C and E. For example, case study D was rated as the most favorable case study according to traits of being useful (vs. useless) (M = 8.51, SD = 1.65), superior (vs. inferior to alternative) (M = 7.50, SD = 2.3), and beneficial (vs. not beneficial) (M = 8.00, SD = 1.75). Case study B was rated as the most favorable case study according to traits of being responsible (vs. irresponsible) (M = 7.35, SD = 2.59) and safe (vs. not safe) (M = 6.55, SD = 2.09), while case study A was rated as most favorable according to being not risky (vs. risky) (M = 6.39, SD = 2.37). Conversely, case study C was rated as least safe (M = 3.00, SD = 1.62), and case study E was rated as the least responsible, useful, superior, beneficial, and not risky against the other case studies (Fig. 5, Table S3 in SI).

When asked to rate the nano-agrifood case studies according to traits of being hazardous/beneficial to human health/environment/society using differential semantic scales (scored 1–10, Q9), participant responses revealed clear differences across the case studies. Similar to our previous results shown in Fig. 5, case studies B and D were consistently rated most favorable to beneficial traits. Case study B (Nanoparticle-encased *Salmonella* vaccine) was rated most favorable to health benefits (M = 7.65, SD = 1.90) and having equitable distributions of benefits (M = 6.76, SD = 2.41) (and in this case, also distribution of risks, M = 6.55, SD = 2.41). Case study D (Zinc oxide nanoparticles to combat citrus greening) was rated most beneficial to the environment (M = 4.65, SD = 2.31) and to respond to a societal need (M = 7.67, SD = 1.84) (Fig. 6, Table S4 in SI). Case study C (Nano-copper as dietary supplement) was rated as most hazardous to health (M = 7.31, SD = 1.45) and the environment (M = 5.85, SD = 1.90), and E was rated second most hazardous to health (M = 7.04, SD = 2.26). Case study E (Titanium dioxide nanoparticles in infant formula) was rated as least beneficial to health (M = 1.76, SD = 1.26), environment (M = 2.02, SD = 1.55), responding to a societal need (M = 2.07, SD = 1.82), and providing equitable distribution of benefits (M = 3.51, SD = 1.88) and risks (M = 3.23, SD = 2.13) (Fig. 6, Table S4).

3.3. Challenges to nano-agrifood responsible innovation

After completing questionnaires on the nano-agrifood case studies, participants were asked to provide their final thoughts on nano-agrifoods and responsible innovation. When asked to indicate their level of agreement that food and agriculture nanotechnology is being conducted responsibly using a scale from 1 to 5 (1 = Strongly disagree; 5 = Strongly agree) (Q10), nearly half of participants neither agreed nor disagreed (44%) (Fig. 7A). Only 27% of participants agreed that nano-agrifoods were conducted responsibly, while 22% disagreed and 7% strongly disagreed. None (0%) of the participants strongly agreed that nano-agrifoods are conducted responsibly.

When asked "Overall, what do you think is the most important challenge that needs to be overcome to achieve responsible innovation for nanotechnology used in food and agriculture" (Q11), the most prevalent theme among participants was *Limited nature of safety studies (*e.g., study length, design) (Fig. 7B), mentioned by 29% of participants and exemplified by the stakeholder quote "Chronic long-term studies need more support. We're pretty good at steering away from acute risks, but chronic impacts are a major blindspot. They're also the most difficult to remedy." The second most frequently mentioned challenge to achieve responsible nano-agrifood innovation was *Public understanding and acceptance*, cited by 22% of study participants and exemplified by the quote "I think the challenge comes down to educating people about nanotechnology." The *Lack of adequate regulation* was the third most frequently mentioned challenge, cited by 18% of study participants and exemplified by the quote "We need to have an inclusive regulatory process that inspires trust by the general populace in general and as well as the ultimate consumers. As we've seen with the ongoing COVID-19 guidance debacle, we don't do this very well. Until we somehow rebuild the level of trust that people have in what the government (or other regulatory authority) says, we are not going to achieve this." Other identified challenges included *Policy & its impacts/pressures*, *Funding*, and *Stakeholder engagement* – all mentioned by 9% of stakeholder participants. *Innovation that lacks benefits* (5%), *Lack of transparency* (4%), *Cost of safety studies* (2%), *Researcher awareness of responsible innovation* (2%), and *Need more interdisciplinarity* (2%) were also stakeholder-identified challenges to achieving responsible innovation.

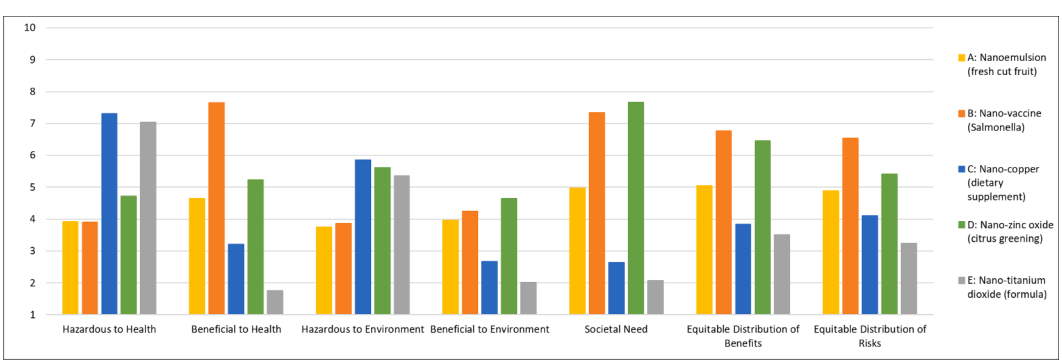

Figure 6. Views of nano-agrifood case studies, according to traits of hazardous/beneficial to human health/environment, societal need, and equitable distribution of benefits/risks. Participant responses to "Please use the slider to rate the application of nanotechnology described in this case study on the following traits. Use the slider to indicate your response based on your own judgment." (Scale 1-10)

Fig. 6. Views of nano-agrifood case studies, according to traits of hazardous/beneficial to human health/environment, societal need, and equitable distribution of benefits/risks. Participant responses to "Please use the slider to rate the application of nanotechnology described in this case study on the following traits. Use the slider to indicate your response based on your own judgment." (Scale 1–10).

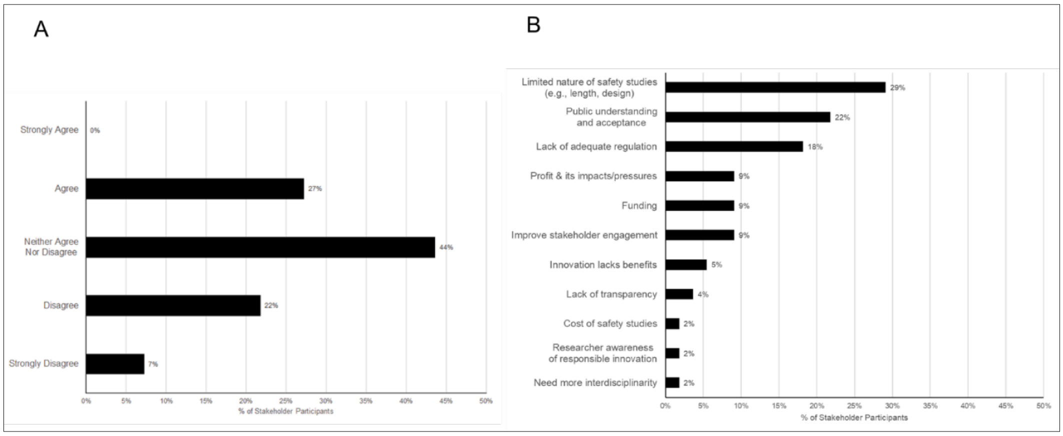

Figure 7. Views of nano-agrifoods and challenges to responsible innovation. A: Participant responses to "How much do you agree with this statement: Currently, food and agriculture nanotechnology is being conducted responsibly?" B: Participant responses to "Overall, what do you think is the most important challenge that needs to be overcome to achieve responsible innovation for nanotechnology used in food and agriculture?"

Fig. 7. Views of nano-agrifoods and challenges to responsible innovation. A: Participant responses to "How much do you agree with this statement: Currently, food and agriculture nanotechnology is being conducted responsibly?" B: Participant responses to "Overall, what do you think is the most important challenge that needs to be overcome to achieve responsible innovation for nanotechnology used in food and agriculture?"

4. Discussion & conclusion

4.1. Views of responsible innovation

Our study was motivated by the desire to understand and elucidate meanings of responsible innovation in communities of practice surrounding nano-agrifoods, as it is important for innovators to understand stakeholder perspectives on what it means to responsibly innovate to fulfill their broader societal obligations. We found that stakeholder views of responsible innovation were largely framed in terms of EHS considerations. This was illustrated by their views of responsible innovation and responsible innovation practices as well as what constitutes NOT responsible innovation. These findings are consistent with overall strategies to pursue responsible development of nanotechnology more broadly, where investigations of EHS impacts often play large roles (Zinsius, 2008, Shelley-Egan et al., 2018, National Nanotechnology Iniatitive (NNI), 2020). However, we note that stakeholders' recommendations to address EHS risks do not align completely with commonly accepted scholarly definitions of responsible innovation, including but not limited to the RI principles from Stilgoe et al. (2013) that also factor in practices of inclusion and the need for diverse perspectives among other aspects. In fact, one of the key interventions in the literature on responsible innovation calls for research and policies that transcend the traditional focus on "downstream" impacts, such as EHS risks, to better incorporate "upstream" practices in innovation ecosystems. As envisioned by researchers, upstream engagement would occur earlier in innovation cycles, and incorporate feedback, perceptions, and values from diverse stakeholders or members of the public. By shifting the focus from the impacts of technology on society (such as the final product and associated outcomes) to the interactions between technology and society (thereby, focusing more on process and practices used to innovate responsibly), upstream engagement promises to move beyond a deficit model of science communication and shape research and development priorities (Rogers-Hayden, 2010). More broadly, the need for better integration and institutionalization of responsible innovation practices within existing organizations and innovation systems has been noted by several authors (Shelley-Egan et al., 2018; van de Poel et al., 2020; Cummings et al., 2021) and seem to be a continuing challenge in terms of institutionalizing theory and practices of responsible innovation outside of academic circles. One starting point to improve the institutionalization of responsible innovation practices could be to implement regular discourse among researchers and innovators in terms of what responsible innovation means, followed by an opportunity to reflect upon their own research and innovation in a broader societal context.

Although stakeholder views of responsible innovation are largely within EHS considerations, they also mention a breadth of broader considerations that are notable. These include ensuring nano-agrifoods address a significant problem or societal need, engaging stakeholders, considering societal impact, and not focusing solely on profit/self-interest. In these four considerations, we can see a subset of stakeholders pointing to a broader set of concerns that have been emphasized in the RI literature (Stilgoe et al., 2013; Groves, 2015; Schroeder et al., 2016; van de Poel et al., 2020; Bauer et al., 2021). For example, nano-agrifood products that do not pose adverse EHS-related impacts are quite different than nano-agrifood products that pose no adverse EHS-related impacts *while also*: i) addressing a significant societal need (as informed by stakeholder engagement activities), ii) not posing adverse societal (i.e., social, ethical, political) impacts, and/or iii) not being pursued for only profit or self-interest reasons. While all stakeholder participants were not calling for these, it is noteworthy that a subset were aware of and calling for these types of considerations to inform responsible innovation of nano-agrifoods.

These results indicate that stakeholder views of responsible innovation were dominated by themes that focused on the impacts of products, whereby three of the four main themes of responsible innovation related to considering EHS and societal impacts as well as responding to societal needs. These themes largely relate to the responsible innovation pillar of *anticipation* (i.e., EHS and societal impacts), and *inclusion* (i.e., stakeholder engagement). Although notions of the pillar *responsiveness* were mentioned by participants (i.e., responding to societal needs), delays to innovation from responsiveness were not acceptable for most participants (i.e., agreed by only 18% of participants). The responsible innovation pillar of *reflexivity* was notably less pronounced than the other pillars but not totally absent (i.e., to reflect on goals of innovation). These findings reveal that stakeholder views of responsible innovation overlap with the scholarly literature on responsible innovation, albeit primarily focused on impacts of products, while the field of responsible innovation encourages research and innovation systems to move beyond a primary consideration of downstream technological impacts to more upstream considerations.

4.2. Views of nano-agrifoods case studies

In terms of stakeholder views of nano-agrifoods, this study reveals that participants consistently viewed case studies D (Zinc oxide nanoparticles to combat citrus greening) and B (Nanoparticle-encased *Salmonella* vaccine) as most adhering to responsible innovation, followed by case study A (Lemongrass nanoemulsions for fresh cut fruit). Case studies C (Nano-copper as dietary supplement) and E (Titanium dioxide nanoparticles in infant formula) were consistently viewed as least adhering to responsible innovation, and participants overwhelmingly (82%) ranked case study E as the least responsibly innovated case study. We also found that participant views of the nano-agrifood case studies were predominantly influenced by EHS impacts, whether the case studies fulfilled a societal need, and risk/benefit comparisons. These results again point to the emphasis that stakeholders place on downstream impacts in aligning with responsible innovation. These results are consistent with the literature on perceptions of nano-agrifoods and nanotechnology more broadly. Several studies demonstrated that perceptions differ across nano-applications (Gupta et al., 2015; Porcari et al., 2019) and risk perceptions increase with applications that are closer to the body or those that are ingested, such as food and agricultural products compared to other uses (e.g., food packaging) (Brown and Kuzma, 2013, Steenis and Fischer, 2016, Henchion et al., 2019, European Chemicals Agency (ECHA), 2020). Other studies have reported that perceptions of nanotechnology were heavily influenced by factors of risks and benefits (Ganesh Pillai and Bezbaruah, 2017, van Dijk et al., 2017), as well as being deemed useful, necessary, and important (Brown and Kuzma, 2013; Brown et al., 2015; Gupta et al., 2015; Yue et al., 2015a, 2015b; Henchion et al., 2019). For example, van Dijk et al. (2017) found that perceptions of nano-food applications were influenced by high levels of perceived uncertainty regarding risks and safety, direct exposures to consumers, and a lack of urgency in using nanotechnology in food products. The European Chemicals Agency (ECHA) also recently reported that stakeholder reluctance to purchasing nanofoods was attributed to perceptions of them being unhealthy, harmful/dangerous, attributed to unknown effects, and unnecessary to use (European Chemicals Agency (ECHA), 2020). Other studies have also found that nano-agrifoods are more acceptable to consumers if they fill an important safety, nutritional, or health need rather than a more frivolous need of taste or appearance (Brown and Kuzma, 2013; Brown et al., 2015; Yue et al., 2015a, 2015b). The low ranking of the nano-titanium oxide in infant formula for whitening and high ranking of the Salmonella-vaccine case study are consistent with this prior work.

4.3. Challenges to nano-agrifood responsible innovation

Overall, stakeholder participants largely held neutral views of nano-agrifoods being responsibly developed. The top three challenges to achieving responsible innovation of nano-agrifoods according to participants were the *Limited nature of safety studies*, *Public understanding and acceptance*, *and Lack of adequate regulation*. Interestingly, these findings are consistent with the top three barriers to responsible innovation of nano-agrifoods that we identified in a recent study based on interviews with 20 nano-agrifood researchers and innovators that involved different study participants (Cummings et al., 2021). In our previous work, the *Lack of data* was the most pronounced barrier to responsible innovation of nano-agrifoods, followed by the *Need for ensuring marketability & use*, *and Lack of product oversight* (Cummings et al., 2021). This finding reveals that the lack of EHS studies, and more importantly the presence of substantial uncertainties related to EHS impacts, continues to be a key challenge to ensuring responsible innovation of nano-agrifoods. This finding comes after several studies and reports have documented the serious role that uncertainties play in evaluating risks and impacts of nanomaterials in diverse applications, including food and agriculture (Grieger et al., 2009; Grieger et al., 2016a, 2016b; Chang et al., 2017; Grieger et al., 2019; Cummings et al., 2021). The stakeholder identified challenge of *Public understanding and acceptance* also aligns with previous studies that have noted that perceptions of nanotechnology are still forming, and hence strategies to help ensure acceptance should focus on clear communication efforts that report the potential benefits of nano-agrifoods (Parisi et al., 2015; Steenis and Fischer, 2016; Chang et al., 2017; Siegrist and Hartmann, 2020). We also note here that the *Lack of adequate regulation* was the third-most cited barriers in our study, although regulatory aspects played a rather limited role in participant views of responsible innovation overall. Therefore, we note this tension in the role of regulation; that is, between its relatively minor role in the concept and framing of responsible innovation compared to its relatively importance in ensuring responsible innovation is achieved for nano-agrifoods more broadly.

4.4. Study limitations

In addition to reporting the results of our study, we also find value in discussing potential limitations of our approach. First, this study reports stakeholder views based on a sample of 55 participants in the U.S. across sectors of academia, government, industry, NGOs, think tanks, and advocacy groups. We recognize that these participants may or may not represent all views within these stakeholder groups, and study participants based in the U.S. may not be representative of stakeholder views in other parts of the world, due to socio-economic and cultural differences. Further, it was not scientifically sound to perform statistical analyses across stakeholder groups to gain insights on how different stakeholder views differed from one another due to the sample size in this study. Larger sample sizes may have allowed for interesting insights into whether, for example, some stakeholder groups held different views of responsible innovation or nano-agrifood case studies differently than other groups. Even so, a smaller number of participants lent itself well to our mixed-method approach of analyzing open-ended items along with closed-ended responses, as well as to the participant interactions in the online stakeholder platform, which may have become overwhelming with a larger number of participants. Second, we chose to conduct our study using an online engagement platform in order to utilize new, virtual engagement approaches that are more convenient for participants and have decreased environmental impacts and costs compared to organizing in-person meetings. We recognize that this approach limited in-depth dialogue and conversations between participants. To address this limitation, we required participants to respond and comment on each other's posts and discussion boards. Third, we conducted the engagement study during the fall of 2020, in the midst of the COVID pandemic, which may have influenced who was able to participate due to time or availability constraints. Fourth, and somewhat related to the last point on participant selection, it is possible that participants who signed up and completed the study may have had more interest in the topic of nano-agrifoods and responsible innovation, and therefore were more eager to participate in the study compared to others. While we recognize this potential limitation, we also acknowledge that this challenge is not unique to this work and can be a common challenge across other stakeholder engagement studies (Bogner and Torgersen, 2018). Finally, we did not provide formal definitions of responsible innovation to study participants, as we were interested in eliciting their views on what it means to innovate responsibly in nano-agrifood contexts. While participants may have lacked familiarity with the broader responsible innovation literature, our study in fact aimed to investigate their views of nano-agrifood responsible innovation without a priori knowledge of the scholarly RI field.

4.5. Future work

In conclusion and in light of stakeholder-identified challenges from our study, future research efforts should continue to investigate EHS impacts of nanotechnology and engineered nanomaterials used in food and agriculture sectors, across a range of materials and applications. Such research efforts would naturally continue and leverage the wide range of nano-safety research programs in the U.S. (e.g., NNI) and within international consortia (e.g., OECD, ISO, EU nanosafety cluster). Complementary research efforts should also focus on developing, applying, and harmonizing strategies for risk-benefit evaluations of nano-agrifoods, given that stakeholders largely viewed nano-agrifood products and their adherence to responsible innovation within risk-benefit framings, following their perceptions of nano-agrifood EHS impacts and whether a problem or need was being addressed. While several frameworks are available to perform risk-benefit evaluations of nanomaterials (van Harmelen et al., 2016; Isigonis et al., 2020; Malsch et al., 2020) and agrifoods more broadly (Ruzante et al., 2017; Pires et al., 2019; Membré et al., 2021), more research is needed to develop, test, and validate risk-benefit frameworks specifically for nano-agrifood products. The availability of risk-benefit frameworks tailored for nano-agrifoods would respond to stakeholder framings of nano-agrifoods and their responsible innovation as well as aid in decision-support. Future work should also explore differences among stakeholder groups and potential barriers to responsible innovation from these differences in perspective. Previous studies have identified barriers to responsible innovation in biotechnology that were derived from differences in attitudes towards responsible innovation based on stakeholder affiliations and individual core cultural values, as well as which pillar of responsible innovation (inclusion, anticipation, reflexivity and responsiveness) is being considered by the stakeholders (Kuzma and Roberts, 2018, Roberts et al., 2020, Kuzma and Cummings, 2021). Future work focused on responsible innovation of nano-agrifoods should explore these and other factors that might drive stakeholder attitudes and pose barriers to implementing practices of responsible innovation of nano-agrifoods. Related to the latter point, investigations into new or different models to engage stakeholders more directly within early stages of nano-agrifood innovation cycles may be beneficial to identify potential barriers and formulate mechanisms for multi-stakeholder engagement and communication with innovators. Finally, future studies should explore stakeholder perspectives and views of what effective regulation looks for nano-agrifoods, given that regulation played a relatively minor role in terms of what it meant to responsibly innovate while it was also the third-most cited challenge to achieving responsible innovation.

Author contributions

KG and JK obtained funding for and oversaw the project; AK, KG, AB, CC, and JK designed study; AK, KG, and MC developed case study descriptions; AK, KG, and MC oversaw execution of study; CC and AB conducted statistical data analysis and provided feedback on presentation of quantitative results; AB and AM prepared figures and guided presentation of findings; KG drafted and revised manuscript; JK, AM, CC, MC provided feedback and revisions to manuscript; AM developed Graphical Abstract.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.impact.2021.100365.

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